Preparing the Next Generation of STEM Innovators

Adding wings to a caterpillar does not create a butterfly.
It creates awkward and dysfunctional caterpillars.
Butterflies are created through transformation.
Stephanie Pace Marshall

Igniting and Nurturing STEM Talent, Innovation and Leadership, By Design

The New Paradigm and Ecology of STEM Learning and Teaching

Stephanie Pace Marshall, Ph.D.
Committee on Education and Human Resources
National Science Board
24 August 2009

Mind-Shaping is World Shaping

In a world of unprecedented connectivity and undisputed global interdependence, our future will belong to a "new breed" of STEM talent— *decidedly different* STEM minds that:

- understand interdependence;
- discern, analyze and connect illusive patterns within vast amounts of unstructured data;
- deftly change course when hypotheses and prototypes fail;
- systemically unravel complexity;
- creatively generate new ideas, questions, technologies and inventions;
- embrace ambiguity and uncertainty;
- ask inconvenient questions;
- seed and cross-pollinate ideas;
- fluidly integrate and navigate within and between a broad spectrum of STEM disciplines and domains; and
- globally collaborate to wisely advance the human condition.

"Both/And" Thinking

By design, we must create STEM learning environments and experiences that invite children to develop the full range of their talents, leadership and innovative potentials by cultivating the adaptive expertise, innovation and wisdom of "both/and" thinking.

Such thinking integrates and validates the power of:
- the intellect *and* the imagination;
- information *and* relationships;
- research, hypotheses testing, and experimental design *and* prototyping, simulation, problem-solving, and storytelling;
- observation and evidence-based truth *and* improvisation and experiential truth;
- analytical measurement *and* aesthetic insight;
- observation *and* intuition;
- reason *and* passion;
- curiosity and skepticism *and* wonder and awe; and
- expertise *and* wisdom (Marshall, 2006).

The nature and quality of how our children think and what they think about is the new "currency" for breakthrough thinking, research and problem-solving, pioneering collaboration, groundbreaking life-enhancing innovation, and transformative global change.

Innovation: "Catalyzing Irreverent Stances" (Gardner, 2009)

Innovation happens at the edges and intersections of disciplines.

It happens when:
- new and irreverent questions are asked;
- conventional wisdom is challenged;
- disruptive hypotheses are explored;
- possibilities of "what if" or "how might we" capture the imagination;
- curiosity, wonder and uncertainty are provoked;
- it's safe to risk, tinker and venture into unexplored and unconventional territory.

Innovation is a messy, dynamic, unpredictable, and nonlinear process; and it requires a generative and integrative learning habitat within a vibrant innovation ecosystem that invites experimentation and discovery, rewards design and invention, and encourages intuitive forays and the passionate pursuit of often absurd questions and solutions wherever they may lead.
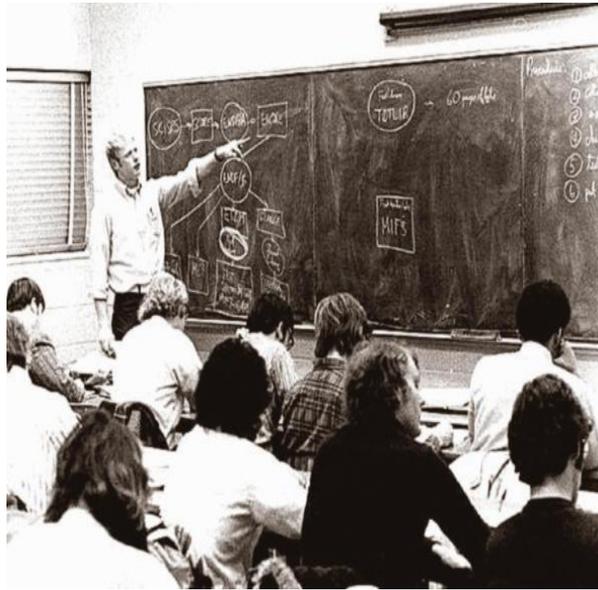
There is a growing chasm between the collaborative, exploratory, future-oriented and applications-focused ethos and environment essential for nurturing STEM talent and innovation, and the constrained, prescriptive and risk-averse culture and conditions of schooling.

Every school must become a center of inquiry, imagination and innovation.

We get what we design for.

"School Science" Is Not *Real* Science

**School science has become a spectator sport,
even for our most talented students.**

Currently, for most students, "school science" is experienced as:

- passive acquisition of excessive amounts of often unconnected and topical content presented in disciplinary silos;
- devoid of emotion, joy, and wonder;
- isolated from its social context and detached from the human experience;
- compliant and disengaged observation;
- inert information unconnected to the real world—their needs, interests, curiosities or questions;
- de-contextualized and prescribed content with little time for exploratory forays or following intriguing questions;
- rote adherence to the prescribed "steps" of the "scientific" method;
- getting right answers, and memorizing taxonomies and unalterable algorithms;
- an individual endeavor.

"School science" completely distorts and misrepresents the nature of the scientific enterprise and its contributions to the human future.

How Did you Learn in School Today?

Every way of knowing becomes a way of living.
Every epistemology becomes an ethic…
Every mode of education,
No matter what its name, is a mode of soul-making (Parker Palmer)

Habits of mind, mental models and patterns of thinking and behavior are shaped through immersion, experience and practice. When children:
- engage in deep disciplinary and interdisciplinary research, investigation, and experimentation, they learn to inquire, explore, discover and invent;
- creatively practice identifying, framing and solving messy and challenging global problems, they learn to innovatively resolve complexity;
- collaboratively wrestle with moral and ethical dilemmas, they learn to wisely grapple with issues of social, economic, political and environmental justice.

They become more agile, autonomous, failure-resilient, improvisational, and metacognitively aware and in control of their own minds and behavior, assuming responsibility for shaping the nature and quality of their thinking and manifesting it in action.

By design, we can inspire, ignite and nurture our children's inventive genius and enable it to flourish by immersing them in mind and practice fields rooted in:
- **meaning**, not memory;
- **engagement**, not transmission;
- **inquiry**, not compliance;
- **exploration**, not acquisition;
- **personalization**, not uniformity;
- **interdependence**, not individualism;
- **collaboration**, not competition; and
- **trust**, not fear.
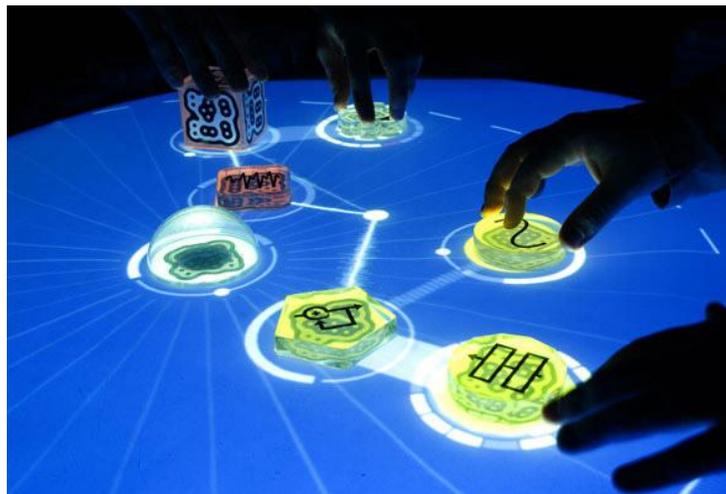
Learning In a Digital World

Our students live and learn in a digital world of global connections, intelligent machines and networks, immersive technologies, multi-user virtual environments and social networks. In this world:

- learning is experiential, purposeful, self-directed and on-demand;
- expertise is multi-generational and distributed;
- thinking is shared;
- problem-solving is collaborative;
- knowledge is co-constructed;
- boundaries are intentionally blurred; and
- learning, social relationships and play seamlessly converge.

To develop the STEM innovators our nation and world require, we must design conditions that engage students' minds and hearts and nurture their sense of wonder, infinite possibility and extraordinary contribution.

The generative learning environment(s) we design must stimulate students to develop those "hybrid" competencies needed for:

1. **Knowledge Creation and Application** *(disciplinary, interdisciplinary and inquiry-based thinking);*

2. **Radical Innovation and Invention and Imaginative Human-Centered Design** *(innovation and design-based thinking);*

3. **Ethical and Entrepreneurial Leadership and Sustainable Whole Systems Change** *(systems-based thinking).*

Gaming as a Dynamic, Interactive & Possibility-Abundant Learning System

"Principles" of Game Design
- Meaningful play; high levels of internal motivation and emotional engagement
- Situated learning
- Uncertainty; game responses are not predetermined; system is emergent
- Holistic connection of players' actions and system responses
- Immediate and continuous feedback
- Choice
- Competition
- Balanced challenge, not threat
- Reflective action—thinking
- Agency—experimentation with identity and point of view
- Distributed knowledge, intelligence and expertise; co-creation
- Proactive participation and production (ownership and investment; players have a stake)
- Learning in community (collaboration, peer-to-peer, communities of practice, cross-functional teams, multi-generational)

As a learning system, gaming fosters: risk-taking, hypothesis testing, possibility thinking, pattern discernment, acceptance of failure, emotional engagement, personal efficacy and agency, focused attention, complex problem-solving, shared decision-making and knowledge construction, reflective experimentation and trust.

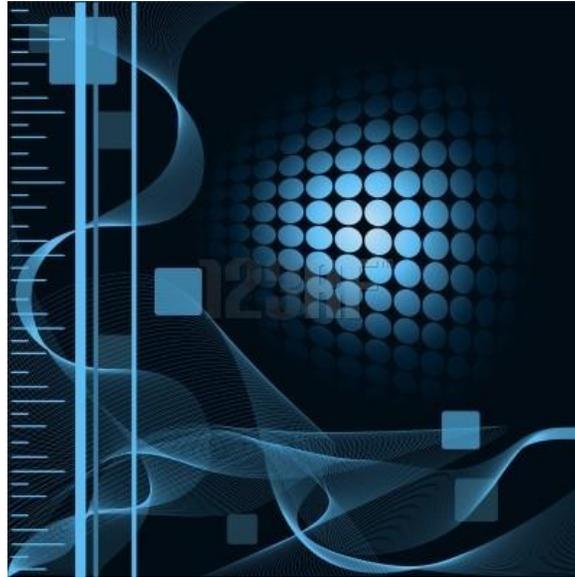## Key "Moments" of Game Demonstration When the Game Is Well-Designed

When a player:

- Unconsciously reaches for the game controller or mouse and asks, *"Can I try?"* (Requires **clarity** on the part of design)

- Turns to ask, *"Can I save it?"* (Requires **depth** on the part of the design)

- Turns to another and asks, *"Want me to show you?"* (Requires support of **reflection and interpretation** on the part of designers)

- Asks another, *"How did you do that?"* (Requires support of a **community of practice** on the part of the design)

"….these moments point to one of the most basic reasons that games are recognized, without reservation, by players as learning systems—*trust***. Players trust that the game system will teach them everything they need to know in order to play. When games don't do this, players walk away"** (Katie Salem, editor. *The Ecology of Games: Connecting Youth, Games and Learning*. p. 11-3).

The New Paradigm and Ecology of STEM Learning—from pipelines to networks

Mapping the ways the multiple dimensions of STEM learning and teaching—from standards to curriculum, to learning experience design, to pedagogy, to metrics and assessment—interact to shape the culture and conditions of STEM learning.

Our nation must transform our system of STEM education and create an inclusive and robust learning and innovation ecosystem that ignites and nurtures a more "hybrid" and blended generation of STEM talent, innovation and entrepreneurial leadership.

The Problem with Pipelines
In an age of innovation, the pipeline model and metaphor are prescriptive, restrictive and exclusive, and do not serve to ignite, nurture, advance and sustain STEM talent, innovation and entrepreneurial leadership within a dynamic, highly emergent and generative global network.
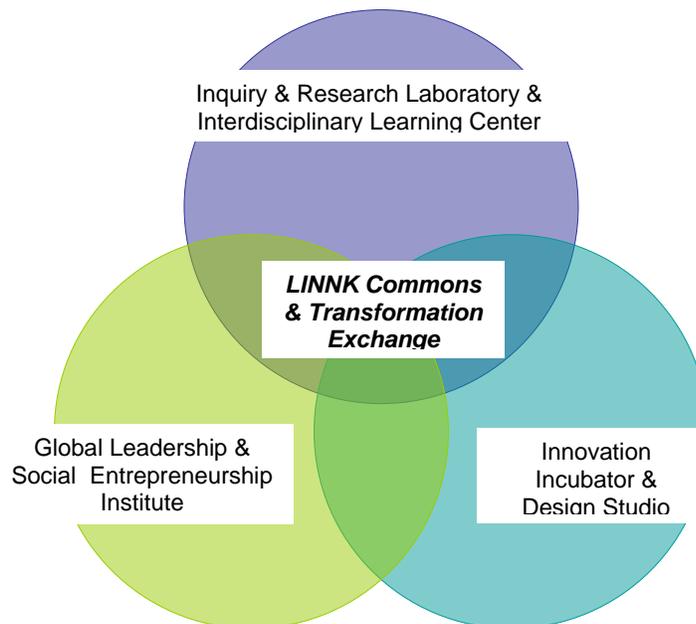- It's too linear, uni-dimensional, inaccessible, and closed;
- It does not permit interaction, collaboration, generation or self-organization;
- It implies that "one pipe fits all"—limited access and entry, constrained uni-directional focus, inability to get out once in, or inability to enter if you change your mind.

Pipelines are not for <u>all</u>.

We need a new innovation paradigm that is invitational, dynamic & generative.

The Conceptual Learning Design: A New Ecology

To develop the next generation of STEM Innovators, the program of studies and curriculum are reconceived within the context of four differentiated, yet dynamically integrated core learning and teaching "complexes." **These unique learning habitats are designed to immerse and engage students in the real work and modes of inquiry, problem-solving, knowledge creation and application, that distinguish four fundamental STEM learning cultures and communities,** **each designed to develop high levels of understanding and knowledge application.**

Inquiry & Research Laboratory &
Interdisciplinary Learning Center

*LINNK Commons
& Transformation
Exchange*

Global Leadership &
Social Entrepreneurship
Institute

Innovation
Incubator &
Design Studio

1. ***Inquiry and Research laboratory and interdisciplinary learning center*** **focuses on knowledge and meaning construction and developing advanced levels of competence and expertise in all disciplinary domains**, through self and mentor-guided inquiry, extended internships and apprenticeships, intensive research and investigation, and experimentation and problem-solving. The emphasis is on high levels of knowledge and skill acquisition, integration and use, research and scholarly production, and creative knowledge generation valued and evaluated by experts and practitioners in the domain. ***Focus is on developing disciplinary, interdisciplinary and inquiry-based thinking.***

2. ***Innovation incubator and design studio* focuses on creative ideation, production and the application of science, mathematics, engineering and technology expertise to serve more tangible and pragmatic human needs**; focus is on imaginative, improvisational and creative design; igniting, seeding, "hatching," accelerating, and scaling promising prototypes and innovations in products, services, processes and systems; emphasis is on generating disruptive (Christensen, Horn, & Johnson, 2008) new ideas and connecting current ideas in new ways to create useful solutions valuable to others. Students use brainstorming, innovative scanning, modeling, storytelling, rapid prototyping, mindmaps, simulations, and multiple innovation platforms; the incubator serves as a magnet, disruption amplifier, innovation and design accelerator. ***Focus is on developing innovation and design-based thinking.***

3. ***Global leadership and social entrepreneurship institute* focuses on developing the knowledge and skills necessary to be a "citizen in service" (Clinton, 2009) and to proactively work in areas of social justice, fostering meaningful change in principle, policy or practice, generating changes in thinking and behavior, and creating innovative solutions (new processes and systems) for real world problems** in areas of compelling social need; nurtures high levels of knowledge and competence in complex and adaptive systems thinking, conflict resolution, social and organizational change, and public influence and advocacy; fosters proactive global citizenship, empathy, and diversity of perspective; serves as a leadership catalyst, change accelerator, and movement generator for social change. ***Focus is on developing change leadership and systems-based thinking.***

LINNK (Leadership, INNovation, Knowledge) Commons and Transformation Exchange:
As an integrative hub, LINKK acts as a global commons and facilitates idea and problem exchanges between individuals, initiatives, or multinational projects that often have their genesis in the work created in the learning cores. Its purposes are to: (a) **share, integrate, synthesize, and leverage the knowledge, ideas, questions, designs, and innovations** being studied, prototyped and tested in each of the three cores; (b) engage, connect, distribute and **accelerate the collective intelligence, imagination, and creative capacity** of the community and their innovation networks; (c) identify, generate, and solve **shared problems** of mutual interest; (d) invite, perturb, and catalyze **new conversations**; (e) create opportunities for **new thinking**; (f) activate the creation of **new partnerships and networks** for fluid global knowledge construction, sharing, and collaborative work; (g) seed, connect, accelerate, and support the design, development, and scaling of **research, innovation, and social entrepreneurial initiatives**; (h) **stimulate the emergence of local, national and global STEM innovation networks**; (i) attract, generate, and sustain intellectual, technological, and financial **resources**; and (j) connect **prototypes and innovations into a dynamic learning exchange network** (unpublished article, *Roeper Review*).

I LOVE THIS PLACE!

"This is the strangest place I've ever been. It is the only place I know where people can sit around at lunch and argue honestly about the velocity of a falling blob of ketchup. (Yes, that really happened. I was arguing as well, but my point was from how high you dropped the ketchup.) I think that this is the only place where people can sit around and discuss physics and feel NORMAL while doing so.

. . . As soon as sophomores arrive here, [the school] begins to affect them. I know it is affecting me. People I know have observed this changing, and have told me about it. [Yesterday my friend] was drinking soda from a glass cup, and for some reason all the foam stayed at the top so that while the liquid went down in the glass, the foam remained up so that there were gasses in between. She shouted, "Hey, look!" We all rushed over and stared at her soda for a few minutes. Then we tried to figure out why it did that. Finally, one of my [friends] grabbed a camera and took a picture of it for our photography class. It was really an interesting occurrence.

I love this place!

<div align="right">IMSA Student</div>

IMSA Student Application
Igniting Imagination & Inquiry

To be completed by the Student.
Please respond on separate pages to the following:*(No word limit)*
It is your task to develop a working equation/formula for learning mathematics and science, that will mathematically portray the relationship of factors in being successful in advanced study in mathematics, science and technology. Here are some factors from which you can choose: (You may add any variables of your own.)

<div align="center">Describe in your own words the formula you have created.</div>

C = Change	**K** = Knowledge	**Q** = Questioning
CO = Collaboration	**L** = Love	**T** = Time
IM = Imagination	**P** = Play	**TE** = Technology

IMSA BY DESIGN:
The Story, Map and Landscape of the
Illinois Mathematics and Science Academy

The Story (mission, beliefs and objectives) "The mission of the Illinois Mathematics and Science Academy, the world's leading teaching and learning laboratory for imagination and inquiry, **is to ignite and nurture creative, ethical scientific minds that advance the human condition**, through a system distinguished by profound questions, collaborative relationships, personalized experiential learning, global networking, generative use of technology and pioneering outreach."

- IMSA's Beliefs:
    - All people have equal intrinsic worth.
    - All people have choices and are responsible for their actions.
    - Belonging to a community requires commitment to the common good.
    - Diverse perspectives enrich understanding and inspire discovery and creativity.
    - Honesty, trust and respect are vital for any relationship to thrive.
    - Learning never ends.
    - Meaning is constructed by the learner.
    - No one's path in life is predetermined.
    - The ability to discern and create connections is the essence of understanding.
    - We are all stewards of our planet
- IMSA's Strategic Objectives:
    1. All learners achieve their personal aspirations and explore their potential to contribute to the common good.
    2. Each IMSA graduate will live a life of exemplary service to humanity.
    3. Educators use teaching and learning strategies grounded in imagination and inquiry.

The Map (Design)
- IMSA's Learning Outcomes include:
    - Standards of Significant Learning (habits of mind of integrative ways of knowing)
    - Disciplinary Standards
    - Leadership Competencies
    - Inquiry Competencies
- IMSA's program is grounded in:
    - Learning principles
    - Development of diverse talent, creativity, innovation and leadership in STEM
    - Advances in scientific knowledge
    - Generative use of technology
    - Collaborative relationships and partnerships
    - Global networking
- IMSA's program is designed to be:
    - Personalized, experiential and technologically generative
    - Competency and curiosity-driven, Concept-centered & Integrative (Curriculum)
    - Inquiry-based & Problem-centered (Instruction)
    - Generative, Multi-dimensional, & Understanding & Performance-based (Assessment)

The Landscape
IMSA's **personalized experiential learning program** offers over 120 courses; local, national, and international research & mentorship opportunities; intersession, seminars & independent study options; cultural & scientific exchanges, research, problem-solving, engineering and entrepreneurial competitions; an annual student research symposium (IMSAloquium) and collaborative multidisciplinary projects. Formal class time is variable and classes meet four days per week; one day is for off-campus research. (visit www.imsa.edu for a full picture of the IMSA story).

IMSA's Return on Investment is distinguished by a Return On:
Imagination, Inquiry, Ingenuity, Invention, Integration, Innovation

The Evolution and Design of a Prototype

"…organizations need a place where specific opportunities and projects can be explored in a freewheeling, no intellectual holds-barred manner. They need spaces designed to elicit questioning, discovery, experimentation and prototype development" (Kao, *Innovation Nation*, 2007)

IMSA is developing such a place. CoolHub.imsa is a virtual toolbox, a meeting place (real and virtual), a think-tank, a self-organizing network and an accelerator of innovative ideas that can transform STEM education.

CoolHub.imsa will:
- Connect learners of all ages (mostly online);
- Provide tools—virtual meeting rooms, multi-media conferencing, Second Life interaction, searchable databases, project-related artifacts and publications—to explore "big" questions, develop ideas and innovate together;
- Provide resources and opportunities (physical and virtual) for collaborations that accelerate research, rapid prototyping and program development;
- Promote self-organization around the solution of real-world problems.

Sample Goals and Activities
Create Structures and Processes that Support and Evaluate Collaborative Innovation Networks
- Create an interactive-open source Web platform (Liferay) that enhances innovation, creativity, communications, and collaboration, and builds a sense of connected community with a vision of transforming STEM education. Through the use of the Web platform and Second Life, collaborative innovators post ideas, questions and problems, share knowledge, access resources and leverage the intellectual capital of the people in the network.

Build Communities of Collaborators
- Build networks of collaborators by recruiting specialists, innovators and early adopters in fields such as education, energy, nanotechnology, and software development.

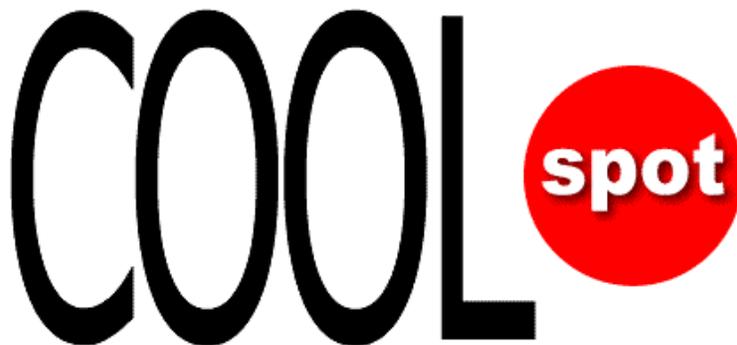### Launch Collaborative STEM Projects That Address Societal Needs
- The CoolHub.imsa infrastructure and network of real-world experts and practitioners enable IMSA students in the Energy Center to spark innovative inquiry focused on sustainable energy sources, usage and policy;
- Students involved in IMSA's TALENT (Total Applied Learning for Entrepreneurs) program use CoolHub.imsa resources to connect with research universities, national labs, state and federal government, and business groups globally in their pursuit of

HANDOUT: "Developing STEM Innovators Through the Education System"
National Science Board Presentation (24 August 2009: 10:00am-noon)

entrepreneurial applied science and technology projects and ideas for potential commercialization;

- IMSA's One Laptop Per Child Student Chapter uses CoolHub.imsa resources to globally connect to support large-scale implementations in underdeveloped areas of the world;
- The technical and social structure of CoolHub.imsa enables the Illinois Innovation Talent Project to develop collaborative working relationships with business and school partners. Through virtual forums, businesses share their challenges and students from various schools develop plans to address those challenges.

Document and Disseminate New Models for STEM Teaching and Learning
- Developing new applications and policies for using portable digital devices (iPhones, etc.) in school;
- Working with Free the Children and the Clinton Global Initiative to equip a girls school in Kenya with technology, a CoolSpot and a plan for using them;
- Creating multiplayer digital games for teaching and learning science subject matter;
- Researching and prototyping affordable, renewable energy sources to reduce our dependence on fossil fuels;
- Encouraging students to create (and schools to allow) personalized learning networks using Web 2.0 tools.

CoolSpots -- tech-enabled zones conducive for small group work -- serve as pathways to a robust virtual network that supports innovation and learning through videoconferencing, online forums, wikis, blogs, immersive online worlds and a searchable database of session recordings and published innovation projects. Initially located on campus, CoolSpots will also be placed at IMSA's Field Offices in Illinois and other partner locations—nationally and globally.
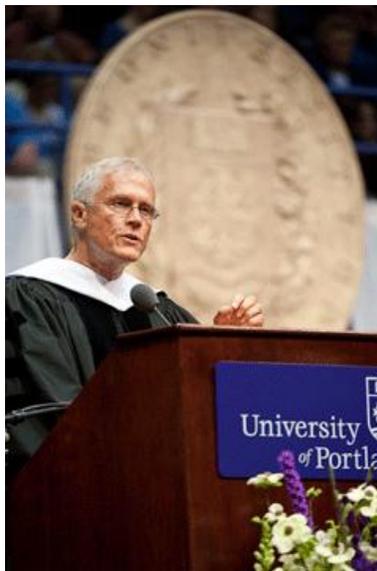
Now it's your turn—to develop one or more representations—working equations, models, mindmaps, scripts, drawings—for preparing the next generation of STEM innovators. Your representation(s) should portray the relationships among multiple factors that will lead to:

1. Igniting and nurturing a "new breed" of diverse innovative STEM talent;

2. Designing a seamless innovation-centered STEM learning system, P-20; and

3. Creating & sustaining a robust national and regional innovation ecosystem.

First, select the factors you will use, then describe what you have created; finally, explain why you created what you have.

The Real Invitation STEM Education Offers to the Next Generation

Commencement Address by Paul Hawken,
University of Portland, May 3rd, 2009   (http://designthinking.ideo.com)

Hey, Class of 2009: You are going to have to figure out what it means to be a human being on earth at a time when every living system is declining, and the rate of decline is accelerating… Basically, the earth needs a new operating system, you are the programmers, and we need it within a few decades… There is invisible writing on the back of the diploma you will receive… I can tell you what it says: YOU ARE BRILLIANT, AND THE EARTH IS HIRING. Take the hint. And here's the deal: Forget that this task of planet-saving is not possible in the time required. Don't be put off by people who know what is not possible. Do what needs to be done, and check to see if it was impossible only after you are done… Humanity is coalescing. It is reconstituting the world… You join a multitude of caring people. This is the largest movement the world has ever seen. Rather than control, it seeks connection. Rather than dominance, it strives to disperse concentrations of power… You are graduating to the most amazing, challenging, stupefying challenge ever bequested to any generation. The generations before you failed… They got distracted and lost sight of the fact that life is a miracle… Nature beckons you to be on her side. You couldn't ask for a better boss. This is your century…