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Introduction:

A new sensibility is emerging in our culture. An awareness of the environmental overhead of our civilization that is compelling us to reevaluate our habits and habitat. No longer can we regard the value of goods merely in a context of cost-benefit but must also consider the importance of where and how things are made and their fate after we use them. And such questions not only relate to environmental impact but also community resilience. How and where the things our lifestyles depend on are made can create or break-down economic dependencies, influencing our personal freedom and ability to deal with crisis.

Relating to this, a new independent production or ‘Maker’ movement has emerged, seeing new value in the products of our own individual industry and personal empowerment in the cultivation of an industrial literacy. No mere Do-It-Yourself revival, this movement seeks the cultivation of an ecology of ‘open source’ designs and technologies as a societal commons, whittling-away at market hegemonies and dependencies of the passing Industrial Age, bringing industrial--and with it political and economic--power back to the community.

Much has been made of the new tools of digital fabrication that have come to epitomize both this new movement and a new fourth industrial revolution. But the roots of this movement lay in much simpler technology that has not, as yet, received the curation it has long deserved; multipurpose modular building systems. Though the idea of modular component systems is quite old in architecture and industry, the notion of universal or multipurpose building systems may have its roots in building toys emerging early in the 20th century. The idea then moved to architectural building systems and systems for the creation of novel furniture inspired by Modernist design.

The work of Buckminster Fuller in particular influenced many young designers to consider modular building systems as not only a way of pursuing sustainability through the efficiency of high performance structures, but also a way of empowering unskilled builders through the physical encoding of knowledge into systems of standardized components, as also emerged with the personal computer. Design Science, as Fuller called it, was seen as a potential new means of social empowerment, facilitating personal creativity and industry by reducing the overhead of skill and technical knowledge needed to build. Through the power of modular design we made the computer--the most sophisticated artifact human civilization has so far created--simple enough for a child to assemble in minutes from parts made all over the world. Imagine that applied to the rest of our built habitat!

For independent production to overcome the lure of consumer products it must compete in their context. While the personal cultivation of production skills is valuable in itself, to be a practical alternative to consumer products in meeting everyday needs user-made or ‘prosumer’ goods must offer a comparable convenience and economy. Modular building systems, relying on pre-finished components, afford the user that potential convenience. With a modest household stockpile of parts, self-made solutions become at-hand solutions competitive with the goods in stores. The repurposing of parts as needed affords an essential economy while reducing waste. A particular piece of furniture may become obsolete, but, when based on modular systems, its components can be perpetually reused for something new until they truly wear-out. The most efficient method of recycling is reuse.

Today there exists a vast assortment of modular building systems readily available to the Maker. Most have experience with one to a few. But, until now, there has never been a good overview of these systems and their features. Indeed, users are often unaware of even the general name for the systems they routinely use, knowing them only by the particular brand of product they've stumbled-upon and unaware of the full range of hardware at their disposal. With this book we would like to introduce readers to the broad range of possibilities on offer, presenting a much-needed overview of the basic categories of multi-purpose modular building systems, their key features, and how they work. Within each category we will list specific example systems with either instructions for the fabrication of their parts or manufacturers they can be sourced from. Though many of these systems are utilized at large, architectural, scale, we will emphasize their more modest scale forms suitable to personal use. Though we will focus on open source systems whose parts can be easily user-made, many systems, based on high-performance materials, still require manufacturing beyond the means of the average Maker. The next-best thing to being open source is being multi-sourced or generic. We will also demonstrate each class of system with example projects that readers can build on their own.

Section 1: Bricks, Blocks, and Boxes

Perhaps the first modular building element ever invented was the mud brick or block common to earthen architecture around the world. Deriving from the hand-formed loaf shapes of earlier 'cob' construction, the mud brick afforded more uniformity in earthen wall construction and allowed the material to be fabricated and stockpiled in locations separate from where they might be used for building, facilitating what may have been our first forms of industrial mass production. Brick masonry has been a staple of the built habitat ever since, with most every culture in the world developing its own vernacular forms in common use to the present day. Even the ancient mud/earth brick has found new use in the most sophisticated of sustainable homes and has even been proposed for use in future habitats on the Moon and Mars. But it has only been very recently that we have begun to think of these elements as the components of high-performance structures with a possibility of reuse.

The traditional brick is largely intended to make a high mass building material easier to transport in bulk by reducing the size and weight of unit elements. A more convenient alternative to large blocks of stone and large loose masses of earth. Though inherently modular, it has rarely been used as a modular building system, imposing its topology on the design of structure. Rather it has generally been used as a means of filling space to approximate arbitrary forms that are then trimmed or sculpted to a final shape. It's structures rely on assembly with mortar creating permanent monolithic forms that are not intended for adaptation without careful demolition. It requires a lot of labor and a certain amount of skill to use and the structures produced are not easily recycled. While earthen brick construction offers low environmental impact, the more conventional fired brick has a very high fossil fuel energy overhead in production. And so, while some forms have seen recent revival in contexts like green building, in general the use of brick masonry has long been in decline as building has become a skilled profession with a growing labor cost that, today, is the predominant factor in the cost of building in developed countries.

With the introduction of the Lego brick building toy in 1949, designers and inventors have developed a new perspective on the brick. Lego is a true modular system and its constructions have a very specific topology throughout that all elements used with it must integrate with. Since its introduction, many people have dreamed of being able to build at a larger, more, useful scale with the same snap-together ease offered by Lego. But this has proven difficult to realize as the unique snap-together functionality of Lego is specific to the properties of its plastic at its particular scale. It has been difficult to make larger bricks and other materials perform in quite the same way. Nonetheless, a variety of systems have developed to offer us some of the characteristics of Lego with different materials and forms. A radical new idea has also recently emerged; bricks as 'logic matter' that encode information into their topology and thus afford self-assembly through stochastic kinetic motion. In effect, bricks that align themselves and thus allow structures to come together on their own when their parts are layered or tumbled.

1:1 Interlocking Blocks

Interlocking blocks are blocks with complex shapes that allow them to join together like puzzle pieces, restricting their movement along one or more axis. Interlocking blocks are typically intended to reduce the skill needed in masonry construction while improving the resistance of masonry structures to lateral forces. Countless designs for such blocks have been explored, but none have proven successful enough to supplant traditional brick and block shapes because of the added effort in their manufacture and the brittle nature of most masonry materials. Interlocking blocks are typically limited to constraining movement and locking together along just the horizontal plane, relying on vertical load from their own mass or friction to hold them together. Thus most such block systems are intended to also use conventional mortar and, more recently, advanced masonry adhesives, for permanent construction. However, some function for more modest uses without any additional bonding and so are suited to the modestly skilled builder. These include interlocking landscaping blocks and unusually shaped blocks made of light materials, like gypsum or plastics, intended for decorative uses such as partitions and screens. These can often be repurposed for ad-hoc furnishings and gardening structures and in some cases can incorporate lighting and other electronics within hollow forms.

Recently devised complex block topologies have emerged from research in self-assembling components systems that afford interlocking along multiple planes.

Some new building toys based on these have emerged taking advantage of digital cutting and 3D printing methods. Though still limited to low-strength materials and very light applications, they show promise as the basis of new kinds of construction and more variations of these are likely as digital fabrication becomes the norm, perhaps one day taking advantage of the 'cold welding' phenomenon known to occur with metals in the vacuum of space.

1:1:1 Auram Modular CEB
Compressed Earth Block or CEB is variation on the ancient mud brick developed in the 1950s as a basis for housing in the developing world. It was introduced with a hand-operated machine called the Cinva Ram, invented by Raul Ramirez and named for the Columbian Inter-American Housing Center. (CINVA) As the name suggest, CEB is made by mechanically compressing earth into a dense block, often with the addition of a small amount of cement. This allows earth at a building site to be used directly and rapidly for the creation of a functional equivalent of the adobe brick, and one much more resilient and usable without the protection of a traditional adobe plaster surface 'rendering'. Many manual and powered variations of the Cinva Ram have been developed, including an open source design for a powered block maker developed by the Open Source Ecology project. Recently, engineers have discovered that Martian regolith can be similarly compressed and form a strong dense building block, and so in the future we may see CEB used in settlement structures there --though likely in some form specifically suited to handling by robots.

As CEB slowly gained popularity in green architecture toward the end on the 20th century, attempts were made to improve upon their production and techniques. An important center for this work was the international spiritual community Auroville in Tamil Nadu India --home to some of the most sophisticated earth block architecture in the world. They developed a new approach to the simple earth block that elevated it to the status of a true modular building system. They devised a variation of the Cinva Ram called the Auram Press using interchangeable molds allowing for blocks with complex surface features that could partially interlock, allowing for use with less or no mortar and reducing the skill needed in the construction process. They also devised a large assortment of special purpose block shapes never before used with this material; roofing, ceiling, and floor support shapes, column shapes, and more. These special blocks allow for many more details of a building to be made with the same earthen material and integrated into the rest of the interlocking block structure with ease.

For small simple buildings, CEB is well suited to use by the Maker, though quite high in labor overhead even with the innovations offered with the Auram Press. The manually operated machines usually require three or more people to operate. Powered forms are relatively expensive machines intended more for the commercial builder or intentional community use. The Auram Presses come in both manual and powered forms and are somewhat more expensive than other forms owing to the cost of the many different steel molds. Though having been on the market for over a decade, the Auram Press remains little known in western countries but could greatly improve and advance the use of CEB if properly introduced.

1:1:2 Landscape Blocks
Landscape blocks are a kind of prefabricated concrete block commonly found in many variations at home improvement stores and landscape and construction supply companies. Landscape blocks are intended for use in creating retaining walls, raised gardening beds, garden borders, and some small water features and typically feature a flat wedge shape that allows them to be laid without mortar in overlapping courses following round or curved profiles. They rely chiefly on their mass and the friction between their flat surfaces to hold them together, though a masonry adhesive is also often used. However, a number of these blocks feature grooves, holes, ridges, knobs, and other features allowing them to interlock for greater strength, to create a predetermined slope, or just to provide a more precise, finished, appearance without additional skill. These often come in sets of special blocks for fractional sizes, corners, and top surface caps. Some feature holes or grooves intended to be combined with timber pieces, usually serving for garden and walkway borders. These more modular blocks offer the possibility of repurposing for many alternative uses, though mostly intended for outdoor use owing to their roughness. Structures for outdoor furniture, fire pits and barbecues, small enclosures, complex garden systems, and more can be devised with these modular blocks. Unfortunately, there seems to be no specifically open source designs for these blocks, but many are more-or-less public domain.

1:1:3 Troxes
A derivative of the work on ‘logic matter’ and self-assembling systems being done at MIT, Troxes are a very recently introduced form of modular block invented by Jonathan Bobrow that offers a vast new field of possibilities. Troxes are blocks made of folded card material that form complex interlocking surfaces. Most interlocking blocks are limited to interfacing along one or two planes to restrict sliding movement along that plane. Troxes interface along many planes and thus can form structures with considerable tensile strength. However, this is still limited by the simple light materials currently used with these in order to allow them to be cut from flat sheets and folded together, the blocks currently intended as a creative building toy with decorative uses. These could qualify as a kind of box building system (1:4) but the blocks are not intended to be open and used for storage, though they could easily be fitted with internal elements such as lighting or other mechanisms. Some experiments have already been done with surface-mounted circuitry using the clever Chibitronics line of self-adhesive stick-on electronics components. The very complex

shapes, small size, and light materials of Troxes probably limits their current uses to less practical applications, but this is just the beginning for this interesting invention and we may well soon see more durable molded/3D printed blocks with larger sizes.

1:1:4 Waterbricks

In 1963 the Heineken beer company tried a clever experiment in design-for-reuse by creating a new kind of bottle called the WOBO, or World Bottle. Noting that many sustainable architecture enthusiasts had explored the repurposing of glass bottles as bricks in the construction of low-cost homes, they decided to design a brick-shaped stacking beer bottle specifically for this purpose so as to create a steady supply of recyclable bottles to support relief housing projects. The experiment was short-lived, the logistics of collecting and transporting all these empty bottles too difficult, but inspired the occasional follow-on project to make waste bottles and other consumer packaging easier to up-cycle.

One of the latest ideas along this line is the Waterbrick, made by the US company Waterbrick International. The Waterbrick is a molded polyethylene bottle designed to stack very stably while also providing many possibilities for repurposing and, ultimately, easy recycling. The bottles come in two basic forms; a 9″ x 18″ x 6″ 3.5 gallon block and a 9″ x 9″ x 6″ 1.6 gallon block. These, in turn come in variants for liquid storage or dry goods storage as well as a variety of colors. The Waterbrick's primary purpose is to provide long term storage of water and food and is marketed for both relief and emergency preparedness uses. However, it can also be used as a convenient form of storage for many kinds of items and put to many alternative uses such as cooling blocks, sand-filled bullet-resistant barriers, partitions, supports for simple forms of furniture, flotation structures, play structures, and even relief shelters or small houses and buildings.

1:1:5 Gablock (https://gablok.be/)

Another Lego-inspired concept, the Belgian-made Gablock system employs a novel combination of box building system and stacked, interlocking, blocks as the basis of a full home construction system. It is based on the use of remarkably simple blocks made of CNC-cut oriented strand board panel glued and nailed together and then filled with pre-formed expanded graphite/polystyrene blocks providing insulation and a pair of 'studs' (as they are called with Lego) over which the next layer of blocks fit. Layered in an alternating pattern starting with baseplates bonded to a slab foundation, the blocks need no other interconnection or any adhesives, though angle plates are used to affix walls to floors and so-called 'screwed rafters' attach roof systems. The blocks are thick but light, allowing for easy handling by the individual. In addition, a kind of box-beam or box-truss is used for flooring decks. Roofing must use other systems, with the manufacturing offering prefab truss roofing matched to a chosen design. Exterior and interior cladding are conventional, the walls and floors providing a SIP-like surface for conventional nail and screw attachment. Specifically intended to aid the owner-builder, the Gablock offers a very easy method for building a super-insulated structure that could be easily learned by the unskilled. And though not ideally based on sustainable materials, the use of OSB makes for a greener material than conventional lumber (in Europe, at least…) and offers the possibility for other lumber alternatives. However, as a patented system limited to a single company, it's development is constrained and it may not see as much future experimentation as it might with open building systems.

1:2 Snap-Lock Blocks

Typified by the famous Lego toy, snap-lock blocks are block building systems that rely on the friction between interlocking features to hold them together. This affords them the ability to potentially interlock in all axis, but is generally not intended as a permanent or durable bond so that they can be easily disassembled and reused. Such capability has been limited largely to plastics and the features of Lego have long proven difficult to replicate with other materials and at larger scales. However, recent innovations have actually realized the long-dreamed-of 'Lego for adults' suited to building light temporary structures and novel furnishings.

1:2:1 Lego

Perhaps the most famous, successful, and ubiquitous of all modular building toys, Lego had its origins in a British building toy called Kiddicraft developed and patented in 1939 and then, delayed by war, released to market in 1947. It was adopted and modified for injection molding by the Danish Lego toy company in 1949. Lego long produced a diverse line of toys that included scale model cars, but eventually came to concentrate primarily on the building toy that now bears its name.

Lego bricks represent one of the most universal modular building systems ever devised, with thousands of different standardized components, more and less specialized, all conforming to a common topology and interface. Though considered a 'toy' it is probably the most well developed modular building system in human history and continues in vigorous innovation to this day. Made with a durable ABS plastic, Lego bricks rely on the friction between the interlocking knobs and hollows of the brick forms to hold structures together, achieve a special limit on the tensile strength of this bond that balances the durability of structures against their easy disassembly, thus making for a very pleasing building toy. Over decades of refinement, Lego has realized a characteristic aesthetic that now carries its brand far beyond the building toy to things like games, computer software, clothing, and even movies and the company has its own chain of specialty stores and even theme parks. It may be the first modular building technology to realize its own category of literature.

Lego has long inspired its users to seek alternative uses for the toy parts in order to apply the same aesthetic and reusability to more practical objects and uses. Lego bricks are commonly used as tools for many crafts, such as resin casting, and people have experimented with the bricks for use in all sorts of furniture, electronics enclosures, and more. It has often been used in education and for the prototyping of new machines, which the company capitalized on with the development of the Lego Technic system, integrating into Lego many features similar to those of the Meccano and Fischertecnik building toys used in mechanics and robotics education. This eventually led to the development of the Lego Mindstorms platform for hobby robotics. However, the small sizes of Lego components continues to limit its large scale uses, compelling people to try and reinvent a ‘Lego for adults’, and for homebuilding in particular. Most of these attempts have seen mixed results as the physical properties of Lego are very keyed to the properties of their plastic at their usual scale. They don’t behave in quite the same way at large sizes and with different materials. But, recently, some promising products have emerged such as the EverBlock building system. (1:2:3)

1:2:2 Locking/Linking Cube Toys

Lego has inspired countless imitators, but few have proven as effective or sustainable. One exception are the largely generic lines of locking/linking cubes. These are cubes, usually of a one or two cubic centimeter size, made of injection-molded polypropylene plastic that feature an alternating pattern of holes and knobs allowing them to interlock. Some sets include blocks in other prismatic polygon shapes to combine with the cubes. These toys have been developed primarily for use in education and have seen little adoption outside that area because, curiously, they have been sold almost exclusively through teaching supplies channels. Though nowhere as popular as Lego, they have a somewhat better ability to create pixelated pictures and sculptures like those of video game sprites and Minecraft models, often featuring a much broader range of colors, and have been used for computer and mathematics inspired art. But they’re friction interface is much weaker than that of Lego and so they have not been put to the same kinds of repurposing.

1:2:3 KOOV (pending Indiegogo campaign)

KOOV is a newly introduced building toy created in collaboration with the Sony Corp. combining a novel form of linking cube and a set of modular programmable electronic and electromechanical elements that is intended as a teaching tool for programming. Bearing some similarities to cellular robot building toys, only a small number of specialized components are actually active elements, more intended to add programmable motion or animation to figures created with the non-active blocks, much like the robotics elements long featured in more advanced Lego kits. KOOV features an interesting system of blocks made of colorful gem-like plastic based on a cubic grid but with seven different unit shapes as well as platform pieces. Active components integrate with matching socket grid surfaces. A microcontroller core unit integrates the active elements while a visual programming language based on a mobile device application allows programming through a USB cable link.

1:2:4 EverBlock
Often described as 'Lego for adults', EverBlock may be the first successful attempt to produce a Lego-like modular building system at a scale of components suitable for furniture and small shelters. EverBlock is very similar to Lego but with square rather than round knobs and basic blocks at a size of 12" x 6" x 6", 6" x 6" x 6", and 3" x 6" x 6". Additional components include cap, footing, shelf, lintel, and desk/counter top pieces, illustrating its intended uses in furniture and room partitions. Reinforcement pegs offer additional strength for large structures and larger wooden dowels and threaded rod can also be added. Lintel pieces serve as mounting for window and door frames and the blocks can be easily illuminated internally for novel lighting uses.

EverBlock fulfills many of the promises of an adult scale Lego and has been experimented with for light shelter use. The blocks are quite strong and can bear significant loads. However, they're not waterproof by themselves, have no insulation, and no means, as yet, for integrating floor and roof support systems. Though relatively light, they are bulky in great numbers. And being in limited production at present, prices are high. Still, the potential of this building system is probably almost as great as the Lego toy that inspired it and has only just begun to be explored.

1:2:5 Frutonyanya (Фрутоняня) Bottle Caps
Frutonyanya is a Russian-made fruit puree product for infants whose multi-colored plastic bottle caps are uniquely designed to be repurposed as a building toy. With a stacking hexagonal prism block shape, the bottle caps feature side grooves allowing them to stick together by friction-fit side-to-side allowing for the assembly of various shapes conforming to a hex pattern. A clever example of design-for-reuse in packaging.

1:3 Mechanically Joined Blocks
Since the stone masonry of ancient times, the mechanical joining of blocks has been used as a way to improve the lateral strength of masonry structures. In the past this was achieved by carving dovetail or 'T' shaped depressions into the top surfaces across blocks and then pouring molten metal into the depressions to make a solid joint across them. Variations on this technique developed more-or-less independently in many parts of the ancient world. With the advent of industrial machining, the use of various bolted mortar-less connections between masonry blocks was frequently experimented with but struggled with the same limitations of

interlocking blocks due to the brittleness of typical masonry materials. However, with the advent of reinforced concrete it became practical to form-in-place many kinds of alloy fittings to allow for the mechanical assembly of precast building elements. These have tended to be based on quite large components, but some more modest scale mechanically joined cast block systems have been developed, chiefly for the purpose of emulating old cut stone masonry without the high skill that traditionally requires. Such blocks feature hollow cores with mechanical fittings intended to host steel bolts that link facing blocks together along one or more axis. These still tend to be based on quite heavy blocks much larger than the traditional brick, sometimes requiring the assistance of heavy lift equipment.

1:4 Magnetic Blocks

Magnetic blocks are simple blocks held together by the magnetic attraction between internal magnets or magnetic and metal elements. Until recently, the magnetic power of typical permanent magnets limited this approach to toys which had limited appeal as the fixed polarity of magnets limited possible ways of joining them. There was also a chronic problem of small magnets becoming dislodged from a block and ingested by small children. However, the introduction of powerful neodymium magnets has seen the introduction of new building toys based on them, though some of the problems still remain. (product recalls due to misuse by young children a persistent issue) However, some clever solutions to the polarity issue have emerged allowing for much more versatile connection, though these generally still remain limited to use in toys.

Magicube

Magicube is a magnetic block toy that allows it plastic blocks to link to any side in any orientation. Similar in size to traditional wooden blocks and thus suitable for young children, Magicubes feature both solid color designs and printed character designs along with some accessories such as magnetic card shapes in the form of animals. Magicube is made in Switzerland by the Geomagworld company, producers of the original Geomag magnetic ball and stick space frame toy.

PIXL

(https://www.kickstarter.com/projects/antsylabs/pixl-a-magnetic-building-system)

PIXL is a new magnetic building toy that cleverly overcomes the limitations of polarity alignment with old magnetic block toys through the use of internal magnets that can freely rotate. Thus these simple cubic and rectangular blocks can freely join on any side. Using powerful neodymium permanent magnets, they can form strong connections allowing for large assemblies. Several sizes of blocks from one to six unit cubes allow for filling in larger volumes or lengths. With a large pallet of 52 colors and a very small unit size, PIXL blocks are intended to be used in the manner of computer pixels or pearler beads to create dimensional pixel art. The very small size of the blocks precludes their use by young children.

1:5 Box Building Systems

Masonry materials are generally heavy and rough and thus both high in labor to use and not well suited to things like interior furnishings. Where the high compression strength of these materials isn't necessary many modular building systems have employed hollow boxes instead, most often made of wood and plywood. This has been common for many kinds of simple modular shelving and storage systems and are easy for the maker to create from various materials and in various designs, often by upcycling packaging and other waste materials. There are many commercially-made modular shelving systems that consist of nothing by simple wooden boxes in standardized sizes/shaped designed to neatly stack into larger assemblies, sometimes with added forms of attachment to improve their sturdiness. More recently, boxes has been used for the construction of homes and buildings based on CNC fabrication. Relatively large box elements puzzle-fit assembled from machine-cut sheet materials are used as large building blocks which can contain insulation and utilities channels or other fittings and are joined together mechanically, using bolts and screws. In some cases these are used in hybrid building systems, combining engineered wood beams.

1:5:1 Crates

Perhaps the most common of all forms of boxes to be repurposed as a modular system have been the commercial wooden and plastic crates commonly used for the shipping of various foods to stores. The most popular of these have been the plastic milk crates used for shipping milk cartons, which were specifically designed for long term reuse and were much more standardized in size. Long repurposed for storage, shelving, and displays in the stores that received them, milk crates were popularized for home use by early proponents of 'upcycling' --so much so that their theft from stores became a common problem as they were not commonly available to the general public. Today they can be found from many sources, with many specifically made as consumer products, though often of non-standard size and generally inferior in the quality of plastic used. A few have been re-designed specifically for their new role as modular shelving, featuring formed-in knobs and holes to help them nest together more easily, sometimes pre-formed places for holes to accommodate connecting bolts, and more uniform cube shapes, the original crates being a bit more rectangular. But the traditional commercial style crate still remains the most popular.

The standard milk crate is designed to stack vertically, the bottom edge of the crate recessed to nest within the top of the crate beneath it. To be used in other ways one must employ other kinds of connection. The simplest is the use of zip-ties but for more permanent assemblies the more solid edges of the crates can accommodate the use of bolts in drilled holes. Wooden spacers, cut to fit in the channels along the edges of the crates, can help in preventing the crates from slipping when stacked side-on-side. When properly secured, fairly large assemblies of crates are possible with little modification. The open grid in the sides of the crates can accommodate dowels or pegs, allowing for the addition of dividers or shelf planks. When used as shelving it's common to use a small piece of board--cardboard, pressboard, or wood, in each crate to create a smoother surface protecting items stored in them, particularly when used for books or records which can have their edges damaged by the open grid.

1:5:2 Bolted and Mechanically Joined Boxes
Many kinds of modular box shelving/cabinet systems feature various forms of connection to make their stacked assemblies sturdier. This can be as simple as the use of zip ties, metal clips and clamps, or bolts. More elaborate designs may feature the use of concealed pin connectors based on cam-locks or similar joint connectors designed specifically for furniture use. With secure joining of their edges and a sturdy means of side-to-side connection, hollow boxes can be used as strong structural elements. Architect Shigeru Ban is well known for his 'furniture series' of home designs which derived from his observation that furniture fabrication often produced much stronger, more durable, structures than was typical of housing construction. And so he began pursuing home designs where reinforced modular furniture--shelving and cabinets--was designed specifically to serve double-duty as the load-bearing elements of a house. With the advent of CNC fabrication, new homebuilding systems have been devised based on the use of large hollow plywood boxes as basic structural elements, joined together with bolts or screws and sometimes used in combination with wood beams or trusses. Few of these system have been truly demountable modular systems, however, relying instead on the manufacture-on-demand capability offered by CNC fabrication to allow for more economical ad hoc construction. However, the potential is there to make truly modular building systems based on such elements.

1:5:2:1 Clamp and Clip Box Shelves
1:5:2:2 Angle Joined Boxes
1:5:2:3 CNC Box Building Systems

1:5:2:3:1 House Block (https://automatedarchitecture.io/)

Developed by the design team Automated Architecture Ltd. in the UK, House Block is one of the first CNC-based box building systems to employ a fully standardized topology intended to facilitate unskilled end-user construction of home scale structures as well as robotic construction. While seeing much use in CNC-based plywood house building systems, most uses of box building systems have been proprietary or bespoke in nature, not intended to be demountable, and often used in combination with laminate beam systems. House Block is the first attempt at a universal building system that is fully demountable, allowing for spontaneously created and freely changed structures. However, accomplishing that while including insulation and maintaining a waterproof shelter has yet to be fully worked out with this system.

House Block is based on plywood boxes cut by CNC and assembled with glue. These are then bolted together along the faces of the boxes using steel bolts and washers accessed from an opening in one box face. This is an intuitive building process thanks to the natural simplicity of these box elements. Some box faces appear to have shou sugi ban surface charring treatment as a means of preservation. The system is intended for both light house construction and furniture design and there is expectation of adding to the system with active elements contained in similar box modules. Though touted as an imminent low-cost housing solution, the system of clearly very experimental at present and it remains unclear if there are any plans to make the system Open Source as other CNC building --originating in the Fab Lab community-- have tended to be.

1:5:2:3:2 U-Build (https://u-build.org/)

A CNC-made box block building system designed very specifically for unskilled assembly and easy disassembly and reuse. Very similar to House Block and, likewise, developed in the UK. It is unclear from the web site information if there is any relation to that project. It appears to have a more refined foundation, drainage plane cladding, premade rubber roofing, and finishing approach. Though it is not considered Open Source, the developers claim to have fostered comparable freedom of use, while being somewhat doubtful about the Open Source concept. Found use in creating spontaneous structures for Extinction Rebellion protests. Kirsten Dirksen video: https://www.youtube.com/watch?v=dmeiZ90BKH8

1:6 Self-Assembling Blocks and Logic Matter

In recent years a new field of modular design has emerged thanks to the work of MIT's Self-Assembly Lab, founded by designer and computer scientist Skylar Tibbits. (http://www.selfassemblylab.net/) Systems of modular components have been devised that can self-assemble when more-or-less random motion is imparted to them, their unusual topology allowing the modules to link together only in certain correct ways so as to form a specific structure. Motion can be imparted to these modules by shaking, tumbling in rotating drums or baskets, or with the flow of fluids. In some designs these modules have changeable features that allow them to be ‘programmed’ for particular alignments, thus allowing series of modules to incorporate a kind of program to control the way they assemble, hence the term ‘logic matter’. By this means sets of modules applied serially can, in a way, ‘knit’ themselves into complex structures. At present no commercial applications for this technology has emerged but the availability of 3D printing affords an option for makers to experiment with this new technology.

1:7 Cellular Block Robots

It is possible for modules in a building system to incorporate many kinds of built-in mechanisms or electronics to give their structures additional functions and features. Many accessories for block building systems like Lego incorporate this as do many electronics and programming themed educational toys. Cellular robotics is an area of robot design where this combination of modular elements and mechanisms is used to make reconfigurable robots from a common kit of modules or to allow modules to automatically link-up, traverse each other's surfaces, and self-assemble into complex structures or machines. Recently a number of robot building toys have emerged based on manually interconnecting blocks and, though still largely experimental, a number of designs for self-assembling cellular block robots have also been developed. Such modules are, at present, still very small, relatively complicated, and fragile assemblies, their connection methods usually trading strength for quick plug-in assembly. But these first steps offer the prospect of future self-assembling/adapting robots and temporary structures of progressively larger scale and practical use.

Barobo Mobot (now Linkbot) https://www.barobo.com/
Robotis Co. Bioloid and Smart Servos http://www.robotis.us/dynamixel/
CellRobot http://www.keyirobot.com/home.html (was Kickstarter, may be awaiting production)
Cubelets https://www.modrobotics.com/cubelets/
Dtto https://hackaday.io/project/9976-dtto-explorer-modular-robot
Mabot https://www.bellrobot.com/
MOSS https://www.modrobotics.com/moss/robots/
Tinkerbots https://www.tinkerbots.de/en/

Section 2: Interlocking Log/Beam/Plank Systems

Most people are familiar with traditional log cabins and the rustic overlapping timber elements they employ. The principle is simple; notching the ends of logs so they can be simply laid atop each other and tightly overlap and interlock while resisting lateral forces. This is one of our most ancient building methods, utilizing natural timber with a minimum of modification and, in the past, few tools beyond an axe. Such rustic homes, built typically in or near wilderness, remain popular to the present day and many highly refined variations on the traditional building techniques have evolved, often involving precision shaping or milling of logs to improve their uniformity and interface. Precut log kit homes are popular in many countries and many of their building systems are quite sophisticated. And, of course, there is the long popular Lincoln Logs building toy that has been a toybox staple worldwide since the early 20th century.

Though not intended as modular systems and traditionally used ad hoc, such structures hint at the potential for modularity and their kit forms are highly modular, though usually specific to particular designs rather than being general multifunctional building systems. However, while small log cabins have sometimes been built by solitary individuals, such structures are typically very demanding in labor because of the heaviness and large size of timber (their great mass key to holding structures together), putting them beyond the capabilities of most individual builders. In recent times some lighter building systems have emerged employing similar approaches of interlocking and overlapping beams and planks of smaller scale, sometimes with additional mechanical fixtures. These have often been used for light structures like farm and garden sheds, pet housing, and small cabins. When employing standardized lengths of wood, they can become useful modular systems and by repurposing commonly found tongue-in-groove plank used for flooring and wall paneling one can quickly devise simple demountable building systems for use in many modest applications.

2:1 Lincoln Logs Toy
The traditional Lincoln Logs toy was invented in the early 20th century by John Lloyd Wright, son of the famous American architect Frank Lloyd Wright. Over a hundred years later, it remains a popular building toy found in variations worldwide. The original toy has continued under the K’NEX toy brand, though countless immitations have been created around the world, some using square sticks or thinner planks and some using plastic instead of wood.

The original Lincoln Logs system is composed of set or ¾” (2cm) thick milled and notched wooden sticks in various lengths along with various accessory pieces such as doors, roof supports, and colored roofing planks and sometimes miniature character figures in a ‘western’ theme. More elaborate sets have even included miniature trains and simulated landscape shapes. Recent sets have focused on the nostalgia aspect of the toy and a return to use of wood accessories and packaging in tin containers.

2:2 Jack McKee Builder Boards
Introduced in a book by woodworker Jack McKee, Builder Boards is a building toy intended to be fabricated by parents (but also available as prefinished sets) that offers Lincoln Log type construction on a much larger scale, allowing kids to build

their own child-scale playhouses and other structures. Instead of logs, the system uses rounded-edge wooden planks that slot-fit together, along with a number of accessory parts for roofs. The intuitive nature of Builder Boards allow even young children the ability to construct quite substantial structures and has inspired woodworking hobbyists to explore a number of variations on the basic parts designs, which are well suited to recycling wood scrap or the use of plywood and CNC fabrication. Some practical uses are also possible with this system, such as garden planters, pet shelters, and light furniture.

2:3 Eurowood/Eurovudas

Originating in Lithuania but fabricated under license in a number of countries, Eurowood/Eurovudas is a cabin-building system that takes the basic concept of Builder Boards and Lincoln Logs to an architectural-scale building system. Originally marketed for use as owner-built kits for summer cabins and backyard sheds, Eurowood has evolved to a broad spectrum of kits including Tiny Houses and other small but full-scale houses. Using milled, slotted, plank components akin to those of the Builder Board system, Eurowood adds the use of tongue-in-groove edges to form a more secure interface sealed and bonded with the use of silicone joint sealant. Most Eurowood designs are based on single-wall construction and are delivered unfinished, but larger scale designs do allow for a double-wall construction to accommodate internal insulation and utilities. Though intended for ad hoc designs, Eurowood has obvious potential as a more universal, demountable, building system using more strictly standardized components, though such a system has yet to be devised. Eurowood offers much of the character of traditional log cabins with a scale of components easily handled by the solitary individual.

2:4 Light Tongue-In-Groove Plank Systems

Section 3: Post & Beam

Post & beam construction is one of our oldest and, to this day, most widely used methods of building, in ways mimicking the form of trees with their vertical trunks, outstretched branches, and leafy canopies. And, of course, wood remains to this day the most common material employed in the many variations of this kind of construction.

Our earliest methods of building with wood were the placing of relatively thin wooden branches and poles into conical shapes to serve as support for simple huts, as with the tipi and lavvu. Though originally intended to be disposable, we soon learned to repurpose the materials for such structures, making them reusable and portable. We then learned to bend, weave, and lash such poles when the wood was still fresh or ‘green’ and still flexible and could create basket-like arch and dome shapes. With the advent of stone, then metal, axes and chisels and eventually various planes and saws we could work with progressively larger scales of logs and devise more sophisticated means of joinery, ultimately leading to various traditional timber framing methods and to the vast diversity of post & beam building systems we see today.

The basic principle of post & beam systems is to create a rectangular or 'box' frame of horizontal beams supported by vertical posts connected with some kind of joinery formed into or added onto members. Sometimes the corners of structures may use diagonal braces or gussets to improve stiffness. Traditional forms, based on wooden timbers, commonly used simple mortise and tenon and dovetail joints relying on pins or pegs. Today, many kinds of joinery methods using all sorts of mechanical fasteners are employed, though variations on the traditional methods and materials remain common.

Though we have long tended to build things bespoke and ad hoc, communities have evolved building traditions or 'vernaculars' that led to standardization in style and form. This in turn tended toward standardization in dimensions leading to the evolution of nascent modularity. And so modular forms of post & beam construction developed in quite ancient times, one clear example being Japan and its traditional timber framing where challenging conditions ultimately led to the standardization of building materials by government edict. Between war, fires, and natural disasters the survivability of the average home in feudal era Japan could be doubtful. And so it became crucial to both citizens and their rulers that communities be able to rebuild quickly and easily. To facilitate this, the stockpiling of precut lumber became important and by standardizing on the dimensions of this lumber it became much easier to design and build. Eventually a standard system of measurement and proportion called the 'ken' was devised based on the distance between supporting posts and the common sizes of tatami floor mats. This system allowed homes to be quickly and intuitively designed, and their costs easily estimated, in conversation between homeowner and craftsman. No wonder, traditional Japanese architecture eventually became an important inspiration for many Modernist designers in the 20th century.

In more recent times modular post & beam systems have evolved to facilitate the creation of factory prefabricated kit housing and industrial buildings, taking advantage of the simple mechanical assembly afforded by modular wood joinery. This then advanced to newer materials, like iron, steel, aluminum, and most recently composite materials like fiber-reinforced plastic. In modern Japan the traditional timber frame building methods have evolved into quite sophisticated building systems relying on automated milling and alloy connecting joints intended to increase earthquake resistance while still maintaining a quick hand-assembly process. But in general, most kit housing remains ad hoc, not intended for demountability and reusability, and not extending to true multifunctionality.

However, with the influence of Modernist design and Fuller's Design Science, designers began exploring the potential of simple post & beam systems as highly intuitive tools for the DIY builder. Particularly significant was the work of designer Ken Isaacs, whose Matrix building system, developed for his 'living structures', inspired the creation of Box Beam, once popular among solar energy experimenters and enthusiasts and which continues to this day as Grid Beam. Such multipurpose building systems eventually became important in fields like science, robotics, industrial automation, and electronics, resulting in a vast assortment of post & beam buildings systems based on many different materials, making this, perhaps, the largest and most diverse category of building systems in this book.

3:1 Modern Japanese Timber Framing

Though having the potential for modular use and often readily demountable thanks to nailless joinery, traditional western style timber framing was primarily applied in bespoke designs using large, heavy, building elements whose joinery required considerable woodcrafting skill. Subsequently, it declined in housing use across most of the world in favor of nailed 'stick' or 'stud' framing systems requiring less skill and which could use smaller dimension lumber that was more efficient to produce, dried faster, was more easily shipped, and was more easily handled by smaller groups of builders or individuals.

But modern variations of traditional timber framing systems have supplanted the need for high crafting skill with the use of various alloy joints or joinery milled by CNC machine. In contemporary Japan timber framing is still commonly used in home construction and uses smaller scales of components than is typical in western traditional timber framing, putting it at the limit of what this author would consider convenient for the average maker. Traditional home construction in Japan is based on nailless hand-crafted wood joinery which, in modern times, has been supplanted by CNC milled precut components as the skill base for that intricate joinery declined. Such home frames are assembled with remarkable ease and speed, a typical Japanese home frame being built in a single day by a handful of workers using only wooden mallets. More recently such joinery has started being supplanted by concealed alloy joinery which has offered greater resistance to earthquakes and an even greater ease in fabrication and assembly. These systems are often devoid of nails, screws, or bolts, relying instead on wood or steel friction pegs that are actually less likely to become loose over time as wood shrinks.

Though still predominantly used for bespoke designs, these methods of joinery afford the potential for truly modular building systems when based on standardized timber lengths, finishing components, and rules of structure. Such has been the case with systems like Volkshaus which, despite its German-sounding name, was developed in Japan in the 1990s by an architectural firm known as Be-h@us (http://www.landship.co.jp/ http://www.be-works.jp/blog/ should reference site or Be-h@us book?) as a basis for prefabricated kit homes suited to modestly skilled users. Based on a modular alloy joint system called Kuretec or Tec-One, Volkshaus combines modernized Japanese timber framing with a unique modular structural insulated panel system and sometimes pre-finished elements. Its designs typically revel in the beauty of exposed wood, whereas more conventional homes have adopted the western practice of concealing wood structure.

Kuretec System
Power Build/Suteki System
Volkshaus

3:2 Matrix/Grid Beam/XYZ
This closely related family of building systems all derive from the work of designer Ken Isaacs and the ‘living structures’ he devised in the 1960s. A futurist anticipating a new kind of Post-Industrial DIY movement long before the contemporary Maker movement, Isaacs was keen on empowering the low-skilled builder to quickly make practical furnishings and goods from the cast-offs and detritus of the commercial/industrial culture. Starting with the furnishings for his own home, Isaacs devised a collection of what he called ‘living structures’ based on simple box frames that could make better use of limited living space by organizing it volumetrically. Looking a bit like indoor playground jungle-gyms (and just as appealing to children) these living structures afforded endless and easy personalization and adaptation.

To facilitate easy design and assembly, Isaacs devised a simple construction method based on 2”x 2” lumber pieces and the use of an overlapping corner joint called the ‘trilap’ joint. Using standardized lumber lengths, common plywood panels, and simple bolt-together assembly this system, dubbed Matrix, afforded easy fabrication and repurposing of parts, and intuitive design, often in combination with many other common hardware and industrial items. Through books and workshop courses Isaacs spread the knowledge of this simple building method and encouraged countless others to customize his example designs or create new ones to suit their own needs and uses, cultivating a library of what we would today refer to as open source designs.

Isaacs went on to explore many other modular building methods, many of which are shown elsewhere in this book, exploring the concepts of ‘microhousing’, leading to today’s Tiny House movement, and ‘Mobilism’; the idea of a lifestyle based on seasonal migration as a way to reduce to one’s fossil fuel overhead. Isaacs envisioned a near-future movement emerging as a counter to rampant consumerism. An 'urban nomad' movement where highly mobile young people would learn to appropriate and repurpose the detritus of the declining Industrial Age to use as the basis of their own more authentic and sustainable culture.

Isaacs' work and ideas inspired many other designers, such as Victor Papanek and James Hennessey whose books Nomadic Furniture 1 + 2 in the 1970s helped catalyze a craze for DIY furniture building using industrial cast-offs that would later become the 'upcycling' design movement well known today. Proving popular with sustainable technology or 'eco-tech' enthusiasts inspired by the Energy Crisis of the late 1970s, Matrix was applied to many new and interesting experimental uses in areas of solar energy, wind energy, gardening and hydroponics, and more.

As the popularity of the Matrix building system grew, others sought to improve upon it. Across the 1980s designers Phil and Richard Jergensen comprehensively revised the older Matrix system to support the use of pre-made frame pieces with pre-drilled holes, the use of new materials like aluminum and steel tubing, and the scaling of the system to larger sizes of lumber that might be suited to larger scale construction. These improvements greatly improved the ease of use and versatility of the concept and expanded its already broad range of applications. Collecting a portfolio of applications for this revised system with a community of enthusiasts, the Jergensens published the Box Beam Sourcebook in 1994, founding also the small business Sun Tools in the hopes of making and distributing pre-made components for the system. The book was featured in the Whole Earth Catalog and its companion Whole Earth Review magazine. With the rise of the Maker movement post-millennium the Jergensens re-introduced the system under a new name in a new and more detailed book called How To Build With Grid Beam. It has been featured in various Maker Faire events ever since. However, maintaining consistent production of the pre-drilled beam parts has proven difficult for the inventors and supply tends to be sporadic.

The rise of the Maker movement is typically associated with the emergence of open source electronics, the MIT and Neil Gershenfeld's development of the 'fab lab', the advent of Make magazine, and the end of the suppressive patents on 3D printing technology that catalyzed the creation of open source hobbyist digital machine tools. But a very strong argument could be made that the movement's foundations were, in fact, built from Matrix and Box Beam with the work of these Eco-Tech pioneers.

Recently, another variation on the Matrix system has emerged using aluminum called the XYZ Node system, devised by the design group N55 in Denmark. This system has been used to build a great variety of demonstration structures including a series of modular utility bicycles and other vehicles.

Matrix System
Grid Beam System (https://gridbeam.xyz/)
N55 XYZ

3:2:1 Grid Kit (https://gridkit.nz/)
Grid Kit is a recent derivative of the Grid Beam system developed by a startup business in New Zealand and based on the metric dimensions described in the Grid Beam guide book. A valuable alternative source, given the intermittent supply of these parts from their original creators. Largely identical to Grid Beam functionally, the company offers a variety of kits and some interesting tools including a simple but very helpful cutting jig to make correct end-cuts of the stock beam pieces easier. They also include a series of pre-holed plywood plate panels matching the beam hole grid as well as hex-socket connector bolts which can often be difficult to find independently, owing to their rarity in conventional hardware stores and diversity of names in the metal fastener industry.

3:3 Pinned Beams
Possibly originating with the Lego Technic building toy deriving from the well known Lego snap-lock bricks (and partly intercompatible with that), pinned beam systems bear some of the characteristics of grid plate building toys like the famous Meccano and Erector systems and some characteristics of holed post & beam systems like Matrix and Grid Beam. They are based on variously shaped beams and other components with a standard pattern of regularly spaced holes that are linked together side-to-side using flush snap-lock pins or nuts and bolts. The beams link on only one axis, with holes and pins all running parallel, and more solid panels are formed by stacking beams together, though many special shapes are often also featured for this purpose and they can also combine easily with gridded plate parts. Most are based on injection-molded plastic and the greater thickness of the beams, compared to the metal plates of other systems, allows for the use of softer recyclable plastics, though these are also made with milled aluminum for more durable structures. At present these are limited to small scales and uses such as building toys and robot kits.

Lego Technic
Jimu (UBtech) Robot Kits
MINDS-I Robot Kits
Makeblock Robot Kits (aluminum beam and plate hybrid with threaded channel feature)

3:4 Angle-Iron

Though more usually made of various grades of steel, and more recently aluminum, angle-iron is a common material found in building supply and hardware stores around the globe. It is usually found in lengths up to a meter and either with or without pre-drilled holes. There are many approaches to its use for building, but as a modular framing method it usually employs the use of a right angled bolted overlapping corner joint akin to the 'trilap' joint of Matrix and Grid Beam, though with much shorter nuts and bolts. Though commonly used for many DIY projects, it is a bit less aesthetically appealing unless painted, using galvanized steel, or being used as an edge joinery method for simple box structures and is most often used to build simple shelves for garages and work sheds or various garden structures.

3:5 Tubular Profile Systems

Many kinds of tubular profiles made of steel and aluminum are used for light and heavy construction. Though commonly relying on welded joinery, and thus not modular, they can also employ the use of bolted connections, joint and gusset plates, and more sophisticated cast or molded joints that insert into their hollow spaces. With such connections they can be used as the basis of true modular building systems. Owing to its potential for forming by extrusion, many specialized aluminum tube profiles have been developed for use as modular framing for light outdoor structures, electronics enclosures, store and trade show displays, greenhouses, and in a few cases even framing systems for full-size housing. Recently, carbon fiber and fiber reinforced plastic (FRP) tubing have appeared as well and put to large structure uses. First put to use in industrial applications where their non-conductivity was important as a safety measure, they have been adopted more widely for their other virtues. Some sustainable housing advocates now suggest that FRP components are superior in sustainability to steel and wood for housing use because of the low energy involved in their fabrication, though such processes remain beyond the reach of the typical Maker at present and one is limited to repurposing industrial products.

- Quadro Building Toy
- U-Channel and Holed Tubing
- Aluminum Tube Systems
    - Quick Frame and Ready Tube
    - Esto Connectors
    - Electronics Enclosure Framing
    - MHS
- Carbon Fiber Tube Systems
    - Dragon Plate Plug Connectors
    - Rock West Carbonnect
- FRP Profiles
- Structural Steel Profiles and Fittings

3:6 T-slot Framing

T-slot framing is one of the most important innovations in modular building technology of the 20th century, yet is typically only known to its users by one of a variety of brand names. Possibly deriving from the T-shaped rails long used on carpenters' workbenches for clamping workpieces in place, or possibly inspired by the similar profiled building blocks of the Fischertechnik building toy, the first extruded aluminum T-slot profile was developed in 1980 by the German firm Item Industrietechnik GmbH as a form of industrial framing for the construction of custom machine tools. Progress in industrial automation had long been stymied by the very high development costs of new machines to suit very specialized forms of production. Often automated manufacturing systems would become obsolete before they were paid for. With this new modular framing it became possible for engineers to design custom production systems to-order from a catalog of standardized parts and adapt and upgrade them to the needs of changing product lines. T-slot framing quickly gained in popularity across the 80s and by the 90s was being produced worldwide by many companies in a large variety of profile sizes complemented by a vast assortment of accessories and electronic and electromechanical components tailored to its standards. It was soon adopted for many other uses such as laboratory equipment, robots, workbench and workstations, mezzanine structures, shelving, electronic enclosures, office furniture and partitions, and by the turn of the century even the construction of entire full-size homes. Today most of the manufactured goods in the world pass through machines made with this framing while most new robots and machine tools are prototyped using it, yet it remains little known to the general public.

T-slot beams are usually square and rectangular profiles formed with T-shaped slots along their length into which a threaded 'T-nut', tapped 'bar' with multiple holes, or tapped angle piece for angled connections is slid into a desired position and fixed with a hex socket screw. This is used to join frame pieces together side-to-side, side-to-end, or end-to-end, as well as to attach more specialized fasteners, gusset plates, accessories, panels, and other components. This offers a great advantage over systems with pre-drilled holes like Grid Beam which only allow overlapping attachments at the regular hole points, allowing for flush corner joints and rigid connection at any point along the T-slot that can be easily adjusted or changed as needed. However, T-slot beams are generally much more expensive and are not commonly found in home improvement and hardware stores, limiting their access for the casual DIY builder.

The center of the profiles often features a tube which, at smaller sizes, can be tapped at the ends to accommodate a screw, allowing beams to link end-to-side without overlapping. Larger profiles may also use this hollow space to host special concealed end-to-end and end-to-side mechanical joints. In some cases the hollow space is used to host reinforcing steel bars, adding strength over the aluminum alone. Occasionally these hollow channels are used for concealing wiring and sometimes they are simply filled with foam insulation as a means of noise and vibration dampening. But, most interestingly, this volume is also often used as an internal supply line for pneumatic power with added pneumatic fittings. Thus a T-slot frame can replace hoses as the basis of a complex pneumatic-powered mechanism or use portions of a workstation frame as a bus to power pneumatic hand tools.

T-slot profiles are also often used to form trusses for larger scale structures. This is often done using short angled beam pieces to make diagonal members, but more recently some T-slot product lines have added truss plates designed to slide into the slots without additional fasteners, making trusses easier to assemble, lighter, and better performing.

Most T-slot profiles are manufactured to metric size standards with 20mm and 40mm wide beams (their original size) being the most common sizes. However, sizes from as small as 10mm to as large as 200mm have been produced. The 80:20 company is one of a few that have produced them in English units, chiefly to suit the metric-averse American market. T-slot framing is marketed in standard series sizes, usually in multiples of 5mm with individual company product lines specializing in a few series they deem to have the broadest market appeal and which may be used together in a complementary fashion. The series size standard usually refers to the width of a square profile with a single slot along each side, but for profiles with multiple slots on a side it also refers to the center-to-center spacing between slots. Thus a 80mm x 40mm 'series 40' profile would have two slots, 40mm apart, on the wide sides and one slot on the narrow sides. Some large or wide profiles may have many slots and a few product lines feature panel shapes that have many slots light attachments and hanging items.

Over time many special profiles and accessories have been developed and added to the various T-slot product lines to suit different applications. Round, arc, hexagonal, and octagonal profiles are now offered for use in furniture or special structures and are complimented with many kinds of furniture hardware. They may also come in a variety of anodized colors to better suit furniture and finished product uses, though this is still less common. Profiles with various flanges are offered for mounting of enclosure panels, screens, doors, and rack-mounted electronics modules. A couple of specialized product lines have been developed specifically for house construction, though the more generic product lines have been successfully used for this application.

The catalog of T-slot framing components is vast and always expanding and most of this hardware is cross-compatible between the many different product lines. This book can only hope to scratch the surface of this system's range of possibilities. T-slot is probably the most well-developed modular building system in existence today, with more different manufacturers supporting it than any other.

Fischertechnik
item
80:20
Bosch
MK
Minitec
Makerbeam
Quadrant House
Infento (https://www.infentorides.com/)
Docyke DIY Constructible Rides (a Chinese knock-off of Infento including electric motors. https://es.aliexpress.com/item/4000264679705.html?spm=a2g0o.productlist.0.0.5a037140u8G43w&algo_pvid=6481e9c1-67d0-4b30-a81f-10110f61cb3e&algo_expid=6481e9c1-67d0-4b30-a81f-10110f61cb3e-0&btsid=0bb0624316138693785456657efd0a&ws_ab_test=searchweb0_0,searchweb201602_,searchweb201603_)

3:7 Unit Box Frame Systems
Unit box frame systems are modular framing systems that use relatively small box frames--typically in the shape of simple cubes--as a basic building unit. These units are simply stacked to form larger structures, being joined together along their sides by various mechanical connection such as bolts or gusset plates. There is much similarity between unit box frame systems and mechanically joined box systems, the difference being that unit box frames are open frames, whereas the box systems use completely or mostly closed wall boxes. Frame units can be made of a variety of materials but are most commonly based on alloys with flush welded corners. Angle iron, tubular steel profiles, and holed steel profiles are often used in this way but perhaps the most common form of this type of building system today is one of the largest; shipping container housing frames. Unit box frames based on large structural steel tubing are also commonly used in the production of prefabricated modular housing, particularly that based on Modernist designs.

Unit box frames are intuitively simple. One simply stacks the units on top of each other like building blocks and joins them together at points along the adjoining frame members to form a larger rigid frame. Horizontal planks or panels can be dropped in place in the open spaces of the units while vertical panels may be attached by various surface-mount or in-line mounting methods. Most systems of the type use relatively small unit sizes to suit applications like shelving. Large size units can be bulky and unwieldy and so may be designed to disassemble or fold down flat.

Welded Box Frames
Paracity Box Frames (https://www.designboom.com/architecture/marco-casagrande-paracity-habitare-helsinki-08-31-2014/)

Paracity was an urban design concept devised by architect Marco Casagrande proposing a scheme of urban renewal through the use of modular construction based on large prefabricated mass timber/cross-laminated timber box frames in 6m cubes. The cubes would stack and interconnect into a free-form rigid grid which could then be retrofit with various standard and custom panels to host housing, terraces, walkways, and many other uses. Casagrande also experimented with smaller timber box frames of the type for discrete housing applications.

Container Frames
Cubespawn (https://cubespawn.com/)

Cubespawn is a hybrid concept employing modular 600mm cube box frames constructed from aluminum T-slot beams used in industrial automation. The purpose of the Cubespawn project is the design of open source modular production systems where varying production stages use machines fitting within the space of these cube units which, when interconnected, can transfer work between them and thus form more complex production systems.

3:8 Rod & Clamp
Rod & clamp framing systems are, as their name implies, based on the use of simple rods joined together using various forms of clamps. The origin of these systems is something of a mystery but they seem to have emerged from table-top assemblies used in science labs going back a couple hundred years, and this remains one of their most common uses today. Generally limited to modest scale constructions, they have reached larger scale uses in the form of pipe-fitting construction systems commonly used to make hand rails and greenhouses, and gardening structures. Designer Ken Isaacs, known for his development of the Matrix building system that evolved into today's Grid Beam system, pioneered the use of these systems for DIY 'microhousing'.

The most interesting recent use of rod & clamp systems is for experimental machines with the first open source 3D printers, known as RepRaps, having been based on rod & clamp frames as their clamping joints and other attachments could be easily fabricated with 3D printing, affording the machines a degree of self-replication.

- Block Clamp Systems
- Threaded Rod Systems
- Lab Framing
- Pipe-Fitting Systems
    - Kee Klamp
    - Maker Pipe (https://makerpipe.com/)

      Maker Pipe is a pipe-fitting type building system using components repurposed from industrial electrical conduit (EMT - electrical metallic tubing) products used in routing electrical wiring. It has many similarities to other pipe-fitting building systems but is cheaper, much lighter weight, its tubing easier to cut, and easier for the individual to handle, though with the obvious compromise that it is limited to lighter-duty roles. It is especially useful for light DIY custom furniture and utility structures. Connectors rely on clamp attachment with one or two hex socket bolts holding them in place. The broad variety of connectors include fixed and swivel angles suited to simple space-frames of varying geometry. The Maker Pipe company offers a one-stop-shop with a comprehensive selection of these components along with various bundles and kits, reducing the work of tracking these down on the industrial parts market. They also offer free guides to use and links to a user enthusiast community. Being based EMT, Maker Pipe has some potential intercompatibility with geodesic dome systems likewise using that tubing with the crimped-end strut connection method. Many of its connectors could be attached to such struts in-situ without the need for dismantling and cutting, allowing for various extensions of the dome frame structures.

    - Pipe Joint and Dowel - Tent Frame Systems
    - Steel Joint and Timber
- Scaffolding Systems
- Photo Shooting Table Frames
- ALEX System

3:9 Bamboo Framing Systems

The use of bamboo as a building material is as ancient as the use of wood and long established techniques and building vernaculars have evolved for it across Asia. However, because of its differences from wood, it has long been limited in its methods of joinery. Bamboo, being a grass plant, is very strong in tensile strength--as strong as steel in some uses--but quite weak across the fiber grain and so cracks and splits easily along its length. It is also very irregular in form, being composed of a fibrous tube or ‘culm’ with a series of hollow cells divided by thin solid ‘nodes’ where the leaves of the bamboo shed during growth. Thus the most common techniques for its use are based on lashed-together joints, often using bamboo fiber and pegs for this purpose. This is an inherently modular building approach given the reusability of the bamboo elements, though not generally thought of in that context.

In recent times, with interest in sustainable building growing, the use of bamboo as a more sustainable alternative to wood for housing construction has emerged. New methods of preserving bamboo, though borax infusion and surface treatments, have been devised and so-called ‘structural grade’ bamboo cultivated for global export. To overcome the limitations of lashed-together construction, new methods of joinery for bamboo have been devised. Systems of inserted alloy plates or pins, much like that use in contemporary Japanese house framing, have been developed for use with structural bamboo. Other systems based on alloy tubing, in ways similar to the pipe-fitting systems, have also been used. But some limitations still remain. Bamboo structures still can’t be used with nails and need alternative approaches to their interior finishing, favoring pavilion-style architecture where the primary structure is left exposed and largely independent of the rest of the interior. But such differences, giving bamboo buildings a distinctive rustic appearance, are often the reason many people are attracted to such structures aesthetically. Most recently, engineered bamboo has been developed based on reducing the bamboo culms to their fibers and recombining them to form composites akin to plywood or laminated timber. This has proven very practical for thin materials like flooring, but is not yet as commonly used in other engineered lumber forms.

Lashed and peg joinery still remain the more common approaches for working with bamboo at the modest DIY scale, however, and are common for the creation of furniture. Though not commonly used as a modular system, except for scaffolding, devising these based simply on standard pole lengths is straightforward enough and suitable for many applications.

Lashing and Pegged joint Methods
Bolted Joinery Systems
Plate, Pin, and Tube Joinery
Bamboo Scaffolding

3:10 Modular Electronics Racks
The common 19” (482.6 mm) and 23” (580 mm) rack mounting systems, despite their now peculiar dimensions, have long been used in electronics, telecommunications, audio and video systems, and most recently for electronic

music instruments and large computer installations. Countless companies produce modular hardware and cabinet systems for this, and related, standards and though mostly intended for electronics applications, other uses are not unusual, though some of the hardware tends to be a bit expensive for mundane uses. The fundamental component of these systems is the ‘rack’ itself; a pre-holed rail with attachment points in an alternating series of .5” and .625” spacings scaled to the common face-plate dimensions of electronic rack units using a basic 1.75” height. The individual enclosure units are referred to in terms of multiple of the single unit height; 1-U, 2-U, 3-U and so on. In some cases half-width units are also used, with the addition of extra support rails.

The original rack unit mounts, developed in the 1940s for telephone systems and industrial electrical installations, were open frames where the mounting rails were fixed between a floor and ceiling or placed in a metal frame on self-supporting legs. Relatively shallow in depth, they relied largely on front screw attachments to hold unit boxes or boards in place, leaving the back exposed. This is still commonly used in telecommunications and industrial electrical/electronics systems, though the 23” standard is normally only used in telecommunications with the later 19” standard superseding it for other uses. Various surface panels were added to give these a more finished look from the front and eventually they evolved into full enclosures for increasingly deep unit modules where a steel or aluminum box frame supported the mounting rails at the front, sliding rails supporting the units horizontally, spaces for power supplies and ventilating fans, dust filter panels, and a set of metal enclosure panels with various accessories like windows, doors, and vents. There is no standard unit box depth but today they are commonly up to 36” deep.

The variety of these enclosures today is endless and the number of product lines countless. Many special enclosure specifications have derived from the original systems to suit specific kinds of installations and requirements in certain countries. There are even roadcase/flightcase boxes adapted to host these for portable equipment and they now often feature elements of office furniture to make them into elaborate consoles and workstations. Many other modular electronics enclosure systems, using extruded profiles for their basic framing, are also designed to integrated with rack mount components. Despite the peculiar dimensions, this is a long persistent modular building system like to be in common use for the foreseeable future.

3:11 Industrial Mezzanine Systems

To optimize the use of space in large warehouse and industrial buildings, it has long been common to create special free-standing platforms or decks called ‘mezzanines’ which allow more of the volume of the space to be used. Early forms of these mezzanines were built-to-suit using the same heavy timber framing methods used in building construction. But with the adoption of steel framing for buildings, this too was applied to these mezzanines and soon became the basis of prefabricated products. In recent times these systems have become increasingly modular and reconfigurable to allow for the accommodation of varying building layouts and the addition of accessories like handrails and in-plant office enclosures.

Commonly based on structural steel profiles, industrial mezzanine systems offer many possible alternative applications and can be modest enough in parts size to be easily handled by a DIY builder. However, marketed primarily to corporate customers, they tend to be expensive compared to other types of building systems. But their high strength, easy assembly, and demountability can sometimes compensate for this higher cost. They have sometimes been used in loft apartment conversions, their industrial look complimenting an industrial-style interior design.

3:12 Theatrical Truss

Theatrical truss systems should be familiar to anyone who has attended a rock concert or similar event. Designed to support stage lighting and other on-stage equipment, they are ubiquitous in the theater and music industry with many manufacturers and product lines. They are attractive for other applications because, being commonly made of aluminum, they are lightweight, transportable, and their parts are highly modular, quickly assembled and disassembled, and cross-compatible with a vast catalog of accessory components. They are commonly used for trade show displays, many science projects have used them, and they have even been repurposed for the construction of very large robots and architectural 3D printers.

Theatrical truss systems are hybrid structures, using discrete truss beams made of welded aluminum tubing as the parts of a post & beam structural system. Lighting fixtures and other accessories attach to the tubing with clamps, much like those of rod & clamp framing systems, straps, zip-ties, and sometimes tape. Traditional theatrical truss systems relied on hand-tightened clamps and had a common problem with loosening over time due to vibration and thermal contraction. Stage crews needed to frequently go over all the joints in a structure to make sure they were tight and secure, this making the systems impractical for more continuous use. Today many newer systems employ so-called ‘bayonet’ connections with modular joint blocks that will not loosen with time. Thus these systems are practical for long duration or continuous use and are sometimes used to support mezzanines, tension structures and tents. Housing applications may also be possible, but have not yet been explored.

Most theatrical truss systems are quite large and expensive, being intended for many decades of use and reuse. However, some smaller systems have been developed for trade shows and small stage venues and can serve as the basis of shelving and other kinds of furniture.

3:13 Invisible Joint Framing

An unusual form of modular assembly has been introduced with the recent innovation of magnetically driven pins and screws. These simple but amazing mechanisms allow wooden components to be jointed together by otherwise conventional pins and screws that are completely concealed by a finished assembly. The hardware is mounted in drilled holes created using a special alignment jig to insure the screws/pins and their receptacles are properly lined up. The wooden pieces are then finished as desired. To assemble the pieces, a magnetic driving attachment is added to a conventional power drill or power screwdriver and moved next to pieces as they are placed together. The driver magnetically turns the pins or screws to link the components securely together. A typical screw connection uses two or four connecting points while pins can be placed more freely, being well suited to mounting panels.

Currently limited to light structures and used in the novel design of furniture and fixtures like staircases and hand railing, the possibilities of this new technology have yet to be fully explored. A very simple modular post & beam building system can easily be devised for a wide variety of uses, using nothing but this magnetic driver to assemble pieces.

Invis System

Section 4: Space Frames

Space frames are structures that employ a network of struts, typically in triangular or tetrahedron arrangements, to fill or enclose space, distributing their loads and stresses across their network. Though, technically, many post & beam structures can also be considered space frames, they are more usually based on a cubic/rectangular network topology while what we more commonly regard as space frames rely on triangular networks. Space frames evolved from simpler trusses, which use sets of short diagonal members between two long horizontal members to create a light but strong beam. These, in turn, evolved into box trusses where three, four, or more horizontal members are linked by diagonal members. These then evolved into space-filling and space-enclosing forms with regular, repeating, topology.

Space frames can be ad hoc in nature, as in the case of their use with high performance vehicle chassis, but using repeating topology, kits of standard modular components could be devised leading to the modular space frame building systems in wide use today. Space frame building systems are typically composed of strut elements and node elements. Occasionally they may include standard panel shapes as well. In some cases nodes are integrated into the ends of struts but more often they take the form of a joint element in one or more parts.

Space frame structures have a long history, but their modular forms are a very recent invention that became common in architecture in the 20th century. Buckminster Fuller was particularly obsessed with the space frame and became famous for his development of the geodesic dome that has fascinated countless designers and inventors to this day. Some competing systems were devised later in the century, such as the Universal Node System and Min-A-Max systems devised by designer Peter Pearce, used most famously in the construction of the Biosphere II structure.

The most advanced form of space frame system are the tensegrity structures, which combine networks of compression struts with tension cables, reducing the physical mass of structures to the bare minimum while still exhibiting great strength. However, their complex topologies are somewhat more limited than the more common forms of space frames.

And then there are the geodetic structures, where curved space frames, often enclosing tubular forms, are used as elements of other hybrid structures. A famous example is aircraft fuselages such as the British Wellington bomber used in WW2, where the geodetic structure is part of a stressed skin system. More recently, such a fuselage has been proposed for the Skylon spaceplane, currently in development. There have been novel bicycle frames where geodetic tubing is used as joined members of the bicycle’s frame --a space frame made of space frames.

Recently, a new class of materials has emerged based on the use of space frame ‘microlattices’ taking the place of solid materials, offering the same performance as solid material with extreme lightness. Such microlattice structures, now based on high-precision 3D printing, may prove very important in future nanotechnology.

Space frames have often been proposed for use in space as the basis of constructing large orbital structures. The early plans for the International Space Station--previously called Space Station Freedom--called for large space frame structures assembled by telerobots. Similar vast space frames were proposed as the basis of space solar power systems and large transorbital spacecraft built on-orbit. However, in practice, they have so far had lesser roles with space structures built to date, perhaps because we have been slow to develop our orbital construction capability.

The most common application of modular space frames today is with very large scale commercial architecture, serving as the basis of large domes, large span roofs, or large glazed enclosures. Many companies make space frames for these types of structures, though, strangely, few have attempted to produce standardized systems based on mass-produced parts for more general, smaller scale, building, despite the obvious vast range of uses. This has left the Maker to rely more on systems with parts they can make for themselves, using lower-precision methods. Geodesic domes have been especially popular for this and many small businesses now produce DIY dome kits for greenhouses, temporary shelters, exhibitions, and modest light housing similar in nature to the traditional yurt.

Though there was once a craze for wooden dome homes in the late 1970s and early 1980s, this has subsided in recent years as attempting to integrate geodesic structures with typical stick-frame home construction materials proved more complicated and unreliable than hoped and those aspiring to build dome homes today typically go with concrete. Fuller himself never anticipated the geodesic dome being used in such ways, preferring the use of the structures as independent transparent ‘skybreaks’ to shield light reconfigurable homes based on other building systems from wind and rain. But the sophisticated transparent architectural membranes needed to make that practical didn’t appear until very late in his life. Today the simple approach of tent-domes has proven the most practical way of building a modest dome home.

4:1 Ball-Socket Node Systems

Ball-socket node space frame systems employ nodes in the shape of a ball or small polyhedron with socket holes into which the ends of struts are inserted. This is one of the most popular forms of space frame used in architectural applications and has often been explored for applications in outer space. The usual node form uses threaded holes with the struts having screws in their ends. Other forms use a kind of mechanical linking bayonet locked in place by a threaded sleeve. And for simple systems, such as toys, struts may even be held in place simply by friction. Ball socket nodes are by far the most aesthetically pleasing type of space frame joint and one of the most durable. In many cases the nodes are painted, chrome plated, or anodized to further enhance their appearance. Struts too are also often likewise decorated and sometimes enhanced by sleeves of finished wood or other materials. Ball socket node systems also well integrate with a wide variety of strut materials as the threaded or bayonet connectors can be added to the ends of many materials; wood, bamboo, composites, plastics, and all sorts of alloys in tube and solid forms or in round or polygonal profiles. Even super-pressure pneumatic struts made of inflated tubes have been developed to make ultralight space frames and T-slot beams have been integrated into space frames of this type to afford convenient panel and fixture attachment. However, this type of space frame node is very rarely used by DIY builders because of the very high precision metalworking needed to fabricate them and the large number of them needed in a typical construction. Most commercially made parts are for very large scale architectural uses and, though small scale systems for exhibition structures or furniture can be found, they are often more expensive than other systems at that scale. However, the advent of more accessible CNC machining may soon change this.

Molecular Model Kits

Zometool

Magnetic Space Frame Toys

Magnetic space frame toys emerged with the appearance of stronger neodymium permanent magnets and are composed of steel ball joints and magnetic sticks, either entirely made of magnetized alloy or of other materials with magnets embedded in the ends. Early products suffered from manufacturing issues that made them hazardous for small children, much as with many other neodymium magnet toys. However, there are currently many such products on the market today made to safer standards or marketed only to older age groups.

Geomag (https://www.geomagworld.com/en/)

Geomag is the original Swiss producer of magnetic space frame toys, invented by Claudio Vincetelli and inspiring countless imitations. The company currently produces a broad line of products, enhancing the original system of plastic sticks with embedded magnets and steel ball joints with many other components and a broad variety of color options.

TiKA Design Kit (Kickstarter https://www.kickstarter.com/projects/tikatika/tika-your-modular-design-kit)

Exhibition Space Frames

4:2 Block Node Systems

Block nodes are space frame nodes based on a kind of block shape that may itself be made of several modular parts to accommodate connections of differing geometry while still keeping to a minimum of standard parts. They are most commonly made of cast alloys milled to a finished shape and like ball socket nodes are most commonly used in architectural applications. One of the chief reasons for using block nodes is to accommodate square or rectangular profile struts that are joined with pins, bolts, or screws through their sides. This is particularly useful for space frames forming geodesic domes and facilitates the use of heavy timber or laminated wood beams as attractive alternatives to steel. However, like the ball socket nodes, these are rarely used by DIY builders because of the fabrication of these nodes requires such complex precise methods.

Tinkertoy and K'nex

Min-A-Max

4:3 Plate Node Systems

Plate nodes are space frame nodes made of alloy plates relying on square and rectangular profile struts. These are some of the simplest forms and most popular of space frame but are not quite as strong as the ball and block types of nodes. But they offer a good way to work with light wood struts and serve well in applications like DIY greenhouses, exhibition structures, and small light buildings. Many DIY geodesic dome kits are based on this type of node.

Several types of plates--in countless variations--are commonly used for this type of node. The most involved are pressed or stamped plates. These typically have a round, ring, polygonal, or star shape with holes for bolting to struts and pressed into a dish-like shape specific to the 'period' of a particular geodesic dome. The may be used singly or in pairs, sandwiching their struts between them. In some cases star-shaped plates are designed to insert into slotted struts end to be secured by bolts. There are also complex star-shaped plates folded to provide flanges to hold rectangular profile struts. These can potentially suit both domes and space-filling trusses as the individual 'tongues' of the star shapes can accommodate different strut angles.

The next type is a gusset plate which usually has a triangular or 'pie' section shape with a pair of flanges bent to the necessary angles for the type of frame. These form only sections of a node, with several plates needed for a complete joint.

A simple narrow metal plate secured by through-bolts can be used to add flanges to the end of rectangular wood struts, allowing them to be connected in the same fashion as crimped strut space frames by simply overlapping the flanges and securing them with a single bolt. This can be used with one or two such plates on the sides of each strut end or can also be based on a strut with a slot cut to accommodate a single plate. This approach works particularly well in combination with Matrix/Grid Beam components and can be combined with additional gusset plates, braces, or angles for increased rigidity.

Drum and plate nodes use folded U-shaped plates welded or bolted to a central polygonal drum or tube. The U-shaped plates hold the struts--typically lumber--with perpendicular bolts. This type is very common in dome housing but can also be used to make nodes for space-filling space frames as the U-shaped plates can be designed to accommodate different nodes angles. These tend to be an expensive form of hub, however, as their fabrication is a bit elaborate and they are typically used at large scales.

Simple metal angles with holes can also be used to make a node plate similar to the gusset plate and off-the-shelf metal angle hardware can be repurposed for this. The angle piece is first adjusted to suit the corner angle between struts and then the legs of the angle are twisted to suit the long or facing angle between the struts. This is yet another approach well suited for use with Matrix/Grid Beam.

III+1 connector system:
Developed by designer Lukas Wegwerth, the III+1 connector system is a modular plate joint system for structures using square and rectangular tube alloy suited both to space frame structures and post & beam frame structures. Purportedly open source but with no apparent source of design file data at present, the system is intended for uses from furniture to housing and has been featured in a variety of European design exhibitions. However, at present little information is actually available online about the system beyond photos from these exhibitions.

The system appears to be based on a set of interlocking plates that can combine to form octadecagon (18 sided) nodes similar to cast block node space frame systems, but can accommodate different sets of connecting points based on which plates are used, thus supporting clean corners or flat face joints. It appears to accommodate different sizes of rectangular and square tube struts attached by through-bolts as well as variable angles for these based on bevels cut into the strut ends. No other features of this promising-looking system seem to be documented as yet.
http://lukaswegwerth.com/

4:4 Ring and Tube Node Systems
As the name suggests, ring node systems use an alloy ring, tube, or drum as a node element, this being used exclusively for light geodesic dome structures. In general, these are not especially strong or rigid and tend to be limited to uses like tents and greenhouses. But they also tend to be very easy to make from relatively cheap materials.

Several approaches are common with these hubs. In one type a thin metal ring is used to secure tubular struts with slots or grooves on their ends while holes through the struts allow lashing, zip-ties, or a locking pin to hold the connection in place. In another approach struts have angled ends that butt against a round or polygonal tube node and are secured by an end-screw, a locking pin, or lashing running through holes in the end of the strut. Another type uses a holed tubular ring that struts penetrate. As a simple building toy, this may use light sticks and flexible laboratory tubing. For more durable structures, the ring may be made of short pieces of alloy or PVC tubing with oval holes, the struts secured by through-pins or lashing. In the patented Zip Tie Dome system dual hub rings made of PVC pipe are used to secure PVC tube struts using zip-ties.

Tube Hubs
Zip Tie Domes

4:5 Crimped Strut Systems

Crimped strut space frame systems are commonly used for light space frame structures and are some of the easiest to fabricate. They rely on the use of light steel or aluminum alloy tubing for struts whose ends are pressed flat to serve as a joining element. There are two basic types. The most common, and most commonly used for geodesic domes, uses an overlapping joint where the ends of the struts are pressed flat to form a flange and have a hole drilled to accommodate a single bolt. The flange is bent slightly to accommodate the node angle. Several struts are placed together in an overlapping arrangement and a single bolt is put through their holes to join them together to form a complete node. This type of system is very well suited to the Maker, needing a minimum of tools. The type is very commonly seen on geodesic dome climbing play structures in children's playgrounds but also serves very well for greenhouses and tents.

The other type of crimped strut system relies on a kind of cylinder or barrel connector with slots or channels. Here the flattened ends of the struts are rolled and welded to form a kind of plug that fits into the slots of the node cylinder, with the full set of struts clamped in place by a locking nut on the cylinder. The cylinder may be cone-shaped to accommodate the needed angles at the node (in the case of domes) or the rolled end plug of the strut angled as needed. This accommodates both dome frame uses and space-filling planar truss frames, as used for roofs and floor decks, whose diagonal struts have sharp corner angles. However, the more involved crimping processes for these struts tends to restrict their use by DIY fabricators, though the commercially made systems of the type are much more accessible to the general public than the typical architectural space frames and are well suited to homebuilding.

A variation on the barrel connector more suited to DIY fabrication uses an alloy tube or prism with holes drilled to accommodate attachment of each crimped strut individually. This accommodates planar trusses as well as domes as each strut can be afforded a different angle and tubes of different height can accommodate multiple rows of mounting holes. However, this is a much weaker alternative to the more typical barrel connectors.

4:6 Angle Strut Systems
As described in the section on post & beam framing systems, it is possible to make simple box frames using common ‘angle iron’ pieces placed in an overlapping arrangement to form a corner joint secured by bolts. By varying the angle of the metal pieces it is possible to create similar overlapping joints that accommodate more than just the simple right-angle corner of a box frame. One can make many other polyhedral frames and, with a tetrahedron frame unit serving as a basic building block, create modular space-filling space frame system. No commercially-made space frame systems seem to use this approach today, and normal off-the-shelf angle iron is too stiff to be adjusted for this, so to use this approach one must make new angle struts from lighter sheet steel using a metal break. The most well developed system based on this approach is the one developed by the design group N55 in Denmark, which has used it as the basis of a number of buildings, exhibit structures, and even floating platforms and boats.

N55 Space Frame

4:7 Compound Joint Nodes
The simplest of space frame node uses no hub or joint hardware at all but simply forms the ends of struts to join neatly together where they can be bonded by welding or adhesive. Such minimalist nodes are very visually appealing, but this requires the use of a precision ‘compound cut’ to accommodate the multiple angles at the node point. Though this has generally been difficult for the DIY builder, improvements in contemporary power tools have made it much easier to accomplish. Welding and gluing these joints together isn’t particularly useful for a modular building system, however, as you cannot take these structures apart without destroying them. Other methods of connection are needed to make such a node joint truly modular, which is complicated by the topology.

One approach suited to light wooden dome structures is to lash the nodes together with steel cable, zip-ties, or plastic or steel strapping using slots or holes through the sides near the ends of the struts. This, of course, would be most effective with rectangular wood struts and the connection may be considered sacrificial, being cut away to allow disassembly of the structure. Another approach is to employ a concealed star plate connector fitting within slots in the ends of the struts, secured by pins or screws.

But perhaps the most high-tech approach to such a modular node may be the use of concealed magnetic screws, as was mentioned in the Invisible Joint Framing section under Post & Beam systems. Using rectangular wood struts with sufficient thickness to accommodate two concealed holes perpendicular to the face of their end cuts, one could fashion an invisibly joined dome frame that needs only a magnetic driving tool to assemble. This would be most suited to indoor display structures or yurt-like shelters where one seeks a very highly finished appearance for the wooden structural elements.

4:7 Geodetic Structures

As noted at the top of this section, geodetic structures are those based on arched or curved elements rather than the usual triangular tessellation of more typical space frames and are most commonly used for tubular, spherical, or dome shapes. Topologically, geodetic structures are either spheres (or pieces of spheres) formed of intersecting rings or tubes formed of intersecting coils or helixes.

Large scale structures of this sort are generally beyond the means of the DIY builder at present and difficult to realize as multifunctional modular systems. However, at modest scales a number of systems have proven useful for simple, light, shelters and enclosures. These rely exclusively on variations of the dome shape and the use of flexible materials such as bamboo, PVC and polyethylene pipe, and carbon or glass fiber rods, exploiting the natural springiness of these materials to provide a certain tension on the structure improving its rigidity. The most common uses of this are the many designs of ‘dome’ tents based on fabric tensioned by inserted rods.

An important characteristic of geodetic topologies is that, while the usual geodesic structures have nodes linking 5 or 6 struts at a point, the geodetic structures have nodes where only 4 or 6 struts meet --or more accurately, where two or three curving lines intersect. In the case of the helical and squared arch type geodetic structures, all nodes have only two intersecting lines. This makes for much easier node joint types, most of the domes made with these topologies needing only lashed or bolted overlapping joints or puzzle fitted overlapping intersections. The helical type domes have recently grown greatly in popularity as their elegant curving structural lines and onion-dome shapes are very pleasing to the eye.

Hoop Domes

Lashed Bamboo, Sapling, and Pipe Domes

Section 5: Post & Plate

Post & plate building systems originate in the construction methods once applied to clockwork mechanisms, providing a simple method of creating a compact self-contained chassis to host systems of gears. Classic clockwork assemblies were composed of stacks of metal plates separated by threaded or riveted posts on which bearings (in some cases, made of durable gemstone) were placed in small holes to support the shafts of individual gears. Mechanical power would be communicated between different layers of the assembly using gear shafts of different lengths passing through larger holes in the plates. And on a top or front-most plate markings could be engraved or labels mounted to display information by use of various dials and indicators. Similar mechanisms were also used to make locks and the firing mechanisms of guns and where some of our first mass produced modular industrial products.

Some of our earliest examples of this type of mechanism go back as far as ancient Greece, with such artifacts as the legendary Antikythera Mechanism; an orrery and analog computer believed to have originated as early as 205BC. This technology became refined by the 17th century, evolving by the 19th century to a level of intricacy and ease of production to support the common public use of worn and carried watches. The craft of clock and watchmaking, though largely supplanted for practical uses by electronic timepieces, continues to the present day with a still thriving, if modest sized, industry.

The same structural concept eventually evolved to support stacks of electrical and electronic components, changing from the use of metal plates to the non-conductive materials of circuit boards and leading to a great variety of modular standards used across the electronics industry. The typical desktop computer still often employs a set of ‘standoff posts’ to support and isolate the now typically solitary ‘motherboard’ within a variety of enclosures.

As with so many other building systems, the use of this type of structure for more diverse kinds of modular building may have originated with building toys, in particular with grid plate building toys such as the American Erector toy and its British and European counterparts Meccano and Merkur appearing at the start of the 20th century. These toys introduced standardized geometries in the spacing of holes and parts dimensions and often incorporated simple gear mechanisms, miniature steam engines, and eventually electric motors. Many prototype inventions were devised with these toys, such as the first manufacturing system for oxygen-permeable plastic contact lenses devised by Otto Wichterle in 1961 using the Merkur toy. While only a few of these building toys are still produced today, they remain popular among amateur robotics enthusiasts, some robot kits based on gridded plate chassis conforming to the remaining toy set dimension standards.

Also in the early 20th century similar structural systems began to emerge in the area of industrial and commercial shelving products, particularly welded wire shelving used in the foodservice industry. Appearing in the late 1920s, this form of shelving is based on chrome plated welded wire deck panels with corner cylinders that host a set of steel posts notched at regular intervals. Plastic clips that catch in these notches allow the the deck units to be positioned at uniform heights. Casters and other accessories attach to the posts and decks, creating a simple modular system with many possible uses.

Use of this shelving was long limited to industrial and commercial fields but spread into areas of laboratory use compelling the introduction of solid steel sheet or drop-in plastic decks. But toward the end of the 1970s came an interior design trend known as Industrial Style and High-Tech which popularized the repurposing of industrial and commercial furnishings in the household setting. So-called ‘professional’ foodservice equipment became popular for home use and wire shelving soon entered homes around the world. This inspired a vast number of companies to start manufacturing cheaper variations of these shelving systems to compete with the generally high-priced commercial products, leading to some divergence in their once common component standards. New forms of posts based on different profile shapes and different types of connectors have emerged. This shelving is now commonly found most everywhere, though still sees most of its uses in commercial settings.

Most-recently we have seen some novel furniture designs based on the introduction of threaded wood posts, facilitated by CNC milling, that allow for an all wood post and plate system. Threaded rod systems, deriving from components used in electronics, have long been used by hobbyists but this allows for structures at a much larger, furniture-sized, scale. Many possibilities exist for the use of this as the basis of a simple multifunctional modular building system with the attractive features of wood.

5:1 Bolted Plate Building Toys (Erector/Meccano)

One of the more well known, and most sophisticated, of modern building toys are bolted plate building toys, first appearing at the start of the 20th century under two brands; Erector in the US and Meccano in the UK. Meccano was first introduced in England by Frank Hornby in 1900. Erector was introduced by A.C. Gilbert in 1913, at the same time that Hornby began exporting Meccano to the US. When Hornby created a US company in New Jersey to manufacture Meccano there, Gilbert bought out the rights to manufacture Meccano in the US and moved its production to Connecticut, right beside his own Erector factory, though still made sold the product as ‘American Meccano’ or ‘Gilbert Meccano’ until the 1930s. Dozens of copycat products, made by companies around the world, quickly followed and were popular across most of the century. However, by the end of the century they were partly supplanted by plastic building toys that were considered safer. While Erector sets stopped being made in the late 1960s, Meccano persisted in the UK until the 1970s and in France until 2000. Today, only a few of these products still exist but remain popular among amateur robotics enthusiasts who have found new purpose for the building toy in designing and prototyping various robots.

These building toys are composed of sets of metal plates in a variety of shapes with grids of regularly spaced holes, nuts and bolts to assemble them in endless combination, and an endless assortment of accessory parts including wheels, pulleys, and modular mechanisms. Even tiny steam engines were sometimes used with these, leading to the more common later use of small electric motors and other battery-operated electrical accessories. Many modern inventions had their start with experimental prototypes made with these toys and they were often used in schools for teaching principles of physics, mechanics, and engineering.

Ami-Lac
Eitech Construction
Merkur
Clickaloo

Clickloo is a plastic plate construction toy system designed to compliment the use of desktop 3D printers, its parts available free as downloadable '.stl' files for DIY fabrication. It uses snap-lock pins in several depths rather than nuts and bolts and its standard dimensions and interfaces can be applied to any number of custom 3D printed parts and accessories. An online community is expanding the system with shared designs. http://www.clickaloo.com/

Gridded Plate Robot Kits

Tamiya Robot Construction Sets (Educational Construction Series)

The Japanese Tamiya corporation has a long history in scale model kits, RC models, and simple educational kit robots. (most based on post and plate mechanisms) The Tamiya Robot Construction sets, part of their Educational Construction Series, is yet another derivative of the classic Erector/Meccano building toy whose components are made mostly of injection-molded plastic rather than the more common metal. Intended for simple DIY robots and educational mechanisms, the system uses 3mm holes in a 3mm grid with connections made using plastic push-rivets instead of nuts and bolts. The use of plastic instead of metal is apparently intended as a child safety feature (and perhaps to make the most of their established injection-molding production) and as a building system the range of components is limited, with only a few kinds of base plates, beam plates, and angles. The various kits offer few components each and are clearly intended for very light duty. The chief innovation of the system is its integration with Tamiya's large assortment of pre-made modular plastic gear, wheel, and motor mechanisms which have long been popular worldwide among scale model and robot hobbyists. Not all of these may directly connect to this system, and the choice of plastic may also relate to making these parts more 'hackable' using craft knives and glue.

Vex (Vex basic, Vex IQ, Vex Pro)

Vex is a popular robot product line in US STEM education. It features three basic lines all deriving from traditional holed plate construction toys; the basic or original Vex system which is used for relatively small robots, the Vex IQ system which is based on injection molded plastic plates and pins, and the Vex Pro which is based on an alloy parts set called VersaFrame with more post & beam type construction (akin to Grid Beam) and is intended for large scale, more sophisticated, robots in a college setting or for robot competitions.

5:2 Circuit Board Stacks

Likely taking their inspiration from the chassis of mechanical clocks, electrical and electronic circuit boards have long been designed for use with 'stand-off' posts to isolate them from an enclosure and stacked configurations using such posts. Much like large clocks, early electrical and electronic devices were put in wood enclosures that were often made independently and locally by cabinet makers, allowing local dealers to customize them to suit local market tastes while also making it safer to ship the more delicate core components long distances --a practice that persisted well into the era of television. This has its analog even today, with built-to-order desktop computers.

Circuit board materials today are composed of multiple layers of tough fiberglass and are quite resilient, allowing many kinds of industrial and hobbyist devices to function quite fine without an enclosure or relying on the boards for their structural strength. Many modular industrial computer standards are based on this, using standard shape boards with standard configurations of posts, mounting holes, and plug-in connectors to form modular assemblies. These parts will even host hybrid combinations of electronics and mechanical components much like the clock chassis of old. Many small robots, particularly those designed for the hobbyist, are based on bare board chassis. Though there are no definitive systems for general or multipurpose use, there is a vast collection of off-the-shelf circuit board mounting hardware that offer the potential for repurposing into novel modular building systems, though their generally small scale would limit them to relatively small assemblies. This hardware is also not limited to the use of just circuit board material and can be combined with other materials, as we will discuss in the next sub-section.

5:3 Makeshift Post & Plate Systems
Rod & clamp building systems are complementary to post & plate systems, their parts offering many possibilities for crossover uses. Under the Rod & Clamp subcategory of Post & Beam building systems (3:7) we noted the use of common off-the-shelf threaded metal rods as a DIY basis for creating rod & clamp modular assemblies. This is quite suitable for use with a post & plate system as well, using threaded rods as posts passing through plates of various sheet materials and fixing them at desired heights using nuts and washers. Similarly, it possible to employ the locking clamps or fittings of other rod & clamp systems to support plates and panels of various kinds. In fact, this is a common approach to making shelving using the various pipe-fitting systems like Kee Klamp. There are also various metal posts and angles that can likewise be used to connect and offset stacks of plates, such as the many kinds of posts commonly used with circuit boards. (see 5:2) Using these kinds of components, it's possible to devise many kinds of simple modular building systems suited to shelving and other furniture and small devices. The diagrams in this subsection offer a small sample of the many possibilities.

Threaded and Clamped Rod Posts
Pipe Shelving and Furniture
Holed Tubing and Angle Shelving and Furniture

5:4 Threaded Wood Post Furniture
The recent advent of sophisticated CNC milling has ushered in an unusual new modular building product which has only just begun being explored by designers; threaded posts, bolts and nuts made of wood. Working in the same way as metal threaded rods but at a scale more suited to furniture--and much more aesthetically appealing--these new parts offer an interesting way to quickly assemble an endless variety of shelving and other furniture. So far these components remain relatively rare, with few examples on the market. But if this simple way of building catches on we may see more products of the type in the near future.

5:5 Industrial/Commercial Shelving Systems
Modular industrial/commercial shelving appeared in the US in the late 1920s and was greatly popularized by the Metro company, marketing largely to the foodservice industry. Across the 20th century it has become ubiquitous, made by countless manufacturers and adapted to uses ranging from the home and to the workshop and laboratory. Originally based on the use of chromed welded steel wire shelf panels and chromed tubular posts, this type of shelving employs plastic wedge shapes that lock into grooves on the posts when compressed by cylindrical holes in the corners of the shelf panels. These basic parts are complemented by a vast assortment of plug-in and clamp-on accessories such as casters, baskets, sign-holders, lamps, and

more. Recently, other post shapes and materials have come into use, some based on plastic and some using metal encapsulated in molded plastic. Though most of the products of the type have derived from the designs of the original Metro system and are often intercompatible, they have diverged over time as companies were disinclined to actually cultivate a cross-industry standard. But within the confines of individual brands, there is usually enough diversity of multifunctional parts for their use as multi-purpose modular building systems.

Metro

Section 6: Panel Systems

Panel building systems represent another large diverse group with a long history, though most of the sheet materials common today appeared with the advent of industrialization. Perhaps the first hints at modular systems using panels were various types of screens used in ancient forms of housing, particularly in Asia. The compartmentalization of homes into many rooms was a largely Western tradition. In the East, and particularly its warmer and wetter southern regions, the typical building was what we refer to today as 'open plan' and instead of using many rooms it was common to build compounds or clusters of smaller free-standing or adjoining structures with multifunctional space. These often took the form of pavilions; roofs and raised floor decks supported on posts without permanent perimeter walls. Instead, removeable wooden planks, louvered or lattice shutters, wooden screens, curtains, or panels of woven plant materials would be mounted on or between the posts, allowing for the high air flow needed to keep homes naturally cool. Inside, similar free-standing screens, partition panels, and other pieces of furniture would be used to provide privacy. Beds were often designed as self-contained free-standing mini-rooms of their own, much like the sleeping pods that have recently been devised by contemporary designers.

As noted in other sections of this book, Japan saw a very early development of modular technique in homebuilding and this extended to the design of walls. Few of the walls in the traditional Japanese home (as typified by the Higashiyama Bunka era architecture we so often see in media) were fixed walls --those often made using a non-load-bearing clay and woven bamboo infill construction called 'tsuchikabe' reminiscent of European 'fachwerk'. Interior partitions were more commonly made of screens, designed for easy removal and reconfiguration and often placed on waxed wooden grooves to allow them to slide and function as doors. Their sizes relating to the vernacular dimensional system called 'ken' relating to tatami mat sizes, these sliding 'shoji' and 'fusuma' panels were made of light wood, paper, and cloth with fusuma panels developing a tradition of sophisticated decoration and artwork.

During Europe’s medieval period a tradition of interior decoration or finishing using carved wooden panelling became common for homes, castles, and other buildings built of rough stone. In some cases it was even applied to dwellings excavated from rock and, with the much later emergence of fired brick, it came into common use with brick buildings. Such paneling provided not only decoration but a bit of insulation as well and improved the acoustics of such buildings. It could be used both for walls and ceilings, sometimes completely lining the interior of rooms and integrating doors, windows, and cabinets, but often only being used to line walls up to a certain height, with plasterwork covering the rest. Though not intended to be a modular system, this paneling was typically made in sets of uniform panels with repeating design patterns and was easy to remove and repurpose in other buildings. In some cases it was treated much like the rest of the furniture in homes, taken from one building to the next. Elaborate relief carvings were sometimes added to this paneling and in some cases it would be painted, gilded, or inlaid with different wood veneers or other materials.

With the extensive innovation and experimentation in building across the 20th century, a variety of panel-based building systems were devised for construction. However, most of these were either complementary in nature--designed to be combined with other structural systems such as the modular ‘hanging wall’ systems used in commercial buildings--or too large and heavy for use without heavy equipment. But with the emerging ubiquity of large office buildings and skyscrapers, with their large open-plan interior spaces, there developed a burgeoning industry in modular office furniture and partition systems. Designed specifically to be quickly assembled by the typical office staff rather than skilled construction workers, these systems offered a convenient and quick means of adapting these large interior spaces on-demand. Today, countless companies make such systems. With the emergence of the Industrial/High-Tech interior design movement later in the century, these systems were sometimes repurposed for domestic uses, their comfortable fabric-covered surfaces and practical designs well complimenting Modernist aesthetics and suited to comfortably adapting spaces like former industrial lofts.

With the rise in popularity of the geodesic dome among owner-builders and DIY enthusiasts in the late 1970s, there was much experimentation with alternative methods for their construction, given as the more typical architectural space frame systems were largely inaccessible to the owner-builder. Panelized geodesic dome systems offered a way of building such domes with more conventional materials and without the sophisticated node and hub components that could not be easily made by individuals. Buckminster Fuller himself started the trend with his creation of the ‘fly’s eye dome’, based on a system of pressed alloy panels with in-set acrylic windows. However, commercialization of this high-tech design was never realized. More commonly, systems of geodesic panels were devised made of timber and plywood, fashioned into simple modules including insulation. These were similar to the prefabricated wood stick-frame tilt-up panels developed for some modular homes, but easier for the individual to handle. These, however, were not often intended for demountability and reuse, relying on nailed assembly and conventional home exterior cladding. They were also generally opaque, fitting of more conventional windows within the unusually-shaped panel areas.

Many dome home kits were based on these systems and a number exist to this day. But it proved inefficient to translate normally rectangular sheet materials like plywood into the domes' more complex, precise, geometric shapes and the many seams that needed to be sealed proved unwieldy and failure-prone. Conventional rectangular windows didn't well suit the shape of the panels and finding round ones of significant size, like those of the fly's eye dome, often proved difficult. The panel dome home ultimately fell out of fashion by the end of the 20th century, though frame type domes have seen a revival in recent years with designs based on more yurt-like construction using architectural fabric exteriors.

Fuller himself never intended the use of the dome in the manner common to these once popular dome home kits. He envisioned the dome home as a high-tech version of the pavilion as common to Asia and Polynesia. A transparent free-standing 'skybreak' that would shelter a space from wind and rain and provide a large open-plan area in which the rest of home was fashioned of light comfortable elements akin to office partitions, providing privacy and defining function. Sadly, the technology to make that practical--in particular the architectural membranes like Texlon and glazing technology like silicone-joined planar glass systems--didn't arrive until very late in his life.

With the advent of 'ready-to-assemble' or 'flat-pack' furniture based on various sheet and board materials, many designers started employing multifunctional elements to allow these furniture items--shelving systems in particular--to be customized by their users, thus evolving them toward modular building systems. The concept of such furniture originated in the US in the late 19th century but didn't become common until late in the 20th, popularized by firms such as the famous Ikea company. The trend has gained continued strength with the recent advent of CNC routers and laser cutters which have provided a means for designers to use personal computers to automatically produce custom panel components almost as easily as printing documents on from a digital printer. A vast catalog of ready-to-use flat-pack furniture designs can now be found online and these have been a key feature of the emergent Maker movement, many of them specifically created as open source designs intended for free-use and refinement by the Maker community.

Not satisfied with simply making furniture, advocates of this new fabrication technology have sought ways to expand its use to housing, leveraging the power of these new tools to lower the bar in skill and labor for home construction. Evolving the same kinds of puzzle-fit assembly used with this panelized flat-pack furniture, as well as many building toys, they have devised new building systems that not only simplify construction but design as well through ‘parametric’ component systems. Pioneered by the university-based community of Fab Labs originating at MIT, many demonstration houses have been developed based on the variations of puzzle-fit panel construction and it seems well on its way to becoming a mainstream method of housing construction.

Another recent innovation in panelized forms of construction has been the introduction of Cross-Laminated Timber (CLT) systems and their related ‘brettstapel’ systems. The brettstaple concept was invented in the 1970s by German engineer Julius Natterer as a means of repurposing low grade timber into solid panels by nailing successive vertical parallel layers of wood strips together. These panels could then be trimmed and planed to make a large, solid, modular building element. The metal nails proved to be a problem for cutting these panels to shape and were eventually replaced by the use of long diagonal wooden dowels, though this precluded their easy fabrication at small scale. CLT panels are quite similar, but use alternating overlapping horizontal layers of timber bonded by adhesives under high pressure, creating a thick monolithic building element. CLT panels can be exceptionally large and strong, affording the use of wood in high-rise construction once limited to the use of steel and concrete. Most use of these panels has been ad hoc, with panels made-to-order and partly relying on heavy screws for assembly. And their generally large size requires the use of heavy lifting equipment. But some mechanical interfaces for these panels have been developed affording the potential--as yet unrealized in commercial use--for fully modular and demountable systems.

Another recent introduction has been the re-invention of medieval wooden wall paneling as a form of modular retrofit interior finishing for the quick renovation and adaptive reuse of buildings. Similar in nature to office partition systems, these retrofit panel systems are intended to line the walls, floors, and ceilings of bare, rough, concrete and steel structures, giving new life to dilapidated yet still structurally sound buildings. Instead of spending the high labor of conventional stripping, surface-framing, and finishing for such structures, these prefabricated and prefinished panels simply plug-together to create finished rooms within the old building’s shell. They can even integrate various furnishings, lighting, and utilities elements.

6:1 Slotted Shape Toys

A large variety of building toys are based on simple cards, planks, or tiles fashioned with slots to allow them to be fit to each other by being slotted-together and held in place by friction. Perhaps the oldest of these toys are slotted playing cards, either made from card decks by-hand or purchased pre-cut. These toys go back at least as far as the 19th century and were not only popular with children but also adult mathematicians and artists who found that by varying the angle and number of slots they could assemble a variety of complex geometric shapes. With the advent of die-cutting and later laser cutting this become the basis of a variety of slot-together lamp shades using more elaborate card shapes with translucent materials.

Most of these toys, however, employ thicker, sturdier, materials like heavy cardboard, wood, plastic, and semi-rigid foam in a variety of shapes and sizes, a few being exceptionally large to allow children to make play buildings. (and creative adults to repurpose them as decorative room partitions) Sets composed of the basic polygons are typical but more elaborate free-form shapes have also been used.

Another variation on these employs cards, planks, and tiles that do not themselves have slots but are intended to fit into slotted joint pieces made of wood or molded or extruded plastic. These toys have been used with pieces simulating architectural textures and patterns to make toy buildings.

Slotted Playing Cards
Eames House Of Cards and Create-it-All kits
Waffle Blocks
Crystal Climbers

6:2 Magnetic Panel Toys

With the advent of higher performance magnetic materials, the variety of magnetic toys have steadily expanded. Magnetic panel toys are a variety of these modular panel toys that use molded plastic tiles with magnets embedded in their edges to allow them to link edge-to-edge with the flexibility of a hinge. These often feature shapes to allow for assembly of various polyhedra and geodesic domes and spheres.

GeoMag
Magna-Tiles
MagFormers

6:3 Puzzle and Slot Fit Panel Structures

The advent of CNC and laser cutters, with their ability to quickly produce intricate and high-precision shapes from computer image files, has ushered in a great burgeoning in design with sheet materials, particularly among Makers and advocates of Open Source technology and design. The Internet is now host to a vast menagerie of design files for everything from toys to furniture and even simple vehicles based on puzzle and slot-fit assemblies. These often eliminate the need for nails, screws, and bolts by relying on the very tight friction-fit of their puzzle and slot-fit joinery or through the use of various pegs and wedges.

Recently, such technology has been applied to the construction various kinds of shelters (the famous Burning Man festival a popular showcase for them) and even full-size homes, attempting to radically reduce the skills and time required for construction using nailless or screwless assembly. CNC-cut structural elements are making steady inroads into the conventional building industry and, while there is much attention put on 3D printed housing, it is more likely that CNC use may soon become the first common digital production method in conventional housing.

Three approaches are currently common to this new form of construction. The first employed in full scale demonstration buildings are puzzle-fit lattice systems where a dense lattice skeleton of slot-fit panels provide the core of walls, floors, and roofs that are rigidized by tight fitting facing panels forming a structural shell. The lattice can be filled with insulation and host utilities like conventional stick framing while the facing panels serve as foundation for conventional finishing materials. This system was most famously demonstrated by an MIT project showcasing possible housing solutions for New Orleans disaster relief in the wake of hurricane Katrina. Developed to complement computer-automated procedural engineering systems, it favors house designs with complex interior wall arrangements and modest spans and tends to produce structures with very large parts counts. It has not been used as yet as the basis of multifunctional modular systems.

Relating to, or deriving from, this lattice system is stressed-skin structures similar to the semi-monocoque structures of aircraft fuselages. These use larger primary frame members akin to the sectional ‘rib’ frames of aircraft linked by stringers or spars and fully rigidized by one or two layers of surface or ‘skin’ panels providing lateral strength. This approach tends to reduce parts counts by using surface panels and frame members closer to the full width or length of standard plywood panels. A more recent derivation of this employs puzzle-fit and wedge-locked assemblies forming box trusses as those primary frames, serving as the basis of modular larger-span structural bays linked by connectors or purlins and creating a system very similar to the large-span ‘rigid frame’ or ‘portal frame’ construction of pre-engineered steel industrial buildings. This has been used as the basis of an open source system known as Wikihouse, originally developed in New Zealand, that offers potential as a more comprehensive modular and demountable building system, but has so far been used more as a parametric structural system applied to discrete designs. This approach is well suited to Modernist home designs that employ modular bay elements with wide open ends for large windows.

Another approach is based on the use of panels to make unit box modules, as with the bolted and mechanically joined box systems noted in section 1:4:2. This approach is well suited to the more conventional custom free-form home designs when used in combination with conventional home finishing materials, but when using such finishing sacrifices its potential demountability. This is the first of these kinds of CNC building systems to be commercialized, being developed into a proprietary system by the UK company Facit Homes which is notable for its innovation of transporting containerized CNC workshops whole to building sites to fabricate components on-demand.

Laser-Cut Joinery
Lattice Systems
Stressed-Skin Bay-Frame Systems - Wikihouse
Modular Box Systems

6:4 Friction-Fit Systems

Friction-fit or clamp joints take their inspiration from similar panel building toys. Relatively thin panels are linked using plastic slot/channel pieces which hold them in place by friction. For a stronger connection bolts can be used to provide a clamping force. Such clamps can also feature ridges to interface with grooves or slots in the faces of the panels. Aluminum profiles used for roadcase construction can also be used as friction-fit joints, but are designed to be combined with rivets for permanent assembly. Such systems are suited to relatively low-load and require that the corner/edges between panels have a certain gap. These systems have been employed with many kinds modular shelving and simple panel furniture. With the advent of desktop 3D printers many files for various Open Source joints of this type can be found online.

Wire Cube Shelving
PLY90 Connector
Playwood Connector
https://www.playwood.it/
Mozilla Module Corner Connector

6:5 Cellular Panel Systems

Cellular panels are assemblies of smaller sub-panels or tiles linking edge-to-edge allowing for a composite surface of variable shape or variable integral features. Relying on a certain degree of thickness, they may feature puzzle-like forms, friction-fit interfaces, or mechanical connectors. These systems are usually intended to create a rigid vertical or horizontal surface serving as partition, countertop, or table that can be reconfigured as needed. Individual sub-panels can be outfit with a variety of fixtures, mechanisms, or appliances for any number of uses and to create customized workstations. Cellular panel assemblies may also feature as unit parts of other building systems.

Modulos (Kickstarter http://modulosdesk.com/en/home/)

6:6 Modular Screens, Fences, and Trellis

Harkening back to their traditional uses, free-standing screens used as moveable partitions are still in common use today in homes and offices, typically taking the form of panels supported at their base by perpendicular supports or sets of panels joined by hinges that are self-supported by being partly folded. These are modular chiefly in the sense of being standardized in dimensions across a particular product line and sometimes linking loosely together with non-rigid connection. In recent times these have expanded in uses to include modular fencing for use as temporary enclosures outdoors and trellises for the support of plants. These trellis systems may be free-standing or designed to hang off-set on walls in various modular combinations. Some large portable fence systems have also been devised for use as temporary livestock corrals and barricades or enclosures for outdoor events. Recent hydroponics systems have also been fashioned as free-standing or hanging panels.

Many modular screen systems, intended for home and office use, are based on small interlocking or puzzle-fit panels allowing them to be built-up to highly variable shapes. With the advent of laser cutting and 3D printing, many novel designs for these have emerged.

Portable Corrals
Portable Crowd Control Fences
Modular Garden Trellis

6:7 Hanging Wall Cladding Systems

Hanging wall systems are a specialized type of modular system intended to provide easily assembled prefabricated and prefinished cladding for the exterior walls of large commercial buildings and skyscrapers. They form parts of what is referred to as a ‘drainage plane’ system, shielding a building from direct rain impact and sunlight while also serving as a way to conceal cruder-looking wall construction. They get their name from their use of support framing that ‘hangs’ panels offset from a foundation wall, providing a channel for drainage, retrofit utility runs, and an insulating gap. Their proprietary designs often feature hook or latch elements to minimize the number of screws or bolts needed to secure the panels and make them easily demounted, allowing for quick repairs or replacement.

Though generally too specialized to be considered multifunctional modular systems, these systems can sometimes integrate active elements like lighting or thermal management systems and they can be repurposed for other applications. They have often turned up in use in Modernist housing designs and are also used for solar panel installations. Their common panel materials, such as foam-core aluminum sheet, have found a variety of unintended alternative uses in the hands of creative Makers. One particularly interesting type of material that has emerged recently for these panels is extruded corrugated terracotta panels with rich organic coloring and attractive textures.

Commercial Hanging Wall Panels
Living Wall Systems

6:8 Office Partition and Exhibit Systems
Ubiquitous throughout commercial offices worldwide, modular office partition systems are produced by countless companies in countless variations. However, despite being largely identical in features, common standards among them have never been realized, their manufacturers relying on ever-changing proprietary hardware designs intended to lock their customers into their exclusive product lines. They are intended to compartmentalize space in large open-plan offices for use as individual worker spaces or ‘cubicles’, providing visual and sound barriers. They are specifically designed to be assembled without the skills of professional construction workers, allowing office or building maintenance workers to readily assemble them, though some have now become so elaborate in their proprietary designs they require their own unique skill-sets and training to use. Designed to be demountable, they can be easily reconfigured as businesses’ uses of space change and are typically complemented with lines of modular office furniture that integrate with the panel systems. Over time the simple technology for these partition systems have evolved for use in trade show exhibits and the construction of temporary semi-enclosed kiosks and exhibit booths. More recently, they have evolved into large portable/moveable wall systems and in-plant office systems, designed to meet up completely with ceilings in office spaces to create large partitions or enclosed offices and meeting rooms.

The essential element of these partition systems is a built-up panel unit quite similar to the ancient fusuma panels of Japan, using a hollow or foam core and prefinished surface coverings in a variety of materials --most commonly fabrics with a backing that allows items to be tacked to the surface. Glass or plexiglass panels are also used, as are wire screens and, for some speciality uses, slatted panels supporting hangers for the display of art, products, or hanging of shelves, storage bins, and tools. These are supported by an edge frame of wood, plastic, or tubular alloy, with the alloy frames often using a profile shape and integral holes or channels providing light load-bearing support for shelving, cabinets, desks, and other accessories. Most systems require panels to form complexes of right angles to be self-supporting, using leveling feet on the panel bottom edge, but some can employ additional perpendicular supports to be free-standing.

The connection schemes are common for these partition systems. The simplest use U-shaped brackets bolted to their edges creating a kind of friction-fit connector. This type is very visible and more often used in low-cost products In another form the edges of the panels host bolt-on or snap-on corner brackets to link them edge-to-edge or along corners. These are concealed by snap-on cover strips. Other systems employ corner posts that panels latch to or hang suspended on, sometimes also providing leveling feet that keep the bottom edges of the panels slightly off the floor. A few partition system include, or are based on, modular shelving and cabinets rather than panels, adding to their functionality.

The variety of accessories for partition systems is endless and contemporary systems often include integral channels and modular fixtures for electric power and communications cables. In time we are likely to see even large area computer displays integrated into these partition systems.

Portable wall systems and in-plant office systems address the need to fully fit wall-to-ceiling or create a complete independent enclosure within a building while remaining easily removeable. This is complicated by the fact that ceiling heights are not always uniform and most offices use suspended ceiling panel systems that are not particularly strong. So most of these system are combined with some kind of modular rigid free-standing support framing--typically based on alloy profiles--or, at the very least, ceiling rails or adjustable posts that can attach to the core structure of the ceiling. These systems are often used to host glass partitions, which can be too heavy for the more conventional forms of partition panels.

6:9 Interior Retrofit Systems

Interior retrofit systems are a relatively recent concept that revives the role of carved wooden paneling systems originating in medieval European architecture. Such ancient paneling was used to conceal the rough surfaces of stone and brick wall construction to make interiors more comfortable and better insulated. These new modular systems assume a similar role for the quick adaptive reuse of dilapidated concrete, brick, and block structures. Building on the kind of modular component designs featured in office partition systems, portable walls, and in-plant offices these systems form complete integrated interiors with prefinished walls, ceilings, and floors, built-in fixtures and furnishings, and routing for utilities. In this way old buildings and industrial structures can be quickly made habitable and comfortable without the elaborate skilled labor of conventional refurbishing.

There are still only a few examples of such systems and none may be in commercial production today, but this is a promising concept that may be particularly useful in the repurposing of commercial buildings for residential use given emerging urban space trends.

6:10 SIPs, Brettstapel, and CLT

With the advent of industrialization came a steady growth in engineered materials intended to expand the range of useful properties for construction materials and make better use of natural resources. In the ancient past many approaches were devised to improve or combine the characteristics of one kind of material by layering and bonding another material to it. Often one kind of material is very high performing in one characteristic, but poor in others. For instance one material may be high in tensile strength, but not very rigid or strong under compression while another is strong in compression but very brittle. If they can be combined in some way, we may have something that gives us the strengths of both while eliminating their weaknesses. In modern times, the exploration of these complementary combinations has resulted in a vast diversity of what we now call 'composite' materials. One of the most common of these today is plywood, which is made by layering and bonding thin strips of wood together to form rigid, easily cut, boards we commonly use in most kinds of home and building construction. Plywood allowed us to radically change the characteristics of the wood we've long used. Wood is limited in that pieces of it tend to be long and thin. We could make frames of it, but filling in those frames to make a more-or-less solid wall required some other kinds of materials. For instance, in the past it was common to finish the walls of homes by nailing up thin wooden slats and applying thick layers of plaster to make a smooth wall surface --a very high-skill high-labor process. Plywood let us take the properties of wood and put it in a flat sheet form, allowing us to cover wooden frameworks with it, increasing their lateral strength by making them 'stressed skin structures' while providing a foundation to apply other not-so-strong thin materials to make a desired finished surface; wallpapers, plasterboard panels, and so on.

As we sought, across the 20th century, to simplify the construction of homes we devised many more kinds of composite materials that could remove some of the labor and skill needed while enhancing performance. Hand-construction of walls is a pretty elaborate process that manually combines many materials; wooden framework to provide a rigid load-bearing structure, plywood cladding to reinforce that structure and provide a foundation for finishing, insulation to make a thermal barrier, and so on. What if one composite material could do all that work? In the late 1940s engineers began exploring the combination of corrugated paper/cardboard materials with plywoods to make composite panels, sometimes combining them with veneers, decorative paper or plastic, foils, or thin metal sheet to make a pre-finished surface. These have been used as wall and door panels in planes, trains, and ships ever since. Soon they moved on to the use of thick layers of polymer foam bonded to tough plywood such as Oriented Strand Board. Such panels could be made large and as thick as conventional housing walls, could be cut to any shape, and performed comparably to the hand-built structures of conventional walls while being superior in thermal performance, and thus we arrived at the modern Structural Insulated Panel SIP. But change comes quite slow to the ultra-conservative housing industry and routine use of SIPs in housing construction didn't emerge until the 1970s.

SIPs have always had potential as the basis of modular building systems, but this has rarely been explored. People still do not often thinking of building in a modular way --particularly when it comes to homes that we tend to regard as 'permanent'. One area where it proved useful was in industrial and commercial buildings where non-load-bearing SIPs based on metal alloy skins became common, combining characteristics of interlocking metal roofing and siding panels. These could not be as readily cut to shape as their OSB-based forms without interfering with their interlocking features and so compelled more modular forms, particularly with the advent of hanging wall systems.

One modular, though not truly demountable, use of SIPs emerged with the Japanese Volkhaus system, mentioned in section 3:1. Using a timber frame for the primary structure, here special SIP modules fashioned with perimeter sealing gaskets are used as easily placed infill panels within the timber frame, providing a very uniform structure for walls, floors, and ceilings. This approach seems to have moved on to more general use in timber frame Japanese homes.

In the 1960s German engineer Julius Natterer was exploring ways to make better use of scrap lumber in low-cost construction and devised a technique of stacking horizontal strips of lumber and nailing and gluing them in place sequentially to build-up a larger, thick, wood panel which could be cut to any desired shape like a solid piece of wood. Dubbed 'brettstapel' the method proved promising but had complications when being cut due to the use of metal nails. This was later improved by replacing nails with wooden dowels inserted perpendicularly or in crossing diagonal patterns, though this now required the use of large industrial equipment to fabricate the panels. These thick, large, panels can be treated as solid pieces of lumber with all the strength of timber framing, allowing strong structures to be assembled without framing as a series of panels nailed, screwed, or bolted together at their edges or which can use more sophisticated milled joints. Brettstapel panels often use different widths of stacked lumber to create novel ridged or wavy surface details. Brettstapel is now used throughout Europe, though manufactured mostly in Austria, Germany, Norway, and Switzerland.

Further evolution of this technique, employing techniques used in laminated wood beams, has very recently produced a variation called Cross Laminated Timber. (CLT) Here thin wood strips are not just stacked but combined in multiple crossing layers that are bonded together with an industrial adhesive under high heat and pressure, creating large thick panels. This has produced what may be one of the strongest composite wood materials ever created, allowing for timber construction to be applied to high-rise buildings. CLT panels can be used alone for load-bearing structures or combined with very heavy laminate timber posts and are often used in combination with the same commercial rain screen hanging wall systems used in other types of commercial building. However, the panel fabrication technique is limited to a heavy industrial setting. CLT is well suited to truly modular building systems, with some panels designed with interlocking edges for rigid shear connections, but so far has not been applied to that except in bespoke modular assemblies requiring heavy lift equipment to assemble. Most uses of it rely on heavy screw connections with steel angle and strap plates, though semi-concealed mechanical connectors similar to those used in modular heavy timber post & beam construction have been developed. A truly modular system is possible, but the typically massive nature of CLT components may limit its practicality for the Maker.

6:11 Geodesic Panel Domes

Though the late 20th century craze for dome homes has long past, the geodesic dome remains a common obsession for DIY builders today and the same challenges of creating components for them are still compelling a steady pace of innovation and invention. Using systems of modular polygonal panels still has some advantages over the use of geodesic frames given the difficulties with making node joints for such frames and their potentially large numbers of parts. However, when working with materials like wood and plywood that typically come in rectangular forms, making oddly-shaped polygonal panels has never been that efficient and dome structures still have many angular seams that need to be sealed if they are to be made waterproof.

The interesting thing about panel domes is that the dome itself is a self-rigid structure, relying on the rigidity of the panels, with the seams along the edges of panels functioning not in compression but in tension. For simple, light, structures it’s not necessary for the joints holding panels together to be rigid, allowing various flexible connections to be used. Simple forms of panel dome can thus be held together by remarkably simple means, such as repurposed metal hinges, friction clamps as used in the friction-fit panel systems described in section 6:4, laced together with cords or zip-ties, or even joined with tape. The clever relief shelter design developed by Vinay Gupta known as the Hexayurt is a simple geodesic panel structure made of foil-backed foam panels held together and made waterproof by simply taping the panel seams with aluminum industrial tape.

Simple panel domes can also be used as an alternative to using a geodesic space frame where the dome may be clad with another material,as in the case of tent-domes. In this case rigid but relatively thin polygon panels can made with an open volume, joined along their edges, and the completed dome covered by an architectural fabric skin.

More typical panel domes employ more precisely shaped components in a solid, composite, or shell panel form. Solid panels require a relatively rigid, thick, and solid material which is beveled along the edges to suit the topology of the dome and the angles of its corners, creating a snug fit, though still needing some kind of sealing to be made waterproof. The edges are fitted with some kind of in-set mechanical connectors such as bolts or bridge clamps to join the panels together. Alternately, they may use some kind of bridging surface plates to connect them.

With composite panels relatively thick built-up units are made akin to the panels of a tilt-up wall house or the panels of an office partition system. They have a rigid edge frame reinforcing their thinner plate materials which is beveled to suit the angles along the edges of the panels and provide mounting for mechanical attachment. These frames can be as simple as angled metal brackets supporting a single sheet of panel material along the exterior surface and need not continuously line the edges of the unit, leaving the corners free. More substantial panel units may have both outer and inner facing sheets. In some dome home kits these might be semi-finished with an applied panel of sheetrock or a series of tongue-in-groove wall panel planks. Structural Insulated Panel pieces can also be used as the basis of such panels, adding the reinforcing frame within their edges. If made waterproof, some kind of gasket or adhesive seam filling/covering, like a tape, must be used to cover the exterior seams and, for more permanent structures, an additional cladding or roofing tile used on the dome exterior. This approach favors topologies where the dome is made of alternating hexagonal and pentagonal panels (like a soccer ball) rather than triangular panels with very sharp corners. Very sophisticated forms of panel domes have been developed for arctic base shelters, featuring formed alloy or fiber-reinforced plastic composite facing, but have never been made commonly available to the public.

Shell panels are made of relatively thin materials crafted to create a raised ridge seam along their edges providing rigidity and which are bolted-together along those seams with through-bolts, using a sealant or some kind of gasket to make a waterproof seal if needed. The edge ridge can be continuous, forming full corners, or made as flanges folded along the sides. Such panels are usually made of thin materials that can be press-formed, vacuum-formed, or shaped on a form such as sheet alloy, thin thermoplastics, or fiber-reinforced composite. When using pressed allow or vacuum-forming shell panels can include further reinforcement in the form of creases along the faces of the shell plates. Shell panel modules made of sheet acrylic are the basis of the transparent panel dome systems devised by the design group N55 for the creation of novel greenhouses.

Buckminster Fuller's famous Fly's Eye dome featured a very unique approach to its panels, made as they were from fiberglass reinforced resin. This dome relied on large round plastic bubble windows and to minimize the seam lengths of the panels they were used to form three-legged saddle-polyhedra pieces of a very complex curving shape. Such shapes are rather difficult to fabricate even with the benefit of industrial tools, and this is, perhaps, a key reason why the Fly's Eye dome never succeeded as a commercial product. However, such things may prove more practical with the advent of 3D printing.

Hexayurt
N55 Panel Dome

6:12 Plydomes

Layered panel or 'plydomes' are intended to make use of semi-rigid materials like thin plywood in simple rectangular panel shapes --as they are usually supplied from manufacturers) to avoid the need for cutting precise polygonal shapes. They are fashioned by drilling holes in precise patterns on the panels that allow them to be connected by bolts or plastic snap-rivets in successive overlapping layers, bending to create the needed curve shape. This concept derives from the yurt-like 'wigwam' shelters once made with woven mats or sheets of bark by native American people, though these relied on additional lashed-together sapling frames. The plydome gets its name from its original use of plywood material, but today the structures are more commonly made with more resilient coroplast or flexible foam-core panel. Though modular and demountable, they are not particularly practical as it is difficult to make them rainproof.

A more recent variation on this frameless dome was devised by Bruce Hauman in 2013 using three three panel shapes with attachment holes in their corners that overlap from bottom to top creating a more fully covered form for a more practical rainproof shelter. Another variation called Intershelter uses foam core plastic panels in large circular overlapping 'scale' shapes.

Bruce Hauman Frameless Dome
Intershelter Dome

6:13 Making Your Own Modular Panels
Since only a few of panel systems we've discussed in this section are readily available to the average person, in this subsection we will explore the DIY creation of various types of panels and their application in simple modular systems and complimentary use with other modular building systems.

- Basic Rigid Panel Materials
    - Cardboard
    - Hardboard
    - Plywood
    - ECOboard
    - Foam Board
    - HDPE
    - Coroplast
    - Acrylic
    - Polycarbonate Greenhouse Panel
    - Sheet Alloys
    - Wood and Foam SIPs
    - Alucabond and Alloy SIPs
- Built-Up Panels
    - Fusuma
    - Shoji
    - Lattice Screens
    - Tension Screens
    - Fabric Covered Panels
    - Cork and Veneer Panels
    - Fitted Plank Panels
    - Utility Panels
    - Living Wall Panels
- Friction-Fit Joints
- Angle Plate Joints
- Hinge Plate Joints
- Tape and Velcro Joints
- Strap Joints

Mechanical Joints

Mechanical panel joints are based on a variety of simple linking or connecting mechanisms more-or-less concealed within the panel edges. Most are used with relatively thick panel materials or hollow-core panels but the simplest may be the captured bolt joint commonly used with light laser-cut assemblies and which is covered in the subsection on laser-cut joinery. () This employs the use of a short bolt captured in-line along the edge of a panel in a T-shaped channel which holds an overlapping perpendicular panel edge using a through-hole and facing nut. Similar connections are used at larger scales and with thicker materials using various kinds of trapped bolts and nuts; self-locking or anchor nuts, threaded inserts, rivet nuts, cross-dowels and barrel nuts, and T-nuts (not to be confused with T-nuts for T-slot framing) that can be concealed within the edges of panels. In composite board (chip board) knock-down furniture cam-lock mechanisms are commonly used. These use a self-locking anchor nut holding a metal dowel or a screw dowel mounted along one face of an overlapping panel which is then held in place along the edge of the opposing panel using a cylindrical cam lock set in a recess. Variations on these connectors, using double-headed dowels and pairs of cam locks, can also hold panels edge-to-edge, using a tongue and groove to align them. There are also right-angle and articulated dowels for angles joints.

Another kind of mechanism, also referred to as a cam-lock, is used for the end-to-end connection of relatively large structural insulated panels using sheet alloy skins. These paired mechanisms, set in-line in slots along edge frames of the panels, use a hex key to engage a metal hook locking the two halves of the connection tightly together. This mechanism is commonly found in use with container shelters, in-plant office building systems, and prefabbed walk-in freezers.

The newest and most sophisticated of mechanical panel joining systems are based on magnetically-driven screws. These new devices were noted in the subsection on invisible joint framing (3:12) for post & beam systems and work in much the same way for fully invisible panel connections, supporting both right angle and edge-to-edge connections as well as the use of locking pins for blind insert panels. Matching holes are made in the edges or facing sides of panels to host threaded inserts for the screws/pins and their receptacles. When placed together the magnetic screw is rotated and extended into the matching receptacle using a magnetic driving unit attached to a conventional power drill or power screwdriver and placed beside the screw position. Once joined, the connections are complete concealed and the assembly is as easily disassembled by switching the magnetic driving unit to reverse rotation. So far this technology has only been applied to modular furniture, owing to limited availability. Only one manufacturer, Lamello Corp., is currently making these devices under the Invis brand.

Free-Standing Screens/Partitions
Puzzle-Fit Screens
Moveable Wall And Retrofit Panel Systems
Modular Panel Shelters

Section 7: Tension, Tensile, and Tensegrity Systems

Though not often thought of as modular building systems, tension cable and rod hardware offers a vast assortment of interchangeable modular components that are readily accessible and can be combined with many other kinds of structures and repurposed in novel ways. Tensile systems based on flexible sheets of material placed under tension, such as the humble tent or the sophisticated architectural tensile roofs, are likewise potentially modular systems offering, with the advent of modern architectural fabrics and membranes, impressive performance and ready demountability and reusability despite their simplicity. Tensile roofs, serving as 'skybreaks' offer a practical solution for sheltering structures based on other building systems that might lack their own means to waterproofing and can be combined as basic units in a variety of ways. Recently, tensile roofs have been combined with new flexible photovoltaic panels and electroluminescent lighting. Though the actual origins of the concept remain controversial, Buckminster Fuller is noted for coining the term 'tensegrity' to denote structures that combined rigid elements under compression--usually in the form of struts--suspended within nets or webs of tension--usually in the form of cables--creating ultra-minimal ultra-light rigid frames or trusses. These have been used as the basis of modular truss systems that have been applied to various architecture and even proposed for structures in space, though few have ever been realized as off-the-shelf kits.

An Overview of Common Cable and Rod Hardware
Tent and Tensile Structures
Yurts
TensegriToy
DIY Tensegrity Toys
Tensegrity Prisms as Simple Support Modules
Tensegrity Domes

Section 8: Free-Form and Hybrid Systems

We generally think of modular building systems as being composed of components that physically connect to each other by virtue of a shared topology and standard interfaces. But the essence of modularity is in the compartmentalized, interchangeable, functionality of components which, in unison, create a system. Though many are composed of just a single circuit board, some computers today are composed of multiple sub-system boards which, with a common interface, plug into a 'motherboard' to communicate and function as a whole system. This compartmentalization of function allows for the easy repair, reconfiguration, and expansion of those subsystems as needed. Computer scientists predict that some future computers will do away with the common motherboard and even a common enclosure and be composed of random collections of 'network appliances' which are each self-contained and have no physical connection to each other but rather a WiFi network link through which they communicate instead, allowing them, regardless of their placement in a space, to function in unison as a complete system, dynamically scalable and changeable.

Similarly, some building systems can be formed of seemingly independent, self-contained, artifacts with no physical similarity or features in common, no physical interface linking them together, and yet function in unison, each assuming a specialized, complementary role within a shared space. Some elements of these systems may themselves be composed one kind of structural system specialized to their role while other parts feature another, very different structural system within the domain of their role. They may have a specialized interface linking them together as whole units even where their individual subcomponents are completely different in topology. We call these ‘freeform’ or ‘hybrid’ modular systems.

Buckminster Fuller didn’t intend for the geodesic dome to be used for housing in quite the fashion it was often used during the brief dome house craze. He saw it as something akin to the pavilion buildings of the past. A self-supporting ‘skybreak’ that sheltered a given living area from rain and wind but left the other functions of a home to other elements within the dome and which it wasn’t physically connected to. And so, inside the dome, another system of modular parts would be used to make mezzanine decks and partition space into rooms, providing privacy and sound and thermal insulation, defining the functions of space. And yet another system would be used to help support gardens within this space. This skybreak home would be a hybrid of several systems, each responsible for a certain domain of function within the overall habitat, like the different kinds of organisms with specialized roles within a colonial organism such as the Portuguese Man O’ War jellyfish.

There are a great many reasons why one would use modular design of this sort. As we mentioned in the section on Structural Insulated Panels (6:9), often one kind of material has some desirable characteristics but lacks those found in others and so by combining those materials one can create a composite material combining those characteristics. But this is not always so straightforward. Sometimes we want to combine the characteristics of different building systems, but they are too different in nature to be easily physically integrated. As developers of dome home kits in the 1970s discovered, the dome shape presents complications when you try to compartmentalize its volume in ways similar to a conventional house. We have a compulsion to divide space into rectangular units and when you do that within a dome space it results in odd shaped corners and walls. Employing conventional furniture was also something of a problem, since most of it is designed with an assumption of being placed along the walls of rectangular rooms. And this is why Fuller thought it better to leave the dome as a largely independent structure, sheltering a large general space but not physically interacting with the other elements of the home interior --indeed, largely ignored like an artificial sky.

One of the biggest challenges for modular structures is weatherproofing, especially if you want to maintain an option for demountability and easy reconfiguration. There are some practical approaches to making a waterproof roof modular, but the topologies needed are not often compatible with other modular component systems. For instance, we can make demountable modular roof panels from long raised seam metal panels or a tensile roof membrane, but, even though we can take them apart as needed, they're limited to a single whole roof element whose length and width we cannot change with the rest of a structure, or which may be expandable in one dimension but not the other. And so it must function independently of those other elements of the structure, which might freely change within the area covered but not extend beyond it. If we have to go beyond its topological constraints, we need a whole new roof element.

Since the elements of a building or home don't always need to be physically connected to compliment one another functionally, creating hybrids of systems can sometimes be a practical solution to combining their best characteristics while also offering a certain novel eclecticism to the environment. The approach is particularly useful where easy adaptability and potential mobility is needed.

QuaDror
Flowforms
MeshTure

A novel design concept by designer Ariyan Davoodian offering an interesting hybrid of space frame and geodesic panel systems. The concept is based on the use of triangular tube frame units with hinged corners and telescoping tubes with a dual-function clamp. This is covered with an elastic fabric sheath that creates the impression of a solid panel. The telescoping tubes and their hinged corners allow the frame to freely change in edge dimensions to make different shaped triangles. While the clamps allow for an edge-to-edge connection (where the edges are the same length) across multiple frame units with any angle on that edge. This allows for a freely changeable triangulated space frame that can be used to make most any triangulated shape or surface akin to what's known in topology as a Triangulated Irregular Network --which often features in computer graphics and geographic surface modeling. The likely applications are sculpture, partitions, wall hangings, stage sets, simple furniture, and lamps, with the stretchable fabric offering translucency and the tubular frames easy clamp attachment of electrical and light elements. But the system can also be used to make tent enclosures, the individual fabric sheaths replaced by larger fabric coverings. However, the clamp connections are not especially strong and are not likely to support significant loads while the cost of the telescoping tubes and clamps probably preclude use beyond where the number of frames is modest and change in shape frequent. At present it is unclear if a manufactured product is planned, but it presents an interesting example of hybrid structures.

https://www.yankodesign.com/2021/01/08/this-modular-furniture-system-with-telescopic-tubing-is-the-quickest-way-to-redesign-your-interior-every-week/

X-Frame [https://xframe.com.au/]

A recent Australian invention which combines aspects of space frame systems and composite panel systems using components made of plywood using CNC fabrication. The system is primarily an alternative for platform framing or 'stick frame' systems which rely on load-bearing walls built with dimensional lumber using nailed construction. CNC fabricated plywood pieces with slot fittings are used to form walls with a triangulated structure linked by facing plate nodes held together by a bolt in a nylon plastic sleeve. Like a typical ball-socket space frame, the assembly can be extended to any area, though limited to a single plane, and is generally used to make wall modules that can then be linked to the face plates perpendicularly to create a wall complex. The system allows for the ready reuse of its wood elements as only the face place bolts hold them all together. Facing wall cladding is attached to the faceplates with screws or use of plug-in pegs. Conventional insulation and utilities can be used, but batting must be cut into small triangles to fit the triangulated voids.

Furnitecture and Mobilism

In the late 1960s designer Ken Isaacs (inventor of the Matrix building system described in section 3:2) devised a concept for reducing the fossil fuel overhead of modern living through seasonal migration. He reasoned that telecommunications has reduced the need to be in any specific location for many kinds of work and that, given this, it made little sense to spend great amounts of energy on staying in the same location and keeping ourselves comfortable during seasonal extremes. If we, instead, migrated to different optimal climate zones for each season our fossil fuel overhead would be much reduced and our homes could be far less physically substantial, like the traditional homes of Polynesia and South-East Asia, and thus less costly to build and more environmentally sustainable. Isaacs dubbed this idea 'mobilism'.

The challenge with this idea, however, was that even if you made homes relatively light, building and maintaining multiple homes in multiple locations would not be practical. Likewise, making a whole home mobile, as we attempt to do with monstrous RVs, has its own problems. And so Isaacs explored the approach of dividing a home between heavy, resilient elements that could be left in place and light, portable, modular, comfort-oriented elements that could be packed up and taken from one location to another with relative ease. And, in addition, there might be a small amount of disposable elements that could be discarded with each move.