Understanding STEM Education as a Complex System

By Emteqt Solutions
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Personal Background

- Designed software since 1997. Supercomputing, cryptography, etc
- Now really interested in modeling education policy
- This is harder

Examples
- With Boeing: Why doesn’t America’s education system produce enough engineers despite wages higher than any other profession? (Law of supply & demand failing?)
- With Aerospace Future Alliance of Washington: How do we sustain our primary competitive advantage: a strong aerospace labor force?
- With BHEF & Gates Foundation: How do we double the number of low-income youth earning post-secondary credentials in STEM.
Why do we care about STEM & STEM Education?

Technological Innovation Drives the US Economy
Yet we keep seeing troubling signs:
- Student interest seems low
- Student proficiency seems poor

Question then is:
- Why is this?
- What should be done?
### TIMMS 1995 Twelfth Grade Average Scores

<table>
<thead>
<tr>
<th>Country</th>
<th>Mathematics</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>557</td>
<td>Norway</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>542</td>
<td>Sweden</td>
</tr>
<tr>
<td>Switzerland</td>
<td>533</td>
<td>Russian Federation</td>
</tr>
<tr>
<td>Australia</td>
<td>525</td>
<td>Germany</td>
</tr>
<tr>
<td>Cyprus</td>
<td>518</td>
<td>Australia</td>
</tr>
<tr>
<td>Lithuania</td>
<td>516</td>
<td>International Average</td>
</tr>
<tr>
<td>Greece</td>
<td>513</td>
<td>Cyprus</td>
</tr>
<tr>
<td>Sweden</td>
<td>512</td>
<td>Latvia</td>
</tr>
<tr>
<td>Canada</td>
<td>509</td>
<td>Switzerland</td>
</tr>
<tr>
<td>International Average</td>
<td>501</td>
<td>Greece</td>
</tr>
<tr>
<td>Italy</td>
<td>474</td>
<td>Canada</td>
</tr>
<tr>
<td>Czeck Republic</td>
<td>469</td>
<td>France</td>
</tr>
<tr>
<td>Germany</td>
<td>465</td>
<td>Czeck Republic</td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td><strong>442</strong></td>
<td>Austria</td>
</tr>
<tr>
<td>Austria</td>
<td>436</td>
<td><strong>United States</strong></td>
</tr>
</tbody>
</table>
## Supply/Demand Law Violated?

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>$30,800</td>
<td>$39,900</td>
<td>$60,600</td>
</tr>
<tr>
<td>Engineering</td>
<td>38,900</td>
<td>51,400</td>
<td>74,900</td>
</tr>
<tr>
<td>Computer science</td>
<td>33,400</td>
<td>50,400</td>
<td>72,600</td>
</tr>
<tr>
<td>Business and management</td>
<td>33,800</td>
<td>43,400</td>
<td>65,900</td>
</tr>
<tr>
<td>Health</td>
<td>40,500</td>
<td>45,600</td>
<td>65,000</td>
</tr>
<tr>
<td>Biological sciences</td>
<td>29,200</td>
<td>33,900</td>
<td>62,200</td>
</tr>
<tr>
<td>Mathematics/physical sciences</td>
<td>27,100</td>
<td>37,800</td>
<td>58,200</td>
</tr>
<tr>
<td>Social and behavioral science</td>
<td>26,900</td>
<td>39,200</td>
<td>62,300</td>
</tr>
<tr>
<td>Arts and humanities</td>
<td>25,000</td>
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<td>52,800</td>
</tr>
<tr>
<td>Education</td>
<td>26,600</td>
<td>31,700</td>
<td>43,800</td>
</tr>
<tr>
<td>All STEM fields</td>
<td>33,800</td>
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<td>Non-STEM fields</td>
<td>30,200</td>
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</table>
Common (Unsatisfying) Explanations:

• Children today are lazier, they used to have better work ethic. This is the “me generation.”
• Parents are more permissive than they used to be, they either don’t drive children hard enough because they “want them to be happy,” or they don’t pay enough attention at all.
• People raised in poverty will go into (or push their children into) professions that promise comfort but people raised in comfort will feel no such urgency. Because kids today have everything they need and want, they aren’t motivated to study hard subjects with the hope of future return.
• People today fear the prospect of putting time and effort into studying science and technology, only to see all of the jobs in those fields outsourced to developing countries.
• STEM workers are not perceived as nationally important like they were during the Cold War. *(Sputnik effect.)*
• It has something to do with increased participation of women in higher education and their relative tendency not to pursue engineering degrees.
• STEM workers are not respected like doctors or lawyers.
• STEM workers are not ‘cool’ like rock stars and basketball players.
• STEM subjects are harder to grasp and require more homework and time spent out of class.
• STEM subjects are not as interesting as non-STEM subjects.
• STEM subjects are for nerds. The opposite sex will not find you appealing.
• There isn’t as much need for engineers and scientists because computers and automation continue to make the design process so much easier.
• You can make more money in other fields such as business, law, medicine, etc.
Are Today’s Children Lazier?

About ‘Generation Y’:
“The children now love luxury. They have bad manners, contempt for authority, they show disrespect to their elders.... They no longer [are polite]. They contradict their parents, [talk too much], [eat too much], [have no modesty], and are tyrants over their teachers.”
Are Today’s Children Lazier?

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“The children now love luxury. They have bad manners, contempt for authority, they show disrespect to their elders.... They no longer [are polite]. They contradict their parents, [talk too much], [eat too much], [have no modesty], and are tyrants over their teachers.”

The Real Quote:
“The children now love luxury. They have bad manners, contempt for authority, they show disrespect to their elders.... They no longer rise when elders enter the room. They contradict their parents, chatter before company, gobble up dainties at the table, cross their legs, and are tyrants over their teachers.”

-Attributed to Socrates by Plato
Systems Approaches

* Structure -> behavior -> events

* Fundamental assumption that people respond to systemic forces, and that changing the system (rather than the actors) will get results

* Complex systems often characterized by: momentum, delays, oscillations, feedback loops, network effects, tipping points, capability traps, non-linearities
The Architecture

- Extreme modularity and differentiation that minimizes coupling between classrooms, grades, and schools. (Lortie, 1975)
- Evolved as independent teachers came together under a single roof and persisted because of an expectation of high turnover among young female teachers that negated benefits of cooperation.
- Teachers are viewed as interchangeable parts with little need to interact. (Weisberg, Sexton, Mulhern, & Keeling, 2009)
- Boundaries between subjects and content are rigid. Division of labor allows teachers to specialize by content.
- Within each classroom, there is little choice. Everyone must learn the same material at the same pace and be evaluated in the same way.
- Students gain choice by having the ability to dynamically assemble modular subject/teacher packages into their own schedule.
“Running The Gauntlet”

Is STEM disproportionately harmed by the currently dominant educational architecture?
Running The Gauntlet:
Math is highly sequential with strong dependencies

Numerical Manipulation → Basic Algebra → Geometry Trigonometry → Calculus → Probability Statistics → Numerical Methods → Differential Equations

Babies

Elementary School → Junior High → High School → University

K 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

4 million students start

25% Complete Basic Algebra in Junior High

730,000 still interested

340,000 majors

590,000 still interested

200,000 STEM Graduates (60,000 in Engineering)
Theorem: Weak Links Really Matter

\[ n \times E(p_{1..n}) \geq \prod p_{1..n} \]

\( p \) is the probability of continuing after one stage
\( n \) is the number of stages

Numbers from Grismore et al. 2003.
What Causes Drop Off?

STEM Teacher Quality

ABILITY or PERCEIVED BEHAVIOR CONTROL

Intent: Individual Attitudes and Belief About Social Norms

* Theory of Planned Behavior
Math and Science Teachers Have Highest *Opportunity Cost*

<table>
<thead>
<tr>
<th>Total</th>
<th>1-2 years (1994)</th>
<th>4-5 years (1997)</th>
<th>9-10 years (2003)</th>
</tr>
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*Opportunity Costs*
### TABLE 5-1 Students in US Public Schools Taught by Teachers with No Major or Certification in the Subject Taught, 1999-2000

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<tr>
<th>Discipline</th>
<th>Grades 5–8</th>
<th>Grades 9–12</th>
</tr>
</thead>
<tbody>
<tr>
<td>English</td>
<td>58%</td>
<td>30%</td>
</tr>
<tr>
<td>Mathematics</td>
<td>69%</td>
<td>31%</td>
</tr>
<tr>
<td>Physical science</td>
<td>93%</td>
<td>63%</td>
</tr>
<tr>
<td>Biology–life sciences</td>
<td>—</td>
<td>45%</td>
</tr>
<tr>
<td>Chemistry</td>
<td>—</td>
<td>61%</td>
</tr>
<tr>
<td>Physics</td>
<td>—</td>
<td>67%</td>
</tr>
<tr>
<td>Physical education</td>
<td>19%</td>
<td>19%</td>
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Failure Modes

system A
Lower expectations and quality, but coherent

system B
Higher expectations, quality, and coherence

system C
Lack of coherence across grades and institutional boundaries

Big fish from little pond?
interested & possessing raw talent, but facing unanticipated gap

Mid-size fish in big pond?
capable and on-track, but self (or instructor) perception of relative weakness.

Single point failure.
poor instruction or temporary lack of interest at critical juncture.
Simulating the pipeline and other forces

Created simulation model capable of reproducing historical trends in engineering workforce and explaining supply/demand paradox.
Washington State Aerospace Workforce Study

By Emtect Solutions
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Four Forces Impacting Workforce

• Normal market forces, booms, busts
• 7 year cyclic behavior unique to aerospace
• Labor work rules and strike activity
• Baby boomer generational exodus

Understanding, predicting, and managing aerospace workforce trends is a complex problem because the industry experiences multiple forces that operate on vastly different time-scales simultaneously. Many industries have dynamics that are not nearly as complicated.
...
Industry Demand and Training Capacity

Desired WF Hiring Rate : Current
HS Graduate : Current
PHS Graduate : Current
PHS Training Capacity : Current
HS Training Capacity : Current
Two Complementary Educational Pipelines

- Engineering technologists
- Engineers, scientists, mathematicians

Mathematical and analytical knowledge has a unique hierarchical structure requiring a pipeline approach to management. Both pipelines train students for careers conceiving of, designing, implementing, and operating complex machines and systems. These pipelines are embedded within boundaries of existing educational institutions.

These people support technological innovation within an economy and “keep the lights on.”
Both Pipelines Underperforming…
(For many of the Same Reasons)

*Hands-on training is crucial for both future engineers and technologists.*

- These capabilities degraded over past 30 years as shop and other experiential learning was removed.
- Cultural and institutional support declined because the (now departing) baby boomer bubble reduced prospects for new entrants in the technical trades.
- STEM teaching quality has declined dramatically in the last generation nationally because of the liberalization of gender roles and an unwillingness to pay market rates.
- Engineering grads decreased because of the false belief that shop was not crucial for the college bound.
Exodus Ramping Up Dramatically

- Retiring boomers will increase demand on educational institutions dramatically if workforce is to remain the same size.
Educational Capabilities Must Expand To Meet Demand

- Large workforce shortfall may occur due to imminent baby-boomer exits.
- Educational systems do not currently have sufficient capabilities to meet challenge.
- K-12 is the primary pipeline bottleneck. College is secondary bottleneck.
- Both must be strengthened in coordinated way and handoffs should be managed.
Promote Diversity & Lifelong Learning

- There is a large workforce gap between the ages of 30-45. This bifurcation leads to generational culture conflicts. Actively recruiting older non-traditional students and workers can help fill in this gap, causing the workforce to look more even. Failing to do so will repeat the current bubble in future generations, reproducing all of the negative consequences for industry, educational institutions, and communities.

Simulations in which bubble is reproduced. Simulations in which bubble dissipates.
Institutional Considerations

There is no single institution currently responsible for tracking and managing workforce and pipeline issues. Any institution that wishes to understand and help the aerospace workforce must proactively track, understand, and manage the **four forces** and **two complementary pipelines** in a systematic fashion over long time horizons. Most institutions today are narrowly focused, have a short institutional memories. They tend to miss cyclical trends and operate in ‘panic mode.’
Policy & Institutional Design

The Main Goal

• Manage, track, and support the technical trade and STEM workforce pipelines during K-12, post secondary, and lifelong learning.

• Enable coherent policy, interfaces, communication, and coordination between industry, education, and government.

Orientation

• **Strategic** rather than opportunistic operating principles.

• Shielded from immediate term political and funding forces and therefore capable of sacrificing local optimum for global optimum, promoting ‘worse before better’ policy, and acting in the interests of the entire community over the long term.