Remodeling Science Education

SCIENCE is the name —
MODELING is the game!

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The global STEM education crisis

Rapid emergence of *a global economy driven by science and technology* has precipitated a crisis in the education systems of all nations.

⇒ Radical education reform is needed to produce

- ***science literate citizens*** and consumers
- ***workplace readiness***
  (the technical foundation for an effective workforce)
- a ***technology pipeline***
  (educating scientists and engineers
  to sustain economic growth)

⇒ Comprehensive reform is needed in all aspects of
(**S**cience, **T**echnology, **E**ngineering, **M**athematics)
STEM education — the new code word for the crisis!

Reform! Reform?
Aren’t things bad enough already?
— Duke of Wellington

Ultimately, all reform is local! — in the classroom for STEM education!

Therefore, *the teacher should be the focus for reform!*

Before It's Too Late: A Report to the Nation from

The National Commission on Mathematics and Science Teaching for the 21st Century

(Glenn Commission, 2000)

"We are of one mind in our belief that *the way to interest children in mathematics and science is* *__through teachers__* who are not only enthusiastic about their subjects, but who are also steeped in their disciplines and who have the professional training—as teachers—to teach those subjects well. *Nor is this teacher training simply a matter of preparation; it depends just as much—or even more—*
***—on sustained, high-quality professional development*.**"

What is needed to make this happen???

Agenda for K-12 STEM education reform

Essential elements of reform

(1) *Standards of science and math literacy* for all students.
(2) *Integrated K-12 STEM curriculum for the 21st century*

(3) *Pedagogy* promoting *scientific inquiry* and *analytic skills*
(4) Sustained *professional development* for teachers

(5) *Technology infusion*

Essential partners in reform

***(6)** Dedicated STEM teacher *communities of practice*
***(7)** *Institutional support from local universities*
(8) *Buy-in by schools and school districts*

Reform must be systemic!!
All eight components are needed for optimal reform.
Physics plays a central role in all.

To set **baseline goals for STEM curriculum design and assessment**, developers are well advised to follow the internationally recognized

Program for International Student Assessment (PISA) <www.pisa.oecd.org>

PISA assessment is directed at students of **age 15**, because

- *that is near the end of compulsory schooling* in most OECD states <www.oecd.org>
- *attitudes toward science and technology are fixed* in most students by that age

PISA math-science assessment items are situated in real world contexts, with emphasis on modeling as a means of framing both science and mathematics thinking and learning.

PISA Framework *for Scientific, Reading and Mathematical Literacy* (2006)

Addresses: What is it important for citizens to know, value, and be able to do in situations involving science and technology?

Results: Baseline data for evaluating STEM education in any country.

Integration of the STEM curriculum

Unifying Themes recognized by
National Science Education Standards (NRC 1996)
National Council of Teachers of Mathematics (NCTM 2000)

- **quantitative methods**
- **models and modeling**
- **structure of matter and energy**

Note that instruction in energy without matter does not make sense.
There is no such thing as disembodied energy.
The energy concept is more subtle and difficult to teach
than generally realized.

To prepare students for the challenges of the rapidly emerging knowledge–based society, the high school STEM curriculum must be radically restructured (Lederman: ARISE)

Physics first: One year in grade 8 or 9
coordinated with algebra/calculus ***for all students!***

- followed by one year of ***chemistry*** (grade 10)
- ***molecular biology*** and/or nanotechnology (grade 11)
- electives in science and engineering (grade 12)

A sequence of models for the structure of matter:

- *Atoms modeled by analogy with models for macroscopic objects*
- *Particle models and elastic collisions (gases)*
- *Atomic binding from short range repulsion and long range attraction explains phase changes, elasticity and elastic waves*
- *Electric charge and current*: electrons and atomic nuclei,
- *Atomic/molecular forces and structure*
- *Quantized states* revealed by atomic spectra.

Remodeling Chemistry:

- *Proportional reasoning* relating macro to micro properties of matter
- *Models that explain structure of the periodic table and mechanisms for chemical change*

The pivotal point in the STEM curriculum: middle school physical science

Quantitative methods *require mathematical models* to interpret data!

Basic Mathematical Models:

1. Constant rate (linear change): graphs and equations for straight lines
(proportional reasoning, constant velocity, acceleration, force, momentum, energy, etc.)

2. Constant change in rate (quadratic change) graphs and equations for parabolas
(constant acceleration, kinetic and elastic potential energy, etc.)

3. Rate proportional to amount: doubling time,
graphs and equations of exponential growth and decay
(monetary interest, population growth, radioactive decay, etc.)

4. Change in rate proportional to amount: graphs and equations of
trigonometric functions (waves and vibrations, harmonic oscillators, etc.)

5. Sudden change: stepwise graphs and inflection points (Impulsive force, etc.)

Ubiquitous: rich & unlimited applications to science and modern life!

Skill in using these models in a variety of situations

- an essential component of math and science literacy.
- should be *cultivated* deliberately, systematically & repeatedly

Physics must be central to the STEM curriculum because

- It is essential to interpreting our most basic *perceptions of matter, motion and light*
- That is why it was *the first science* to develop historically
- It provides the foundation for *quantitative methods* & an exemplar of *scientific method*

- Integration of mathematics with physics should be strongly emphasized in the middle grades 7 through 9, and implicit throughout the curriculum

- **Quantitative reasoning** with number and unit goes hand-in-hand with *modeling and measurement*, which couples mathematics to science

- The ideal STEM curriculum begins in middle school (or earlier) with emphasis on *proportional reasoning* as a first step in developing the concepts of *function* and *graphs* in *modeling motion* and money transactions

- The divorce of mathematics from physics is one of the most serious deficiencies in current educational systems!

Concurring opinion of a distinguished mathematician:

V. I. Arnold On Teaching Mathematics (Paris, 1997)

“Mathematics is a part of physics.

Physics is an experimental science, a part of natural science.

Mathematics is the part of physics where experiments are cheap.”

“In the middle of the 20th century it was attempted to divide physics and mathematics.

The consequences turned out to be catastrophic.

Whole generations of mathematicians grew up without knowing half of their science and, of course in total ignorance of other sciences.”

Current state: Physics is no longer a required minor for math students!!

Moral: mathematics is too important to be left to the mathematicians!

Pedagogy: The most robust finding of physics education research:

You cannot separate pedagogy from content!!
(as still advocated in schools of education)

Modeling Instruction is a *research-based science pedagogy* founded on the premise that skill in making and using models is the *procedural core* of scientific knowledge, while the *content core* can be reduced to a small number of models organized into theories.

- This pedagogy is *applicable to mathematics* as well as science instruction. Thus, the **concept of function** is central to school mathematics.

  A major source of students' difficulties in applying functions is *an undeveloped concept of variable*. In particular, *students often treat variables as symbols to be manipulated, rather than as quantities to be related.*

- In modeling instruction, abstract mathematical concepts such as *variable*, *function* and *rate* can be explored within the context of mathematical models with concrete applications in physics and deployed to other subjects (i.e. chemistry, biology, economics).

Elements of Modeling Instruction

Impediments to learning physics:

(a) Misconceptions about common physical phenomena.
(b) Misconceptions about scientific method.
(c) A view of science as a fragmented collection of facts, rules and formulas.

Instructional objectives include:

(a) a clear *concept of "physical model,"* including both qualitative and quantitative aspects,
(b) familiarity with a *basic set of models* as the core of introductory physics,
(c) skills in the *techniques of modeling*, especially interplay between diagrammatic and symbolic representations,
(d) experience in the *deployment of models* to understand the physical world--*to interpret and analyze data, to explain, to predict and to plan*.

Modeling Instruction promotes Scientific Inquiry

☆ Instructional design:

The instructional **modeling cycle**

engages students in all aspects of **scientific inquiry**:

- *Empirical*: Design and conduct experiments to investigate *structure* in physical systems and processes.
- *Theoretical*: Construct, analyze and apply *scientific models* and *theories*.
- *Technical*: Use scientific instruments and modeling tools to sharpen scientific investigation and inference.
- *Social*: Scientific discourse and argumentation to negotiate mutual understanding of models and implications of experimental results.

☆ Teachers guide student inquiry by

- organizing activities and discourse around scientific models
- informed by research on student conceptual learning

The *Modeling Instruction Program*:

- Originated at ASU with NSF support (1989-2005)
- Created and conducted a comprehensive program of summer *Modeling Workshops* in physics, chemistry & physical science
- Attended by nearly 3,000 teachers nationwide

The *Modeling Community* has thereby been generated:

- A *community of practice* composed of teachers with *Modeling Instruction as a common vision of science teaching*
- Now sustained by an organization of the teachers themselves: the *American Modeling Teachers Association* (AMTA)
- Cultivating teachers as leaders of STEM education reform

Modeling Instruction integrates curriculum and pedagogy:

- *Curriculum* is organized around a small number of conceptual models as the *content core* of each scientific domain.
- *Pedagogy* promotes scientific inquiry centered on making and using models as the *procedural core* of scientific knowledge
- Applicable to *all STEM disciplines*

Engines for STEM education reform

K-12 schools and school systems lack the resources required for *rapid, deep and sustained* STEM education change

Here is a validated plan to develop those resources at a university:

Stage I: Offer intensive 3-week **workshops** for in-service teachers

- on reformed pedagogy and curriculum for STEM courses
- Can be imported from the ASU Modeling program
- Cultivate a cadré of master teachers to lead reform

Stage II: Offer a **graduate program** for inservice teachers that

- provides ***sustained, high-quality professional development***
- leading to a graduate (masters) degree
- Can be modeled on the ASU MNS program
  <http://modeling.asu.edu/MNS/MNS.html>

Stage III: Create a university-based **Institute for STEM education reform** that

- assists local schools in implementing reform
- organizes and supports STEM teachers in a community of practice
- maintains R&D for continually improving the program

Upshot: Strategies to improve STEM Education

Outmoded: Increase teacher accountability and incentives!!

- Testing to separate good from bad teaching
- Fire the teachers who under-perform
- Raise pay for the best teachers
- Increase student time in school
- Competition among schools, public and private

Enlightened: Improve teacher competence, opportunities and collaboration!!

- Opportunities for lifelong professional development
- Access to the best pedagogy and curricula
- Enlarge the community of scientists to include STEM teachers
- Establish a community of peers to
  - — mentor new teachers
  - — collaborate on improving teaching practice
  - — maintain teaching standards

Teachers must be the agents of change!

Universities must be the engines of change!

<u>The last of the essential elements</u> for STEM education reform:

Technology Infusion

- is sure to increase rapidly and continuously
- but innovation is so unpredictable that you can’t plan for it

So the best strategy is to be prepared for opportunities as they arise.

Be prepared for using

The Computer (or even a cell phone) **as a scientific tool**:

- for *data acquisition* (from probes and other instruments)
- for data processing and analysis
- for *search and data mining* on the internet
- for modeling and experimental design
- for *social networking*
- for word processing

Technology by itself cannot improve education!

Productive learning depends on how the technology is used

And that depends on the preparation of the teacher!

Every gun that is made, every warship launched,
every rocket fired signifies, in the final sense,
a theft from those who hunger and are not fed,
those who are cold and are not clothed.
— Dwight D. Eisenhower

More information available at the
Modeling Instruction Website:
http://modeling.asu.edu

Content core:

Basic Particle Models in Newtonian Mechanics

Kinematical Models	*Causal Models*
Constant velocity	Free Particle: $\Sigma \mathbf{F}_i = 0$
Constant acceleration	Constant force: $\Sigma \mathbf{F}_i =$ constant
Simple Harmonic Oscillator (SHO)	Linear binding force: $\Sigma \mathbf{F}_i = - k \, \mathbf{r}$
Uniform circular motion (UCM)	Central force (with constant $\lvert \mathbf{r} \rvert$)
Collision $\Delta \, \mathbf{p} = \mathbf{I}$	Impulsive force

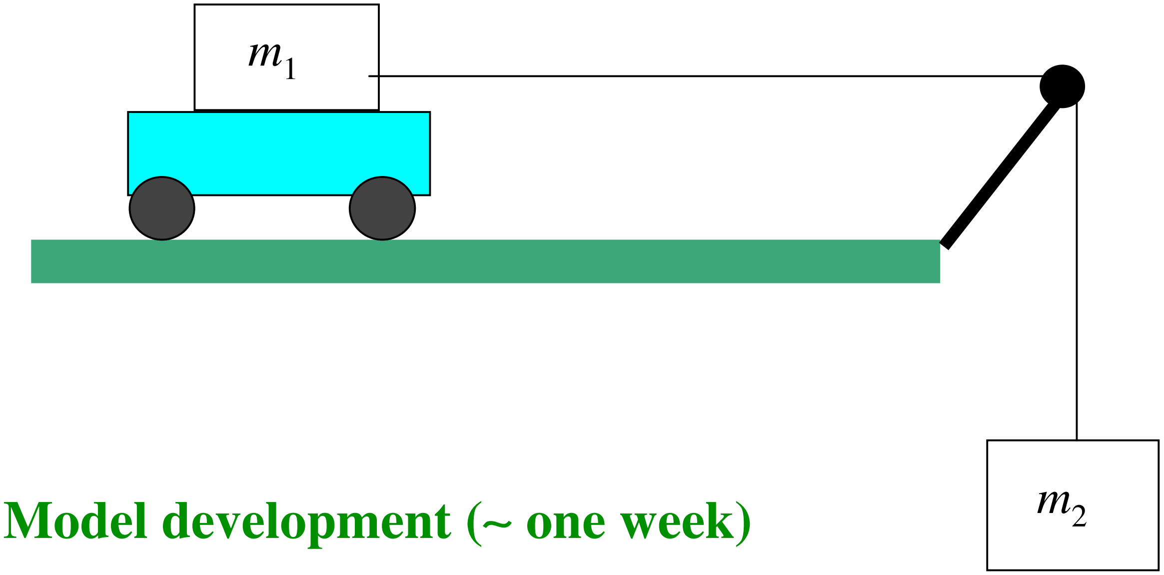
Instructional design: spend two weeks developing each of these models in an instructional cycle that emulates scientific modeling practice!

Instructional Modeling Cycle

Example: Target **Model**: Particle with **F** = constant

Physical **Principle**: Newton's 2nd law

Empirical **Context**: Modified Atwood machine



Stage I: Model development (~ one week)

Stage II: Model deployment (~ one week)

Instructional Modeling Cycle

Stage I: Model development

A. Description

Instructor sets context

negotiates meaning through class discussion

Objective: Guide students to identify the system of interest and relevant variables

Discuss: Essential elements of experimental design (e.g., dependent and independent variables)

B. Experimentation and model formation

Student groups of 3 or 2

- design and perform own experiments
- formulate a functional relation among variables
- evaluate fit to data

C. Post-mortem analysis (shared responsibility)

Whiteboard presentation of a **model** for the observed system with **justification** of conclusions by empirical data and theoretical argument

Instructional Modeling Cycle

Stage II: Model deployment

Objective: to abstract the model from the context
in which it was developed and
apply it to new situations

empirical abstraction (Piaget) — cut the semantic bonds!

i.e., **deploy the model** to *describe, explain, predict or design*

Student study groups
report results orally with white boards,
student articulation is guided with the:

Objective: to improve the quality of **scientific discourse**

Progressive deepening of student understanding of
models and modeling with each pass through the
modeling cycle (6 cycles/semester)…

till students see: **Models everywhere !**

Ultimate Objective: autonomous scientific thinkers fluent in the
vicissitudes of conceptual and mathematical modeling!

Managing Classroom Discourse (talk is not enough!)

- Aim: raise level of classroom talk to scientific discourse
- Establishing the subject of discourse

  Demos
Problems } → Issues
Questions } → Claims to be investigated

- Communication requires shared meaning
  - students get common access with *whiteboards*, etc.
- Meaning (of words, equations, diagrams)
  - — is constructed from situated use
  - — must be negotiated
- Quality of discourse depends on
  - — Representational tools and how they are used
  - — Structure of arguments
  - — Standards – set by teacher
- Scientific argumentation arises spontaneously when students have the discursive resources

Implications for Instruction

I. Curriculum design:

The ***curriculum should be organized around models***, not topics!
because models are
basic units of coherently structured knowledge,
from which one can make direct inferences
about physical systems and experimental data.

Students should become familiar with ***a small set of basic models as the content core*** for each branch of physics, and
elaboration of basic models into more *complex models*.

Theory should be introduced as a system of general principles
for constructing models with a specified domain of validity.

II. Instructional design:

Student learning & understanding can be accelerated & enhanced

- by ***systematic deliberate practice in all aspects of modeling***,
- by more powerful ***tools for modeling & simulation***.

Problem solving should be addressed as special case of
modeling and model-based reasoning.