DeFT: A Framework for Learning with Multiple Representations

Executive Summary

This document provides a comprehensive analysis of the DeFT (Design, Functions, Tasks) framework, a conceptual model for understanding and designing learning environments that use Multiple External Representations (MERs). While MERs offer unique benefits for learning complex subjects, their effectiveness is highly situational. The DeFT framework

addresses this by moving beyond a focus on representational form (e.g., text vs. picture) to provide a more holistic understanding of multi-representational learning.

The framework proposes that the effectiveness of MERs is determined by the interplay of three core aspects:

1. **Design:** The specific parameters used to build a multi-representational system, including the number of representations, how information is distributed across them, their form, sequence, and the support provided for translating between them.
2. **Functions:** The pedagogical roles MERs serve, which can be to **complement** each other by providing different information or supporting different cognitive processes; to **constrain** the interpretation of one representation with another; or to support the **construction** of deeper understanding through abstraction and extension.
3. **Tasks:** The cognitive tasks a learner must master, which include understanding each individual representation (its form and relation to the domain) and, crucially, understanding the relationship *between* the different representations—a task that numerous studies show is a major source of difficulty for learners.

By systematically considering these dimensions, the DeFT framework serves as a tool to identify factors influencing learning, reconcile inconsistent experimental findings, reveal under-explored areas of research, and guide the development of design heuristics for creating more effective multi-representational learning environments.

The Challenge of Learning with Multiple Representations (MERs)

Research has matured beyond the simplistic notion "that two representations are better than one," recognizing that the critical issue is not *if* MERs are effective but rather identifying "the circumstances that influence the effectiveness of MERs." While theories like the Cognitive Theory of Multimedia Learning and Cognitive Load theory have focused on the sensory channel (auditory/visual) and modality (textual/pictorial) of representations, the DeFT framework presents an alternative, broader approach. It argues that a wider range of factors must be considered to design effective multi-representational systems.

The DeFT framework was developed by reviewing a broad range of research from cognitive science, education, and artificial intelligence, covering domains such as mathematics, physics, and biology. It posits that a combination of dimensions influences whether a learner can benefit from a specific combination of representations.

The DeFT Framework: Design, Functions, and Tasks

The DeFT framework organizes the factors influencing learning with MERs into three primary components: Design parameters, pedagogical Functions, and cognitive Tasks.

1. Design Parameters for Multi-Representational Systems

DeFT identifies five design dimensions that are unique to systems employing more than one representation. These parameters critically influence the learning process and outcome.

Design Parameter	Description
Number	The total quantity of representations available to a learner, which can be two or many more, presented either simultaneously or sequentially.
Information	How information is distributed across representations. This ranges from no redundancy (each representation conveys unique content) to partial redundancy (some information is constant) to full redundancy (all representations express the same information, differing only in computational properties).
Form	The characteristics of the representations used (e.g., text, pictures, graphs, animations, equations). This includes aspects like dimensionality, dynamism, and abstraction. DeFT emphasizes that representations interact in a "representational chemistry," creating a vast design space.
Sequence	If representations are not presented simultaneously, this parameter addresses the order in which they are presented or constructed, and the point at which a learner or system adds or switches between them.
Translation	The support provided by the environment to help learners understand the relationship between representations. Support can vary in how active it is (e.g., dyna-linking) and whether it is provided at a syntactic (surface) or semantic (deep) level.

2. The Functions of Multiple Representations

Ainsworth (1999) proposed a taxonomy of the pedagogical functions that MERs can serve in a learning context, which are categorized into three main types: complementing, constraining, and constructing understanding.

Complementary Functions

MERs serve complementary functions when they differ in the information they contain or the cognitive processes they support, allowing learners to benefit from the distinct advantages of each.

- **Complementary Processes:** Representations containing the same information can differ in their computational properties, supporting different learning needs.
    - **Individual Differences:** Presenting a choice of representations may allow learners to select one that suits their preferred learning style, though evidence for this is limited and often confounded by expertise. For example, some studies show high-performing students benefit more from graphical instruction while lower-performing students do better with text.
    - **Task Suitability:** Performance is enhanced when the representation's form matches the information structure required by the task. Learners with access to MERs can choose the best representation for their current goal.
    - **Strategy Encouragement:** Different representations can encourage different problem-solving strategies. The use of MERs can prompt learners to try multiple strategies, compensating for the weaknesses of any single approach.
- **Complementary Information:** MERs are used to provide different pieces of information, which is useful when a single representation would become overly complex or if the information exists on radically different scales.

Constraining Functions

A key function of MERs is to use one representation to constrain or clarify the interpretation of another, less familiar or more ambiguous representation.

- **Constraining by Familiarity:** A familiar representation (e.g., a concrete animation) can be used to help a learner understand a more complex or abstract one (e.g., a graph).
- **Constraining by Inherent Properties:** Representations differ in their specificity. Textual representations can easily express ambiguity (e.g., "the cat is by the dog"), whereas graphical representations are inherently more specific (the cat must be on the left or right). Presenting them together uses the specific representation to constrain the ambiguous one.

Constructing Deeper Understanding

MERs can support the construction of deeper understanding by encouraging learners to integrate information from multiple sources to achieve insights that would be difficult with a single representation alone.

- **Abstraction:** Learners can identify the underlying structure of a domain by constructing references across different representations. This process helps them create more abstract mental concepts.
- **Extension:** This involves extending knowledge from a familiar representation to an unfamiliar one without fundamentally reorganizing that knowledge (e.g., applying knowledge of velocity-time graphs to understand acceleration-time graphs).
- **Relation:** This refers to the process of associating two representations. This can be a learning goal in itself (e.g., learning to construct a graph from an equation) or a stepping stone to abstraction.

3. The Cognitive Tasks for the Learner

The benefits of MERs are not automatic; they require learners to engage in complex cognitive tasks.

Tasks for Learning with a Single Representation

Even before integrating multiple representations, a learner must master several tasks for each one:
1. **Understand the Form:** Learners must learn the format (e.g., axes, labels) and operators (e.g., how to find a gradient) of a representation. This is a complex skill, and novices often make errors, such as interpreting graphs iconically (e.g., believing a "hill shaped" velocity-time graph represents a cyclist going over a hill).
2. **Understand the Relation to the Domain:** Learners must understand how the representation maps to the domain it represents, which is difficult when domain knowledge is incomplete.
3. **Select an Appropriate Representation:** When given a choice, learners must select the representation best suited to the task, a skill that is characteristic of expertise.
4. **Construct an Appropriate Representation:** Creating representations can lead to better understanding, but learners may make errors in both construction and interpretation.

The Core Task for MERs: Relating Representations

Many benefits of MERs depend on the learner's ability to integrate and coordinate information from multiple sources. However, a "very large number of studies have observed that learners find translating between representations difficult." Learners often fail to notice connections or discrepancies and may treat representations in isolation. In some cases, a combination of representations can even inhibit learning if the cognitive demand of relating them is too high.

Factors Influencing the Difficulty of Relating Representations:

• **Representation Characteristics:** The difficulty of translation increases as the differences between representations grow. Key dimensions include:
  ◦ **Sensory Channel:** Auditory vs. visual.
  ◦ **Modality:** Textual vs. graphical.
  ◦ **Level of Abstraction:** Symbolic, iconic (abstract or concrete), or enactive.
  ◦ **Specificity:** The degree to which a representation can express ambiguity.
  ◦ **Type:** Different taxonomies classify types such as graphs, tables, diagrams, and maps.
  ◦ **Presentation:** Physically integrated material is easier to process than separately presented material.
  ◦ **Dynamism:** Static vs. dynamic representations (e.g., animations) require different interpretive skills.
  ◦ **Dimensionality:** Integrating 2D and 3D representations can be challenging.
• **Individual Characteristics:** Learner attributes play a significant role.
  ◦ **Familiarity (Domain & Representation):** Novices focus on surface features and lack the deep structural knowledge needed to see connections between dissimilar representations.
  ◦ **Age:** Developmental factors, such as information-processing capacity, may limit younger children's ability to relate multiple representations.
  ◦ **Individual Differences:** Some individuals may have a greater aptitude for translating across representations.

Applying DeFT to Design Decisions and Heuristics

The DeFT framework can be used to analyze design decisions and formulate heuristics for creating more effective MER learning environments. The optimal design depends heavily on the intended pedagogical function of the representations.

Design Heuristics Based on Pedagogical Function

Intended Function	Design Implications & Heuristics
Complementary Functions	**Goal:** Allow learners to utilize the strengths of individual representations. Relating representations is not essential. **Heuristics:** Learners need to understand each representation in isolation and how to select the appropriate one. Support for translation (e.g., dyna-linking) can be provided to reduce cognitive load, as learners may not need to build this skill. Minimizing co-presence may be beneficial, as learners often attempt to translate between co-present representations even when it is not necessary.
Constraining Interpretation	**Goal:** Use a familiar/specific representation to clarify an unfamiliar/ambiguous one. Relating representations is essential. **Heuristics:** The constraining representation must be easy for the learner to understand (e.g., concrete, simple format). The representations should be co-present to facilitate mapping. Design should maximize perceived similarity (e.g., consistent labels, colors) and dyna-linking could be used to signal the mapping without making the task overly complex.

Constructing Deeper Understanding	**Goal:** Encourage learners to actively integrate information to form abstractions. This presents the most complex design challenge. **Heuristics:** A balance must be struck: if translation is too difficult, abstraction fails; if it is too easy (e.g., representations are too similar, or the system automates the process), learners may not actively construct the knowledge. - Requiring learners to actively integrate representations (e.g., dragging symbols onto pictures) may be more effective than passive integration. Increased information redundancy between representations might help learners reconcile formats that differ. - Representations should be co-present to maximize opportunities for building cognitive links.

Conclusion

The DeFT framework provides a structured and comprehensive approach for analyzing learning with multiple representations. It highlights the complex interplay between the **design** of multi-representational systems, the pedagogical **functions** they serve, and the cognitive **tasks** they impose on learners. By clarifying these aspects, DeFT offers a valuable tool for researchers and designers to explain inconsistent findings, identify under-investigated topics (such as the impact of information distribution), and move toward the development of robust principles for creating educational materials that successfully leverage the power of more than one representation.

Examples Below are examples of multiple representations aligned with Ainsworth's DeFT framework (Design, Functions, Tasks) thEY embody the ideas in her ideas. Each example shows how representations can *complement*, *constrain*, and *construct* understanding in school science.

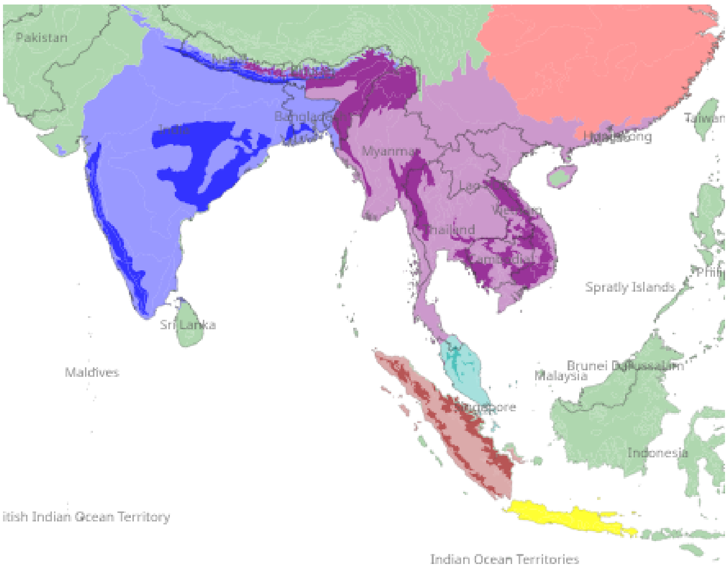
Multiple Representations in Biology – DeFT Framework

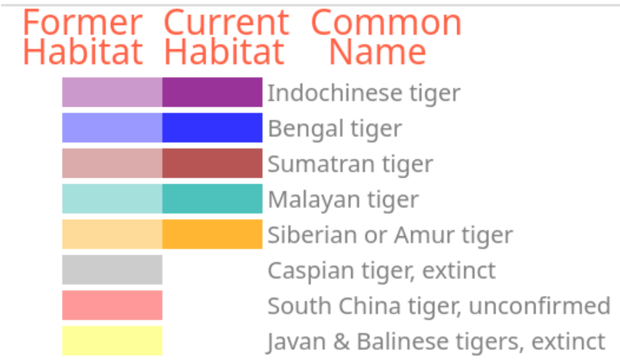
Introduction example for concrete preparation

<table>
<tr><td></td><td colspan="4">Evolution</td></tr>
<tr><td>Question</td><td colspan="4">“Why did dark moths become more common in polluted environments?”</td></tr>
<tr><td colspan="2">Macroscopic</td><td>Particulate / Molecular / Structural</td><td>Symbolic / Quantitative</td><td>Graphical / Dynamic</td></tr>
<tr><td colspan="2">Photographs of moths on trees</td><td>Model diagram: variation → differential survival → reproduction → inheritance</td><td>Frequency tables or population data</td><td>Population graph of light vs dark moths over generations; animation of predation</td></tr>
<tr><td colspan="5">DeFT Functions</td></tr>
<tr><td colspan="5">Complement: photos show context, graph shows trend, model shows mechanism
Constrain: diagram prevents teleological thinking
Construct: students form population-level reasoning</td></tr>
</table>

Novel example for Prediction and Explanation then be given data

Bengal tiger (*Panthera tigris tigris*) shown in blue https://databayou.com/tiger/habitat.html





- Mean *greatest skull length* for adult males from India: 351 ± 2.5 mm (n = 37).
- Mean *greatest skull length* for adult females from India: 293 ± 2.4 mm (n = 23).
- *Cranial volume* (proxy for brain size) for males: 307 ± 4.4 cm^3 (n = 32).
- *Cranial volume* for females: 264 ± 5.0 cm^3 (n = 18).

(All means with standard errors.)

→ These figures come from a comparative dataset of tiger skull measurements, including cranial volumes, based on museum specimens and documented morphometric studies. (ScienceDirect)

Primary Data Sources

Yamaguchi, N. et al. (2009) *What is a tiger?* — Table of *greatest skull length* and *cranial volume* for tiger subspecies including Indian (Bengal) tigers. (Data reproduced in online morphometric summaries.) (ScienceDirect)

Mazák, J.H. (2010) *Craniometric variation in the tiger (Panthera tigris): Implications for patterns of diversity, taxonomy and conservation. Mammalian Biology*, 75:45–68. (Morphometric review of continental tiger skull variation including Siberian tiger morphology.) (faculty.chas.uni.edu)

Map of Indonesia and Malaysia

Look at table 3, the two maps and the information about Bengal Tigers
“Predict What the skull length and cranial volume of Balinese tigers will be and explain why?”

Table 3. Greatest length of skull, cranial volume and Schauenberg's index (Schauenberg, 1969: greatest length/cranial volume) of adult tigers from the Malay Peninsula and Sunda Islands			
Balinese tigers (extinct)		**Greatest length of skull (mm)**	**Cranial volume (cm3)**
Panthera tigris balica	Male (2)		
	Female (5)		
Javan tigers (extinct)			
Panthera tigris sondaica	Male (23)	326.3 ± 2.14	300.2 ± 3.78
	Female (15)	282.7 ± 1.87	285.0 ± 2.67
Sumatran tigers			
Panthera tigris sumatrae	Male (16)	314.8 ± 2.76	281.9 ± 3.55
	Female (22)	272.4 ± 2.00	256.7 ± 3.24
Malayan tigers			
Panthera tigris jacksoni	Male (4)	337.8 ± 11.16	286.0 ± 20.99
	Female (2)	289.8 ± 10.38	267.5 ± 8.50
Mean ± standard error, and sample size (N) are shown and animals are further classified as males and females.			
Yamaguchi, Nobuyuki, et al. "Brain size of the lion (Panthera leo) and the tiger (P. tigris): implications for intrageneric phylogeny, intraspecific differences and the effects of captivity." *Biological Journal of the Linnean Society* 98.1 (2009): 85-93.			

Table 3. Greatest length of skull, cranial volume and Schauenberg's index (Schauenberg, 1969: greatest length/cranial volume) of adult tigers from the Malay Peninsula and Sunda Islands			
Balinese tigers		**Greatest length of skull (mm)**	**Cranial volume (cm3)**
Panthera tigris balica	Male (2)	296.0 ± 1.53	296.0 ± 6.00
	Female (5)	261.2 ± 2.39	263.4 ± 6.58
Javan tigers			
Panthera tigris sondaica	Male (23)	326.3 ± 2.14	300.2 ± 3.78
	Female (15)	282.7 ± 1.87	285.0 ± 2.67
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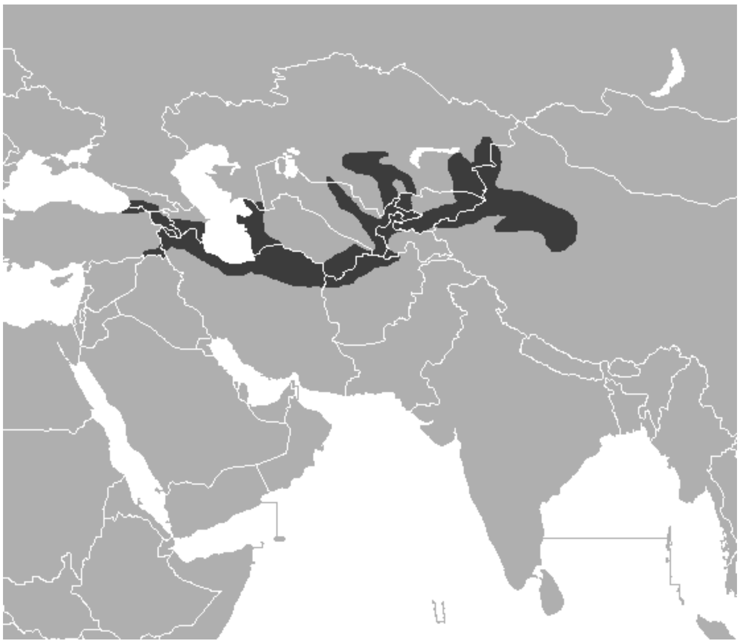
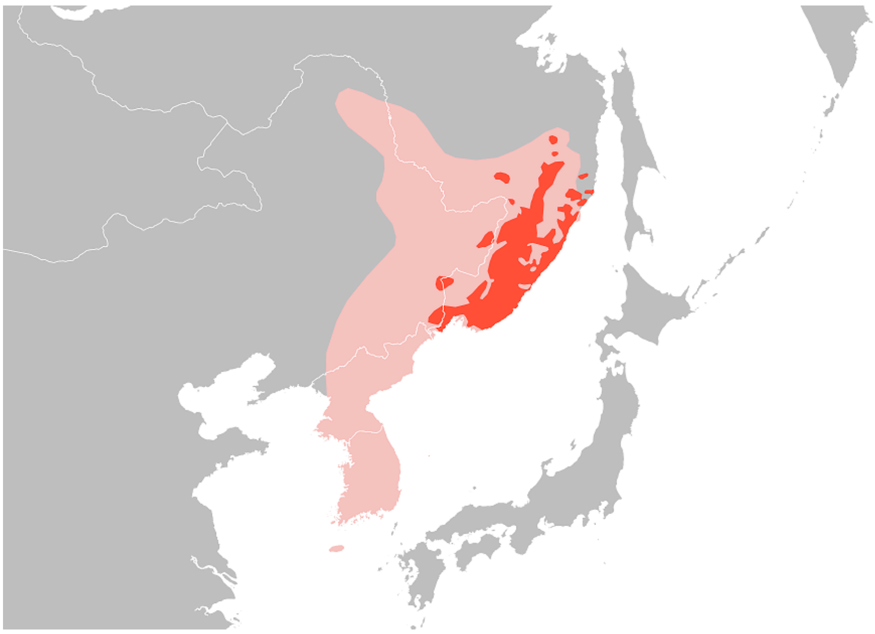
Male Caspian tigers had a Maximum skull length in males was 297–365.8 mm , while that of females was 195.7–255.5 mm.



Heptner, V. G. & Sludskij, A. A. (1992) [1972]. "Tiger". *Mlekopitajuščie Sovetskogo Soiuza. Moskva: Vysšaia Škola* [*Mammals of the Soviet Union. Volume II, Part 2. Carnivora (Hyaenas and Cats)*]. Washington DC: Smithsonian Institution and the National Science Foundation. pp. 95–202.

Siberian Tiger The size variation in skulls of Siberian male tigers ranges from 331 to 383 mm in nine individuals measured.



Topic 2.	Homeostasis and Feedback (Blood Glucose)		
Question	How does the body keep glucose levels stable?”		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Blood glucose readings	Negative feedback loop diagram; cell signaling animation	Equation-like flow model: Stimulus → Sensor → Control → Effector → Response	Time-series graph of glucose levels; dynamic animation
DeFT Functions			
Complement: graph shows dynamics, loop shows logic, animation shows mechanism **Constrain:**prevents linear cause-only reasoning **Construct:** students build systems model of regulation			

Topic 3.	Gene Expression & Protein Synthesis		
Question	“How does DNA produce functional protein?”		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Flow chart DNA → mRNA → protein	3D molecular models of ribosome/tRNA; animation of transcription/translation	Codon table	Concept map linking gene, transcript, amino acid, trait
DeFT Functions			
Complement: structural, symbolic, dynamic views **Constrain:** prevents oversimplified DNA-to-trait misconception **Construct:** students integrate information across scales			

Topic 4.	**Ecosystem Energy Flow**		
Question	"Why are food chains short?"		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Observation of energy transfer in ecosystems	Energy pyramid; particle-level diagrams of energy flow	Equation: E_{n+1} = 0.1 E_n	Sankey diagram; bar chart of trophic-level energy; simulation of population collapse
DeFT Functions			
Complement: quantitative and visual energy loss **Constrain:**pyramid prevents recycling misconception **Construct:** students reason about conservation and dissipation			

Topic 5.	**Metacognitive Reflection on Evidence**		
Question	"Which enzyme model is better supported?"		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Experimental results and observations	Lock-and-key vs induced-fit diagrams; molecular animation	Reaction rate data tables	Claim–Evidence–Reasoning–Limitations scaffold
DeFT Functions			
Complement: structural, kinetic, evidential views **Constrain:**Constrain: data prevents purely pictorial **Construct:** students evaluate and critique models			

Topic 6.	**Photosynthesis & Carbon Flow**

Question	“How is carbon converted into biomass?”		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Leaf color change; oxygen evolution in experiments	Chloroplast diagram; molecular pathway animation	Balanced photosynthesis equation	Carbon flux diagram; dynamic animation of carbon cycle
DeFT Functions			
Complement: observable, molecular, symbolic, dynamic views **Constrain:**prevents ignoring subcellular mechanism **Construct:** students link molecular processes to ecosystem-level outcomes			

Topic 7.	Diffusion & Osmosis		
Question	“How do molecules move across membranes?”		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Movement of dye in water; plant turgor changes	Cell membrane diagram with solute molecules	Concentration gradient equations	Graph of solute movement over time; animation of particle motion https://www.pbslearningmedia.org/resource/arct15-sci-osmosis/osmosis/

DeFT Functions
Complement: macroscopic change, molecular motion, quantitative trend **Constrain:** prevents ignoring gradient-driven movement **Construct:** students build understanding of passive transport mechanisms

Topic 8.	**Evolutionary Trees & Phylogeny**		
Question	"How are species related?"		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Fossil observations; morphological traits	Cladogram diagram showing species divergence	Molecular sequence comparison metrics	Phylogenetic tree graph; dynamic tree-building animation
DeFT Functions			
Complement: morphological, molecular, symbolic, dynamic view **Constrain:** prevents assuming linear progressions **Construct:** students reason about relatedness and common ancestry			

Multiple Representations in Physics – DeFT Framework

Topic 1.	**Question-Driven Motion (Constant Acceleration)**			
Question	"How can we tell whether an object is speeding up at a constant rate?"			
Physical / Macroscopic	**Graphical / Dynamic**	**Mathematical / Symbolic**	**Verbal / Written**	**Diagrammatic / Model**
Cart on track with motion sensor	Velocity–time and position–time graphs	$v = u + at$; $x = ut + 1/2\ at^2$	Student explanation of "constant acceleration"	Motion diagram with equal time intervals
DeFT Functions				

Complement: each shows trends, relationships, mechanisms **Constrain:** motion diagram prevents misreading quadratic graph **Construct:** slope of v–t graph links to concept of acceleration

<table>
<tr><td>Topic 2.</td><td colspan="4">Energy Model Critique (Pendulum)</td></tr>
<tr><td>Question</td><td colspan="4">“Where does energy go at different points in the swing?”</td></tr>
<tr><td>Physical / Macroscopic</td><td>Graphical / Dynamic</td><td>Mathematical / Symbolic</td><td>Verbal / Written</td><td>Diagrammatic / Model</td></tr>
<tr><td>Observed pendulum motion</td><td>PhET simulation with energy pie charts</td><td>$Ek = 1/2\ mv^2$; $Ep = mgh$</td><td>Claim–evidence –reasoning written explanation</td><td>Free-body diagram of forces</td></tr>
<tr><td colspan="5">DeFT Functions</td></tr>
<tr><td colspan="5">Complement: bars show conservation, equations quantify, FBD shows cause
Constrain: simulation prevents misconception of max speed at top
Construct: integrates abstract</td></tr>
</table>

Topic 3.	Force and Motion Argumentation (Newton's Second Law)			
Question	"What determines how quickly velocity changes?"			
Physical / Macroscopic	**Graphical / Dynamic**	**Mathematical / Symbolic**	**Verbal / Written**	**Diagrammatic / Model**
Trolley experiments measuring acceleration	Scatter plot a vs F	F = ma	Written justification	Causal diagram: Force → Acceleration → Velocity change
DeFT Functions				
Complement: data shows pattern, equation generalizes, diagram shows mechanism **Constrain:** graph slope enforces proportionality **Construct:** builds concept of proportionality and causal modeling				

Topic 4.	Model-Building in Waves			
Question	"What is actually moving in a wave?"			
Physical / Macroscopic	**Graphical / Dynamic**	**Mathematical / Symbolic**	**Verbal / Written**	**Diagrammatic / Model**
Slinky demonstration	Displacement–position graph; animation of waveform	N/A	Verbal analogy: stadium wave	Particle model sketch of oscillating elements
DeFT Functions				
Complement: physical shows reality, graph shows structure, animation shows dynamics **Constrain:** particle model prevents misconception that matter travels **Construct:** coherent model of wave propagation				

Topic 5.	**Scaffolding Problem Solving (Electric Circuits)**			
Question	"How does current distribute in a series circuit?"			
Physical / Macroscopic	**Graphical / Dynamic**	**Mathematical / Symbolic**	**Verbal / Written**	**Diagrammatic / Model**
Physical circuit setup	N/A	V = IR	Concept map of current, resistance, voltage	Circuit diagram; flow analogy; potential difference bar model
DeFT Functions				
Complement: highlights variables **Constrain**: bar model prevents current-consumption errors **Construct:** integrated schema of circuit behavior				

Topic 6.	**Thermal Expansion**			
Question	"How does heating affect the length of solids?"			
Physical / Macroscopic	**Graphical / Dynamic**	**Mathematical / Symbolic**	**Verbal / Written**	**Diagrammatic / Model**
Metal rod on track with markers	Graph of length vs temperature	$\Delta L = \alpha L_0 \Delta T$	Student explanation	Particle diagram showing vibrating atoms
DeFT Functions				
Complement: observable change, graph shows trend, diagram shows particle behavior **Constrain:** prevents misconception that atoms grow in size **Construct:** links microscopic motion to macroscopic expansion				

Topic 7.	Projectile Motion			
Question	"How do horizontal and vertical motions combine?"			
Physical / Macroscopic	**Graphical / Dynamic**	**Mathematical / Symbolic**	**Verbal / Written**	**Diagrammatic / Model**
Ball launched; motion tracked	x–t and y–t graphs; trajectory plot	$x = v_0x\ t$; $y = v_0y\ t - 1/2\ gt^2$	Explanation of path	Vector diagram of velocity components
DeFT Functions				
Complement: physical trajectory, graphs, equations **Constrain:** vector diagram prevents treating motion as 1D **Construct:** students integrate horizontal and vertical motions into 2D model				

Topic 8.	Conservation of Momentum			
Question	"How do colliding objects share momentum?"			
Physical / Macroscopic	**Graphical / Dynamic**	**Mathematical / Symbolic**	**Verbal / Written**	**Diagrammatic / Model**
Collision of carts with force sensors	Graph of momentum vs time	$p = mv$	Explanation and prediction	Free-body diagram showing forces and momentum vectors
DeFT Functions				
Complement: observable, graph, equation, diagram **Constrain:** FBD prevents ignoring internal forces **Construct:** links theory to experimental observation and conservation principle				

Multiple Representations in Chemistry – DeFT Framework

Topic 1.	**Reaction Stoichiometry**		
Question	"How do reactant amounts determine product yield?"		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Observing combustion of methane (flame, gas production)	Molecules of $CH_4 + O_2 \rightarrow CO_2 + H_2O$ diagram	Balanced equation $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	Table or bar chart of moles/mass
DeFT Functions			
Complement: shows observable, particle, and quantitative views **Constrain:** particle diagram prevents ignoring mole ratios **Construct:** links observation, molecular model, and stoichiometry			

Topic 2.	**Energy Changes**		
Question	"Why are some reactions exothermic or endothermic?"		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Thermometer readings, heat felt	Bond-breaking/forming particle diagrams	ΔH in chemical equation	Reaction coordinate diagram
DeFT Functions			
Complement: macroscopic temperature, particle mechanism, symbolic ΔH **Constrain:** particle + graph prevent misconceptions **Construct:** integrate energy concept at multiple levels			

<table>
<tr><td>Topic 3.</td><td colspan="4">Gas Laws</td></tr>
<tr><td>Question</td><td colspan="4">“How does temperature affect gas pressure?</td></tr>
<tr><th colspan="2">Macroscopic</th><th>Particulate / Molecular / Structural</th><th>Symbolic / Quantitative</th><th>Graphical / Dynamic</th></tr>
<tr><td colspan="2">Syringe or sensor measuring pressure</td><td>Animated moving particles</td><td>PV = nRT</td><td>P–V or P–T graph</td></tr>
<tr><td colspan="5">DeFT Functions</td></tr>
<tr><td colspan="5">Complement: shows observation, particle dynamics, and math
Constrain: prevents thinking gas shrinks
Construct: link micro and macro explanations</td></tr>
</table>

<table>
<tr><td>Topic 4.</td><td colspan="4">Equilibrium</td></tr>
<tr><td>Question</td><td colspan="4">“How does stress affect reversible reactions?”</td></tr>
<tr><th colspan="2">Macroscopic</th><th>Particulate / Molecular / Structural</th><th>Symbolic / Quantitative</th><th>Graphical / Dynamic</th></tr>
<tr><td colspan="2">Color change in cobalt chloride equilibrium</td><td>Particle diagram showing ratio changes</td><td>Kc = [products]/[reactants]</td><td>Concentration vs time plot</td></tr>
<tr><td colspan="5">DeFT Functions</td></tr>
<tr><td colspan="5">Complement: macroscopic, particle, symbolic, and trend views
Constrain: prevents assumption reaction goes to completion
Construct: coordinated reasoning on equilibrium shifts</td></tr>
</table>

Topic 5.	**Acid–Base Titration**		
Question	“How to find unknown concentration?”		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Color change with indicator	Proton transfer diagram	Stoichiometric equation, calculation of molarity	pH vs volume curve
DeFT Functions			
Complement: observable, particle, symbolic, and graph **Constrain:** prevents ignoring mechanism **Construct:** quantitative and conceptual understanding			

Topic 6.	**Rate of Reaction**		
Question	“What factors affect reaction speed?”		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Time for precipitate formation or gas evolution	Particle collision diagram	Rate law rate = $k[A]^{m[B]}n$	Rate vs concentration graph
DeFT Functions			
Complement: observable rate, molecular mechanism, symbolic law **Constrain:** prevents misconception that all collisions react **Construct:** link collision theory to measured rates			

Topic 7.	**Electrochemistry**		
Question	"How is chemical energy converted to electrical energy?"		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Voltage reading of galvanic cell	Electron transfer between electrodes diagram	Half-equations, overall cell reaction	Voltage vs time graph
DeFT Functions			
Complement: observable voltage, particle transfer, symbolic reaction **Constrain:** prevents ignoring electron flow **Construct:** link micro, macro, and symbolic understanding			

Topic 8.	**Solubility & Saturation**		
Question	"Why does a solution stop dissolving solute?"		
Macroscopic	**Particulate / Molecular / Structural**	**Symbolic / Quantitative**	**Graphical / Dynamic**
Observation of crystals forming	Particles of solute and solvent in equilibrium	Ksp expression	Solubility curve vs temperature
DeFT Functions			
Complement: observable, particle, quantitative, graphical **Constrain:** prevents ignoring dynamic equilibrium **Construct:** connect macroscopic observation to particle-level reasoning and calculations			