System Dynamics in K-12 Education: Lessons Learned

Debra Lyneis and Lees N. Stuntz
The Creative Learning Exchange
27 Central Street, Acton, MA, 01720 USA
(978)-635-9797
lyneisd@clexchange.org, stuntzln@clexchange.org

Abstract

Fifteen years ago in 1992, Jay Forrester laid the cornerstones for a more effective kindergarten through 12th grade (K-12) education based on system dynamics. In this paper, teachers and other educators who have been implementing system dynamics and systems thinking in schools across the United States reflect on their progress. Although all of the educators have been encouraged and inspired by student engagement and insight using system dynamics in their classrooms, wider adoption has encountered obstacles. Strategies to overcome them include: improving the quality and quantity of system dynamics curriculum materials and training opportunities for teachers, integrating the use of systems thinking tools with system dynamics simulation to give students the full benefit of both, seeking ways to work within the K-12 institution to effect change, and working together to learn from successes and mistakes.

Introduction

In 1992, when K-12 system dynamics was still in its infancy, Jay Forrester wrote "System Dynamics and Learner-Centered-Learning in Kindergarten through 12th Grade Education" (Forrester, 1992). The paper presented the cornerstones for a more effective education based on system dynamics, a description of early work in Tucson championed by Gordon Brown, the necessary ingredients for implementing change in schools, and cautionary advice for the future. Forrester laid out the reasons and the means to change pre-college education in fundamental ways:

> "System dynamics offers a framework for giving cohesion, meaning, and motivation to education at all levels from kindergarten upward. A second important ingredient, "learner-centered-learning," imports to pre-college education the challenge and excitement of a research laboratory. Together, these two innovations harness the creativity, curiosity, and energy of young people." (Forrester, 1992, 1)

In 1994, in "Learning through System Dynamics as Preparation for the 21st Century" (Forrester, 1994), Forrester went further to describe the benefits that a systems education could provide to students and their communities A system dynamics education should achieve three broad objectives:

1. It should develop personal skills. Learning to build and use computer simulations should "sharpen clarity of thought and provide basis for improved communication. It should encourage holding unconventional opinions. It should instill a personal philosophy that is consistent with the complex world in which we live." (Forrester, 1994, 5) For

example, students should appreciate interrelationships and search for the interconnectedness that gives meaning to the parts of systems.

2. It should shape an outlook and personality to fit today's needs. "It should give students the confidence that they can shape their own futures…and mold a personality that looks for causes and solutions. Working with systems should reveal the strengths and weaknesses of mental models and show how mental models and computer models can reinforce one another." (Forrester, 1994, 10)
3. It should build an understanding of the nature of complex systems in order to inform better decision-making and problem-solving. After a long study of systems, students would be aware of the deceptive nature of systems. They would know, for example, that cause and effect are not closely related in time or space, that current policies often perpetuate the problem, and that there are trade-offs between long- and short-term goals.

In 2001, after growing evidence in a few schools across the United States began to confirm the possibilities of system dynamics in K-12 education, a group of about twenty classroom teachers and professional system dynamicists convened under Forrester's leadership in Essex, Massachusetts to assess progress and plan for the future. Their work was described in "The Future of System Dynamics and Learner-Centered Learning in K-12 Education," often called the Essex Report (Lyneis, 2002). Many of Forrester's earlier predictions had been affirmed, now based on anecdotal evidence of students working with introductory system dynamics. To move forward, participants recognized the need to focus on three essentials: developing quality curriculum materials using system dynamics, developing good training programs for teachers, and building strategic alliances with others committed to learner-centered interdisciplinary education. The Essex group drew up a 25-year plan to implement the continued spread K-12 system dynamics with a proposed budget to support it.

Now, at the 50th anniversary of system dynamics in 2007, it is time to take stock again. We have asked several of the key players in K-12 SD over the years to reflect on their work and briefly summarize the history of their project, their current work, and their future plans, with the primary emphasis on lessons they have learned in the process. What obstacles surprised them, what worked best, what would they do differently, and what advice would they give to others facing the challenges of infusing system dynamics into K-12 education? Educators from the following schools and other organizations tell their stories:

1. The Creative Learning Exchange in Acton, MA: Lees Stuntz
2. Carlisle Public Schools, Carlisle, MA: Debra Lyneis
3. Catalina Foothills School District and Greater Tucson, AZ: Joan Yates and Tracy Benson
4. CC-STADUS, Portland Public High Schools, Portland, OR: Diana Fisher
5. Harvard Public Schools, Harvard, MA: Larry Weathers
6. Murdoch Middle School at Innovation Academy, Chelmsford, MA: Greg Orpen
7. Portland Waters Foundation Project, Portland, OR: Mary Scheetz and Tim Tabor
8. CIESD, Burlington, VT: Jeff Potash and John Heinbokel

1. The Creative Learning Exchange

Lees N. Stuntz, stuntzln@clexchange.org

CLE: History

The Creative Learning Exchange was founded in 1991 as a 501-C-3 organization to encourage the use of system dynamics and learner-centered learning in K-12 education. Jay Forrester secured funding for the CLE from another Concord, MA resident, John Bemis. That generous support (along with a booming stock market) has lasted through the sixteen years of the CLE's existence. The funding, along with infusions of other supporters, is likely to last another four to five years, unless the endowment is supplemented. The original board of trustees consisted of Jay Forrester, John Bemis, Barry Richmond, and Stephen Stuntz; George Richardson later replaced Barry Richmond on the board.

Over the past sixteen years, the CLE has gone from a mostly paper-based organization, sending out curricula and other materials via the postal system, to an almost exclusively web-based organization. The development of available materials has gone from accepting all offerings to formal submissions and review before acceptance for the website. With support of the Gordon Brown Fund and the services of Debra Lyneis as an editor, writer and coach, the CLE has published two books.

In 2001 the CLE hosted a gathering in Essex, Massachusetts, to discuss the future of system dynamics in K-12 education. Experienced teachers were joined by the CLE trustees and other system dynamicists to formulate a vision. That vision is still guiding and shaping our thoughts and actions six years later.

In 2005, the Educational Modeling Exchange joined the CLE to help create better curricula for dissemination as well as to support educators in their efforts to both create models and help teach students about modeling.

CLE: What is Happening Now?

The CLE has the following on-going activities:

1. CLE website: www.clexchange.org
2. K-12 curriculum materials to download for free, developed by teachers in their classrooms for students across all grade levels and disciplines, including documents on the *What* and *Why* of SD in K-12 education. The books *The Shape of Change* and *The Shape of Change, Stocks and Flows* (Quaden, *et al*, 2004, 2007*)* are published by the CLE.
3. *The CLExchange,* a free quarterly e-mail newsletter featuring new materials, updates from teachers in the field, upcoming events and resources (archived on the CLE website).
4. The Educational Modeling Exchange that provides assistance and direction for curricular and organizational innovation in system dynamics modeling.
5. The CLE biennial conference for educators.
6. The K-12 SD Listserv, a sporadic open e-mail discussion of education issues, technical SD questions, resources, etc.

7. DynamiQue*ST*, an exhibition and celebration of student work held each spring at WPI in Worcester, MA.

8. *Road Maps,* a guided self-study program in system dynamics developed at MIT under the direction of Professor Forrester.

9. A CD with all of the CLE materials, back issues of *CLExchange*, and more.

CLE: Lessons Learned

1. The most successful experiments to date were in situations where interested teachers were actively supported, not only with funding but also by a very supportive administration.
2. The use of ST/SD in the classroom has not been ingrained in any school to such a degree that it has become person-independent. At the moment it is not clear how to do that.
3. There is evidence that students who are exposed to the tools of ST/SD have an ability to think critically which helps them both express their thoughts more clearly and understand more complex problems. This ability needs to be documented.
4. Even the simplest of lessons for young children need to be based in good system dynamics practice. A formalized review process, as well as more teacher training, can help this happen.

CLE: Strategic Partnerships

1. On-going relationship with CIESD, Jeff Potash and John Heinbokel.
2. Helped found the SoL Education Partnership with Peter Senge and Linda Booth Sweeney in conjunction with the Cloud Institute for Sustainability Education.
3. Work with Oren Zuckerman and the MIT Media Lab on Flow Blocks technology.
4. Work with The Discovery Museums, Acton, MA in an on-going effort to incorporate the concepts of ST/SD into an experiential museum setting.

CLE: Going Forward

This is based on the 2001 Essex report modified by experience over the past six years:

1. Create curriculum on all levels of K-12 to aid teachers to implement systems thinking and system dynamics in their classroom.
2. Assess the critical thinking generated by ST/SD learning.
3. Create more strategic alliances with others who could or should be incorporating the tools and concepts of systems thinking and dynamics in their curricula. This may well mean making on-line curricula available to both students and teachers.
4. Train both teachers and administrators in the use of ST/SD tools and concepts to the point that they can infuse them with little effort in their work.
5. Create a set of goals for all K-12 students to become systems citizens, and the steps to get there.
6. Find funding so that our capacity to do the previous five items can be created.

2. Carlisle Public Schools

Debra Lyneis, lyneisd@clexchange.org

Carlisle: History

By 2004, system dynamics was taking hold in the K-8 curriculum and was becoming part of the school culture in Carlisle, MA. It had started a decade earlier with eighth grade math teacher Rob Quaden and it spread to other innovative teachers. With the help of systems mentors Quaden and Alan Ticotsky, classroom teachers developed lessons to complement their current curriculum in math, science, literature, and social studies. Eventually, every student in every grade had some system dynamics in their curriculum every year. By eighth grade, students could build simple models and transfer basic structures to new applications across subjects. Quaden and Ticotsky were developing a sequence age-appropriate system dynamics skills and lessons.

A combination of circumstances helped Carlisle surmount set-backs to get this far. First, Quaden and Ticotsky are skilled, innovative teachers respected by their colleagues. Their work as systems mentors was generously supported for many years by the Waters Foundation, affording them the time to learn, develop lessons and collaborate with others. Furthermore, system dynamics had the whole-hearted support of Superintendent Davida-Fox Melanson and her administration. She fostered a school culture of collaboration, risk-taking, continuous improvement, and above all, a focus on what was best for the children. After years of observing the benefits of system dynamics for students, she made it available to all students through professional development requirements for all teachers. System dynamics also had the support of the community. Debra Lyneis served on the school board and kept townspeople involved, and later, through the Creative Learning Exchange, she published many lessons developed in Carlisle. Finally, Jim Lyneis, a professional system dynamicist, was an invaluable resource. We all worked together because today's students need system dynamics skills and attitudes.

Carlisle: What is Happening Now?

In 2004, when Fox-Melanson retired for health reasons, a new superintendent brought a different set of priorities and management style to Carlisle. Unfortunately, at the same time, Waters Foundation retrenchment eliminated funding for the mentoring positions, so the systems program was dismantled. Quaden and Ticotsky returned to the classroom teaching middle school math, science and social studies. They continue to use system dynamics with their own students, as have a few other teachers, but an unusually high turnover in faculty and administrators has drained the stock of SD trained and committed teachers, causing a steady erosion in student skills as well. Also, new demands have left little time or support for collaboration on systems lessons.

Still, some good programs endure. For example, all eighth grade students will continue to use behavior over time graphs, stock/flow diagrams and causal loops to structure their interdisciplinary ecology research projects. This collaboration among all eighth grade teachers and their students will culminate in student presentations to the public at the annual EcoFair.

Carlisle: Lessons Learned

We learned that young students *can* learn the basics of system dynamics, and that system dynamics *can* enrich their educational experience by making it more learner-centered, engaging, cohesive and relevant. System dynamics works best under certain conditions: it complements the current curriculum, classroom teachers are involved in designing the lessons for their own students, every lesson includes hands-on experiential learning in teams, and students construct a solid understanding of the math underpinnings at their level. It is also important that lessons build on one another in small increments with lots of practice, so that students (and teachers) are not overwhelmed or misled. Finally, lessons must be based on good system dynamics practice.

We encountered two major hurdles to infusing system dynamics into K-12 education: first, learning system dynamics is hard, and, second, instituting *any* change in education is even harder. While students eagerly plunge into system dynamics, it is not so easy for many teachers because it requires time, math/computer facility, and a compelling reason to change the way they think, teach and work together. System dynamics is not another teaching tool that can be picked up at a workshop, nor is it just a software package. It is a broader and deeper problem-solving approach that is learner-centered, inquiry-based and constructivist. Teachers, therefore, not only need to learn and teach unfamiliar math and SD concepts, they also need to structure their teaching to foster learner-centered learning – daunting challenges requiring time, patience, support, and a strong desire for change.

Fortunately, innovative teachers are drawn to SD when they observe its benefits to students. In Carlisle, having systems mentors was a big help because classroom teachers could have on-going curriculum support and the chance to work with colleagues. Also, Quaden, Ticotsky and D. Lyneis worked through Road Maps together and relied on J. Lyneis for help with SD questions, but there is so much more to learn, and SD is not easy. Teachers are already pressed for time.

If we could have foreseen the limited time and resources available, we might have done things differently to address the difficulty for teachers learning SD. The principles of system dynamics unified the school experience for students by giving them interdisciplinary problem-solving skills embedded in a learner-centered, collaborative approach, but perhaps we moved too fast in trying to infuse system dynamics in too many places at first. Rather than reach out to all teachers, we should have invested all our resources in the innovative early adopters already inclined toward learner-centered teaching, built their SD skills, and developed a larger body of lessons for their students. It may have been better to focus on students in fourth grade and older rather than include the primary grades where teachers are necessarily consumed with basic literacy. We also might have focused on math and science lessons at first where the connection to the curriculum is most obvious and where teachers are more comfortable with graphs, equations and computers. Eventually, we could have slowly engaged more teachers (and outlasted the rest) as students' skills grew. We are impressed with the progress students and teachers made throughout the school. However, a more sustainable long-term strategy may have been to focus on quality system dynamics with the most receptive teachers and their students.

The second major hurdle is the difficulty implementing any change in schools. Infusing system dynamics into K-12 education starts with helping a few teachers adopt a few new lessons, but it does not spread further without the solid support of the school administration. A supportive administration can arrange schedules and resources for training and equipment, run interference against the inevitable obstacles to change, build community engagement, and, most important, provide leadership that encourages creative risk-taking, collaboration, and continuous improvement for the benefit of students and their future. We did not fully appreciate Fox-Melanson's pivotal role until she retired. Although we had tried to institutionalize our progress, and funds were available to continue limited mentoring positions without Waters support, we have been dismayed at how quickly our systems work could be extinguished throughout the school with a change in administrative priorities and the departure of just a few key people. For K-12 system dynamics, the lesson is to find administrators who value the principles of a learning organization and its synergy with system dynamics in the curriculum. It is humbling to remember that progress can be very fragile.

Carlisle: The Future

In Carlisle, Quaden and Ticotsky will continue to use system dynamics in their own classes. Quaden, Ticotsky and D. Lyneis will continue to write up the lessons developed in Carlisle so that they will not be lost, and Jim Lyneis will still offer SD support (although the Lyneises now live in Vermont and can no longer serve as Carlisle citizen champions). *The Shape of Change* (Quaden, *et al,* 2004) and *The Shape of Change: Stocks and Flows* (Quaden, *et al,* 2007) are two books of lessons. Quaden and Ticotsky will continue to encourage the systems emphasis of EcoFair and any other remaining initiatives, despite having very limited time or contact beyond their own classrooms now. Future plans remain uncertain.

For the future of K-12 SD, our experience tells us that it is important to continue building our own system dynamics skills so that we can provide students with a solid background for moving forward. A few teachers who understand system dynamics need to develop well-integrated, developmentally appropriate, easily adopted mini-lessons that enhance the current curriculum. That way, students could have quality curriculum materials while all teachers would not be faced with the challenge of learning system dynamics at once or, worse, developing misleading lessons based on partial understandings. We need to learn more SD ourselves, not so that we can teach advanced modeling to kids, but so that we can lay a good foundation for their eventual progress beyond us. It is also essential for students, teachers and administrators to work together in a spirit of cooperation, creative risk-taking, and learning from mistakes, because students will need that perspective and system dynamics problem-solving skills to deal with the dynamic complexity facing them.

3. Catalina Foothills School District and Greater Tucson, Arizona

Joan Yates, jyates@cfsd.k12.az.us and Tracy Benson, tsbenson@aol.com

Catalina: History

1. In approximately 1987, a local community member, MIT Professor Emeritus Gordon Brown, explained the role he thought System Dynamics (SD) and STELLA software could have in K-8 schooling to the CFSD superintendent and then to an Orange Grove Middle School (OGMS) science teacher, who ran with the idea, bringing colleagues on board over time. Shortly thereafter, a privately-funded grant from the Waters Foundation (WF) afforded the school district the opportunity to have a SD mentor to create computer simulations to be used in classes with students. That first mentor, and a

cadre of future WF-funded mentors in the ensuing almost 20 years, also conducted workshops to teach the concepts and tools of SD to other staff members.

2. Once staff members read Senge's newly published *The Fifth Discipline (*Senge, 1990), they combined the concepts and tools of Systems Thinking (ST) within the organization and classroom with their work of incorporating the concepts and tools of SD as learning methodologies in the classroom.
3. The applications of ST/SD in the classroom and organization spread from OGMS throughout the school district, to the greater Tucson area, and to sites throughout the country. The WF has supported the sustainability of this field for many years by having mentors and/or teachers at WF sites write up how they've used ST/SD in their work for inclusion on various websites.
4. Once we knew, through action research results (see: www.watersfoundation.org) and direct student and staff input, that ST/SD was a highly effective way for students to learn and organizations to improve their effectiveness, the focus changed from directly mentoring in classrooms to making the work available to as many students, most likely through their teachers, as possible. This involves training school district personnel (teachers, administrators, librarians, etc.) "in-person" (vs. electronically), making resources available through the internet, and embedding the work within district-adopted curriculum and practices. All three of these dissemination practices continue today in CFSD and Greater Tucson.

Catalina: What is Happening Now?

1. Visitations and planning for a possible Dutch teacher exchange in SY 2007-08
2. Two Level I (28 hour) training opportunities offered in the summer, with school year follow-up
3. Level II modeling class offered during the school year
4. Very limited amount of coaching and assistance in classrooms, particularly as technical support with networked simulations
5. Intense work on a 9-module WebEd version of Level I training, in collaboration with Portland and Iowa colleagues
6. Teachers are documenting their ST/SD work; there will be paid time for writing this summer.
7. Consulting work with schools and school districts outside of Tucson
8. Alignment of ST/SD concepts and tools with Marzano's research-based instructional approaches through teacher training/professional development in systems analysis, decision making, problem solving, and non-linguistic representations
9. AZTEA workshop (Arizona Technology in Education Association)
10. CFSD teachers are explicitly embedding ST/SD concepts within new K-12 district curricular standards and benchmarks
11. Systems thinking has been included as one of twelve skills and attributes of 21st century learners which will be developed and assessed through an integration with core subjects in the CFSD educational program
12. In conjunction with the CLE/Kellogg foundation effort—working to complete the longitudinal study video project of former OGMS students

Catalina: Lessons Learned

We become increasingly surprised at the abilities of young children to comprehend complex and somewhat abstract concepts when using systems thinking/system dynamics tools. We are getting better at being able to figure out how best to introduce, teach, and utilize the tools for deep thinking within relevant curricular contexts.

1. Teachers who embrace a "thinking classroom culture" find success using ST/SD with all children, including those overcoming language barriers.
2. The visual nature of the ST/SD tools provide scaffolding for learners and help them organize and better communicate their thinking.
3. ST/SD training works best when follow-up includes discussions around student work.
4. ST/SD training works best when more than one staff member/site attends training so that subsequent in-school collaboration can occur.
5. When using ST/SD tools, young people (and adults) are able to transfer insights from one setting to novel, seemingly unrelated contexts (e.g. between subjects, curriculum-to-life issues)
6. There has to be someone at the school or district level committed enough to jump in and start doing the work, knowing it won't "be perfect" at the outset and that they may be criticized by ST/SD "professionals" and questioned by those within the school system who are not familiar with the ST/SD field of work. Once they get the learning and thinking results they'll inevitably get with students, though, the school system questions will subside and the external challenges from ST/SD professionals will become an academic exercise that can improve practice.
7. You're not alone. Take advantage of what's already been done and who else is out there doing this.
8. There are many doors through which to bring people into the room that is ST/SD: curriculum/content; teaching methodology/tools; computer modeling; organizational application; 21st century skills; etc. Find what's important to a person/in a system, and show them how ST/SD can help them deal with what's important, and they'll want to enter the room.
9. We still haven't found the ways to make ST/SD accessible to large numbers of educators and, therefore, their students.

Catalina: Strategic Partnerships

1. The Waters Foundation
2. Partnership with the Pima County School Superintendent's Office and the Pima County Regional Support Center
3. Partnership with a Pima County Title 2-A grant involving the incorporation of ST/SD strategies into the research-based best practices of Marzano and Pickering
4. Partnership with Dr. Chris Johnson, retired Univ. of AZ professor in educational technology and current president of AZTEA, for consulting work on WebED
5. Partnership for 21st Century Learning Skills
6. The Metiri Group

Catalina: Going Forward

In Tucson we continue to investigate ways to provide training and opportunities for collaborative follow-up. Teachers who initially show great interest and promise tend to go dormant if that collaboration is sparse.

1. In CFSD, we're headed to a model of embedding the concepts explicitly into curriculum that is assessed. We'll need a way for people to continue to be trained in the SD methodologies.
2. WebEd is a project that is full steam and we hope to have a prototype complete by November, 2007. The Waters Foundation supports this work financially.
3. ST/SD applied to leadership is a topic that seems to be generating increased interest. Continued effort is needed to develop and refine the Level I-type work that is currently being done with school and district leaders.

Resources needed

1. Technology for Tucson schools
2. Greater effort to align all of the wonderful ST/SD work that is being done around the world to build momentum for influence, i.e. create a tipping point.

4. CC-STADUS/CC-SUSTAIN Project

Diana M. Fisher, Dfisher25@verizon.net; Ron Zaraza, Tim Joy, and Scott Guthrie

CC_STADUS: History

Three years after observing the use of STELLA software in a workshop, Diana Fisher, a high school math teacher, was awarded a National Science Foundation grant (Cross-Curricular Systems Thinking and Dynamics Using STELLA - CC-STADUS, 1993) that became Portland Public Schools' first NSF venture into the cross-discipline training of math, science, and social science teachers to design and implement model building activities using STELLA in their classrooms. Ron Zaraza, a physics teacher, Tim Joy, an English teacher, and Scott Guthrie, a science teacher, became part of the teacher-training team. The focus of the project was to keep the topics/teams cross-discipline, hands-on, and directly connected to the classroom. Ed Gallaher, Jeff Potash, John Heinbokel, Andrew Jonca, George Richardson, Barry Richmond and Steve Peterson gave valuable guidance and workshops. The NSF "train the trainers" methodology worked reasonably well. The three-year grant was designated an exemplary project by NSF and extended for a fourth year. A second grant proposal (Cross Curricular Systems Using STELLA: Training and Inservice - CC-SUSTAIN) was awarded in 1997 and extended a fourth year to sustain the use of the model building classroom activities. In all, between 200 and 250 high school and middle school teachers from all over the United States, participated in the three-week summer workshops over the eight years of the two grants.

CC-STADUS: What's Happening Now?

It has been six years since our last training and we have lost contact with our participants. As for the core team, Diana Fisher continues to use STELLA models in all of her math classes (second year algebra, pre-calculus, and calculus) at Wilson High School in Portland where she also teaches a course in Modeling Dynamic Systems. She published two books *Lessons in Mathematics: A Dynamic Approach* (Fisher, 2001) and *Modeling Dynamic Systems* (Fisher, 2005). Ron Zaraza is currently on a leave of absence, but has been working for the past few years developing a set of lessons using STELLA in environmental science and physics. Tim Joy is now an academic vice principle at De LaSalle North High School where time and school finances prohibit him from developing systems thinking and modeling curriculum. Scott Guthrie continues to use STELLA models in his science classes and his "Science, Technology and Society/World Issues" course at Wilson High School.

At Franklin High School, where Diana Fisher started the modeling program 16 years ago, the three most experienced teachers who taught modeling have left, and the fourth teacher has shifted her focus to more traditional statistics. Of the teachers who left, one uses modeling occasionally in her classes, and Fisher uses modeling extensively. So, there is no trace of the system dynamics that once was part of Franklin's curriculum. At La Salle High School where Tim Joy started a modeling program, there also remains no trace. At De LaSalle North High School, Joy taught a systems course for a few years until school finances required deleting it. Public school budgets in Oregon have been reduced every year since Ballot Measure 5 (property tax cap) passed in 1995. With reduced budgets, many elective courses were eliminated.

CC-STADUS: Lessons Learned

During the grant period:

1. Direct access to changing classroom activities always goes through the teacher. If you can't win the teacher over, it won't happen in the classroom. However, administrative support is extremely helpful in fomenting change, if you can get it.
2. Teachers relate most to lessons when they see direct, immediate application to their classes.
3. Teachers learn best from (and are more willing to listen to) instructors who speak the language of their discipline and understand the dynamics of the classroom. It is best to have instructors who are classroom teachers and materials developed by classroom teachers that relate directly to a participant's discipline area.
4. Training for teachers is optimal in the summer and for no more than about 2 weeks duration if the participants have to travel from a remote location and reside in the local area during the training, especially for women teachers with young families.
5. Teachers need well-designed curriculum materials (with suggested answers), appropriate to their discipline area, when trying to incorporate new methods of instruction in their classrooms. It is too time consuming for most teachers to try to develop their own materials during the school year. However, curriculum development during the summer is often a welcomed activity, if financial support is provided.
6. Teachers need person-to-person support (mentoring) during the school year to implement new teaching strategies. When we were able to provide mentoring, teachers progressed well. When we were not able to provide it, many efforts to implement modeling fizzled early.

After the grant period:

1. It is necessary to educate every new administrator on the value of a system dynamics approach so they will be less inclined to cut these elective courses with budget cuts.
2. It is necessary to educate every new counselor so that students are encouraged to consider these courses when forecasting for new classes.

3. Every opportunity to show student work to parents, administrators, business people, and professors should be taken. Schools often have days to promote their activities (parents of middle school students, school fairs for transfer students, science fairs, etc.) The system dynamics work students do speaks volumes.
4. For system dynamics modeling and systems thinking activities to survive in a school system, they must become an integral part of courses that are already part of the core curriculum.
5. The "No Child Left Behind" and "Adequate Yearly Progress" pressures on public schools have kept teachers from adopting new techniques that are not part of district-approved materials for specific basic skills assessment. Many innovative curriculum ideas have been lost over the past seven years.

Other lessons/observations:

1. Not all teachers have to become system dynamics modelers to provide useful and stimulating systems thinking activities in the classroom.
2. Teachers must get more formal training in system dynamics if they want to become serious system dynamics modelers. Until teachers take system dynamics modeling courses, either as part of their discipline undergraduate work or in teacher training, we will not have the requisite knowledge to teach system dynamics correctly. We may find very good, useful applications of the software (STELLA, Vensim, etc) in our classes, but it will not substitute for a thorough understanding of the standard system dynamics method. We must find ways to make courses (such as those at WPI) available during the summer for interested teachers.
3. We currently do not have sufficient discipline-specific curricular materials (using correct SD methodology) for middle or high school teachers to use. This is a serious deficiency and roadblock beyond which we cannot grow our SD-user teacher base.
4. Discipline-specific curricular materials should focus on concepts that are fundamental to a discipline, regardless of the text used to teach the course. The materials should be developed with teachers who actually teach the course so placement of the SD activities/exercises and lead-up/follow-up activities/discussions would be natural for most teachers. There should be "hooks" in these materials to other disciplines that allow for development of "better questions" and foster students' ability to see interconnections.
5. The story aspect of system dynamics cannot be minimized. So long as SD remains the province of mathematics and the hard sciences (biology, chemistry, physics) it will not flourish as it must as a social science. The methods and pattern of thinking inherent in closed-loop dynamics MUST be part of the mainstream, and it won't be in the current instructional (math/hard-science) mode.
6. We need games and simulations similar to Fish Banks in a few key areas: population studies, resource simulations, and health (every student in the United States takes health classes). Fish Banks teaches slowly and seductively - one's natural inclinations lead to ruin. The Fish Banks simulation-STELLA model combo was a huge way to show the efficacy of SD.
7. Software for some remains a roadblock. While Forrester's simple iconography is elegant and sufficient, it does not speak to this and future generations of students who routinely play PS2's or Nintendo DS's. If (this is a risky "if" but still a plausible one) it is in gaming that students learn, then SD software engineers will need to devise more powerful

software that allows students to simulate their ideas more engagingly than a few lines climbing and falling on a graph. Students will ALWAYS need to distinguish a stock from a flow, but, software has to move beyond bathtubs, pipes, and wires (perhaps a gaming layer).

CC-STADUS: Going Forward

Diana Fisher is taking system dynamics courses through WPI and hopes to become involved in teacher training after retiring from teaching in a few years. She also wants to continue to write materials in conjunction with high school teachers. She has a strategic partnership with isee systems which allows her to attend the ISDC and a few other conferences each year. Isee Systems publishes her two system dynamics modeling books.

Ron Zaraza will be retiring at the end of this school year, for health reasons. His plans are in flux as he focuses on regaining his health.

Time and resources permitting, Tim Joy would like to write curricula: a series of SMALL BITS any teacher in any discipline might use as either warm-ups or for whole class sessions, similar to the material in the Systems Thinking Playbook; LONGER LESSONS that explore the stories inherent in each discipline (relationships in biology, population change and pressure in the social sciences, homeostasis in the human body, natural rhythms of weather, and watersheds in ecological studies, etc.). The payoff intellectually in system dynamics comes from closed-loop, dynamic thinking, the kind of thing that stories deliver routinely and which people expect from stories; it is for this reason that only stories can carry system dynamics to the mainstream. Also, Joy would like to teach prospective teachers. SD is not easily learned from reading; therefore, students must encounter SD experientially and in the flow of a well understood story.

Scott Guthrie continues working on his modeling skills informally, developing class lessons, reading SD resources, and maintaining membership in the SD community. He would like to do more coursework in SD (having enjoyed Road Maps) but, as he teaches full time, he is pressed for time. (He wishes that isee Systems and Ventana would add tablet pc functionality to their SD software.)

5. Harvard Public Schools

Larry Weathers, larry.weathers@verizon.net

Harvard: History

The Harvard School District Systems Thinking/Dynamic Modeling venture started in Harvard, Massachusetts in the early 1990s. A community member, Dessa Dancy, and high school physics teacher Larry Weathers were on the steering committee of Educators for Social Responsibility. In that capacity, we were introduced to STELLA software and glimpsed its potential as a technology tool that promoted open-ended discussion and clarification of thinking about tough, controversial topics. Weathers had tried the software and was exploring possibilities in physics classes.

Shortly after that, the Waters Foundation, under the direction of Mary Scheetz, offered to help fund ongoing exploration of these ideas in the classroom. The Waters Foundation continued to develop partnerships with Harvard Public Schools and other school districts around the country. Through the generous support of Jim and Faith Waters, both financially and intellectually, the research on using ST/DM tools and techniques in the classroom flourished and evolved into teacher training modules and curriculum development efforts of significant magnitude and expense. The fortunate geographical location and affiliation with ST/DM experts such as Jay Forester and Peter Senge in the region gave us robust opportunities to interact with and be tutored by nationally acclaimed experts in the field. The CLE gave us space and organizational opportunities to interact with other local schools involved in similar work. These efforts propelled our involvement to higher and higher levels of involvement and understanding of how to facilitate the use of these extraordinary instructional tools in classrooms.

Harvard: What's Happening Now?

Eventually, financial backing was not as available, not for lack of support as much as for externally imposed financial limitations. In 2004, the official Waters Foundation project in Harvard came to an end. It then became the goal of some of the individual teachers in the project to continue the work they started, exploring the use of ST/DM in their new careers in teaching, administration and other walks of life. Project-initiated activities continue to this day in many of the classrooms in Harvard. Lack of a coordinated project there makes measuring the ongoing involvement difficult, though.

Weathers is now Science Director for another local school district in Belmont, MA. He has continued to implement some of the activities originally developed in Harvard into some of the classrooms of eager teachers in Belmont. Activities tend to be those that naturally fit into the present curriculum structure. Progress is slower without the coordinated effort of a dedicated project.

Harvard: Lessons Learned

1. Start with those eager professionals interested in being innovative.
2. Work toward, and maintain support of local leadership.
3. Directly show the significant learning gains made by students publicly and often.
4. Put significant effort along the way into documenting progress and ideas.
5. Focus on infusion of ST/DM by tying concepts to current standards, expectations and curricula, as opposed to stand-alone efforts.
6. Develop significant support structures for individuals to start, but which can gradually be withdrawn to encourage independence.

Harvard: Going Forward

Recently, in concert with a local educational collaborative, EDCO, a grant was applied for and received which may aid the process of bringing critical thinking technology tools to the member school districts. There is good potential that this will include at least some aspects of ST/DM in its cast of players.

6. Murdoch Middle School

Greg Orpen, gorpen@murdochschool.org

Murdoch: History

In 1996 a group of parent advocates in the town of Chelmsford, Massachusetts won approval to open a charter school (originally named the "Chelmsford Public Charter School", later renamed "Murdoch Middle School" after a late founding parent) serving grades 5-8. Use of system dynamics was included in our school's charter as means to help deepen student understanding, particularly in the fields of science and social studies. Systems tools have not only helped focus and engage learning in the classroom, but they have also been used by staff to address broader topics facing our school. Murdoch Middle School was a by the Waters Foundation from 1998 until 2005. This organization not only provided financial support for a part-time mentor, but also allowed Murdoch staff members to attend conferences and other professional development events. In addition to staff development, Murdoch students have also shared their work and ideas as annual participants in DynamiQuest.

Murdoch: What's Happening Now?

Systems thinking tools continue to be used in classrooms, though the depth and frequency still tends to be a function of the experience of the classroom teachers. Teachers are using more "pencil and paper" tools such as BOTGs, connection circles, and stock/flow maps. Creating computer models continues to be a skill that works best for older students (Grade 8), while younger students seem to benefit most from using simulations to test their ideas. One exciting development at our Murdoch is that in the fall of 2007 we will begin expanding our school one grade at a time to eventually become a 5-12 school. Because we will be working with older students, our school can continue to develop "systems thinkers" beyond the eighth grade.

Murdoch: Lessons Learned

One of the biggest challenges that our school has faced with regards to systems thinking is creating the time and space to use these tools everyday. Much of this challenge comes from external constraints: teachers are obliged to "cover" a wide range of topics in the curriculum and staff members often have a long list of required meetings/responsibilities. Developing systems thinking skills and habits of mind takes a long time, even with close mentoring and professional development. The most effective way to combat these constraints has been access to clearly written lessons/units that are engaging to both students and teachers. Having these experiences leads teachers to want to do explore other ways to use systems tools and helps students apply these skills to other domains.

The most effective partnerships have really been other teachers. Murdoch has been very fortunate to be located near two other former Waters Foundation sites. At one point, the Murdoch mentor would meet with mentors from Carlisle and Harvard (MA) every other month. These meetings were wonderful opportunities to discuss areas of success and difficulty. More recently, Lees Stuntz, Jeff Potash, and John Heinbokel helped with a unit to help students think more critically about how to prepare for a potential avian flu outbreak.

Murdoch: Moving Forward

The resources that schools need to develop systems thinking are not surprising: curriculum, money, and time.

Curriculum: This part seems to be the most important. Most lessons currently available through the CLE and WF websites are written for teachers with a fair amount of ST background. (An important exception to this would be the *Shape of Change* (Quaden, *et al*, 2004).) The challenge presented is not an easy one: how do you create really clear lessons that address fairly complex topics? Systems lessons should not be too easy, as that quickly becomes rote; they cannot be too complex, as that can be a very frustrating experience for teachers and students.

Money: Building a capacity to expand one's abilities and knowledge takes guidance from professionals in the field. Registration fees for national conferences and modeling workshops are simply too expensive for schools to afford. Moreover, software is increasingly expensive.

Time: This would definitely rank as number three on the list. Access to the first two resources would greatly diminish this need; however time for teachers and students from different schools to collaborate is an amazing experience.

7. Portland Waters Project

Mary Scheetz and Tim Tabor, ttaber@pps.k12.or.us

Portland Waters Project: Summary

The vision of the Portland, Oregon Waters Foundation Project - Systems Thinking in Schools, is to deliver academic and lifetime benefits to students through the effective application of systems thinking concepts, habits, and tools in classroom instruction and school improvement.

Our mission is to increase the capacity of educators to deliver student academic and lifetime benefits through the effective application of systems thinking concepts, habits and tools in classroom instruction and school improvement.

The strategies that are employed are Development, which includes informing, training and sustaining educators as they become aware of the possibilities of systems thinking and utilize it in their work place; Dissemination of what we do and have learned through our website, publications and conferences; Research, through the support of both action and quantitative research.

The early structure of the Portland Project focused on teacher mentors developing the capacity of interested educators to utilize systems thinking concepts and tools in their work, be it in the classroom or at administrative level. Through workshops and access to leaders in the field of education (Art Costa, Bena Kallick, Michael Fullen, etc.) as well as providing individual mentoring, the project was able to establish pockets of educators in the Portland area using systems thinking. In 2002 a standard, 30-hour Level One training was developed. The initial 20 hours of the training explores and practices concepts, habits and tools of systems thinking through proven activities that are commonly used in the classroom. The remaining time is spent with educators finding connections to their existing curriculum or in the case of administrators, within their organization, and collaborating with others in the development of plans for implementation.

A 30-hour Level Two Training was developed to support teachers practicing in the field. These training are offered in 3 different categories: classroom applications, organizational applications and computer modeling. The meetings were generally held once a month as an opportunity for participants to learn new skills, practice old ones and share, collaborate and plan with others, creating a support system for teachers practicing systems. Both Level one and Level 2 continued to be offered.

Portland Waters Project: Lessons Learned

In 2000, Action Research was brought into the mix to look at the impact systems thinking was having on education. Over a 5-year period, trained educators practicing in the field have reported through action research projects observing the following trends: (for more information see: www.watersfoundation.org/index.cfm?fuseaction=content.display&id=143)

1. Students use systems thinking tools to clarify and visually represent their understanding of complex systems. This visual approach allows the students and others to interact with and explore thoughts, perceptions, and mental models with precision and clarity.
    - Connection circles and causal loop diagrams help students describe their understanding of the connections and interdependencies of complex systems including historical systems, scientific systems, economic systems, cultural systems, political systems, and literary systems, both fiction and nonfiction.
2. Systems thinking tools help students make connections between curricular areas and relevant life experiences.
    - When students use systems thinking concepts and tools, teachers have noted an increased number of incidences of transfer from classroom lessons to students' real-life experiences.
3. Students of all ages learn and independently use systems thinking problem-solving strategies.
    - Students experienced in recognizing and using systems thinking concepts and tools seek out new and varied perspectives when solving problems.
4. Systems thinking concepts and tools help students develop as readers and writers.
5. When students use the concepts and tools of systems thinking, they are better able to:
    - retell and summarize a piece of writing
    - analyze character, plot, setting and theme and the relationships between these literary components
    - identify point of view and the author's/characters' mental models
    - describe cause and effect relationships
    - express themselves descriptively.
6. When using systems thinking concepts and tools, many students show increased motivation, engagement, and self-esteem.
    - When using systems thinking tools as a prewriting strategy, students who had been producing below-average writing wrote more (quantity) and developed more thoughtful, insightful content (quality) than they had previously.

In 2006 the Portland Project provided support to quantitative research done by Richard Plate as part of his doctoral dissertation. (Plate, 2006) The research focused on the effect that systems-oriented instruction has on students' ability to understand a complex environmental system. Using cognitive mapping exercises in which the participants read a brief article about a hypothetical fishery controversy involving ecological, economic, and social processes and then expressed associations and causal connections between key aspects of the situation (as identified by each participant). By converting these maps to matrices, he was able to show quantitatively that the students who had received systems training were more likely to be aware of ecological and social aspects of the fishery described and included a higher level of non-linear causality in their mental maps of the issue. In addition, experts, including systems ecologists, an ecological modeler, and a fisheries specialist went through the same exercise. Comparison of these expert maps to the participant maps showed that the students who had received systems-based instruction created causal maps that were more similar to the expert maps than were the control group's maps.

The 2006-2007 school year saw the launch of the International Learning Community Project. Working with the groups Consent Consulting & Baco Training and Education from the Netherlands, a group of 13 educators, from the Netherlands, involved with systems thinking came to Portland for a week in October. They were hosted by teachers from Portland and worked side by side in classrooms. The following March the educators from Portland went to the Netherlands to work and learn with their counterparts.

Portland Waters Project: Going Forward

Our focus has moved away from face-to-face mentoring in the classroom to training. Live workshops as well as training and support are offered throughout the year and through the website. The Waters Foundation website has existed for the past 7 years and provided a way to introduce systems as well as be a tool for educators after training (www.watersfoundation.org). We are continuing the development of the website. One project spearheaded by the Tucson group will be a series of learning modules; the initial modules will be based on our Level One training. It will be designed for multiple audiences – people with no experience explore a self-paced learning environment about systems thinking or people that have been practicing in the field and want to refresh their memory concerning a concept, habit or tool will be able to enter the modules at whatever point they wish. The big question facing the project as we go forward is: how do we increase our capacity to be able to train the increasing number of people that we believe will be seeking training?

8. CIESD

John Heinbokel, jheinbokel@ciesd.org, and Jeff Potash, jpotash@ciesd.org

CIESD: History

The Center for Interdisciplinary Excellence in System Dynamics, LLP (CIESD) began as The Waters Center for System Dynamics (WC) at Trinity College of Vermont. Charged by its funders, Jim and Faith Waters (Waters Foundation), to utilize system dynamics (SD) to support innovation across the broad educational community, the WC developed curricular materials (largely simulation based), training programs (in both conceptual and simulation modeling), and training software (e.g. DemoDozen and MSST) for a wide spectrum of K-G students and educators (both classroom teachers and building and district administrators).

With Trinity's closure in 2000, WC transitioned into CIESD, a consulting partnership retaining a strong, but not exclusive, focus on educational outreach. During CIESD's first four years (2001 – 2005), its primary educational effort was to direct the Center for System Dynamics at the Vermont Commons School (VCS; a small, private, grades 7-12 college preparatory school with a focus on the local social and natural environment, i.e. "the commons"). The Head of VCS has spoken of SD as representing a set of analytical and communication skills that are critical for students' success in the 21st Century and committed VCS to implementing that vision. CIESD's efforts included contributing SD applications to the existing curriculum, providing SD training and support for other faculty, and taking primary responsibility for a set of "Research & Service" and elective courses that utilized SD. Since 2005, VCS has continued supporting the use of SD broadly, especially in the social and natural science, and has begun an ambitious collaborative program (the "Commons Project") with educators and students in Nanjing, China.

In addition to our collaboration with VCS, CIESD has engaged in K-12 organizational or administrative modeling projects, initially exploring a public school board's vision of "academic quality" and, more substantively in Minnesota, developing a "flight simulator" that exposed and explored the dynamic balances between educational needs and educational resources that define the operation of all schools or school districts. That latter project was a collaboration of CIESD with the Transforming Schools Consortium, directed by Dr. Ralph Brauer.

CIESD: What's Happening Now?

More recently CIESD formalized a long-standing association with the Creative Learning Exchange (CLE) with the formation of the Educational Modeling Exchange (EME). EME has a three-fold purpose: to assist in building classroom and organizational tools; provide training; and seek outside funding for larger-scale projects. Collaboration between CLE, the Society for Organizational Learning, and the Cloud Institute for Sustainability Education, has also been ongoing to identify and support systems thinking and dynamic modeling projects in school/community settings around the globe. In addition to CLE/EME activities, CIESD's educational outreach includes work with watershed education projects in Minnesota and India (funding pending in both cases), school-based asthma education and intervention program in Louisville, KY, and dynamic modeling training in Texas and Vermont.

CIESD: Lessons Learned

Like most educators who have continued to actively use and advocate Systems Thinking and Dynamic Modeling applications, we have seen, and can relate anecdotally, stories of enhanced student engagement; growth in critical thinking; problem-solving empowerment; and gratifying learning achievements, often by special needs students for whom traditional classroom approaches have limited utility. We made a number of fundamental mistakes along the way, however. Perhaps most serious was an excessive focus on computer simulations. Having less skill in the conceptual mapping tools of causal-loop diagrams or behavior-over-time-graphs as preludes to modeling, we tended to ignore those pieces of the SD puzzle that we have since come to appreciate as essential to and supportive of the whole. We also assumed that K-12 teachers would be so enamored of the potential of computer modeling that introductory workshops that focused on technical modeling skills would provide the foundation and incentive for those teachers to go out and immediately begin creating and utilizing powerful simulations with their students. The learning curve is too steep, time too short, and other demands on teachers' time too extensive, for that to have been a realistic approach.

The rewards we experienced have kept us working with and revising our approaches for better results. There ARE benefits to this approach and they are deep in meaning for individual students and specific applications and broad in terms of the range of subjects and students for whom such approaches are beneficial. We can make similar arguments in terms of organizational or administrative applications of these SD tools.

With those strongly perceived successes, the apparently slow growth or spread of SD into wider application has been puzzling and frustrating. We sense, as did most of the educators who participated in a week-long retreat in Essex, MA in 2001 that such slow growth is reflective of a combination of the limited materials available for dissemination, the specific performance expectation placed on public school systems, and the nature of innovation diffusion into the educational community. Except among the relatively small group of "innovators" who have developed and utilized SD-based approaches, there is an understandable reluctance to devote significant energy to weakly documented approaches to meeting educational goals (critical thinking; problem solving; inter- or multi-disciplinary connections) for which our current standardized test-based assessments of classroom or school quality offer little reward. Our experience continues to support the conclusions of the Essex Report (Lyneis, 2002), that spread of SD in the educational system beyond this small cadre of innovators will require strategies that minimize the up-front costs in time and energy by the educators (effective and efficient training and readily adaptable prepared materials) and that maximize SD's contribution to meeting the currently mandated (and measured) educational outcomes.

Three innovative projects that profited from the lessons of our mistakes may be informative:

1. WC: To provide SD training for educators in the Chittenden East School District (a Waters Foundation program directed by Will Costello), we consciously chose a) not to teach SD *per se* but to use SD to support interdisciplinary learning, critical thinking, and problem-solving in a variety of content-based courses (e.g. Plagues and People, Structures of Revolution, Sustainable Development), and we b) included, along with middle-school and high-school teachers, groups of high school students and interested community members who collectively constituted fascinating communities of learners.
2. CIESD: While at VCS we were successful in reaching out to parents by including them in SD-based exercises utilized to support our learning goals for their children. That outreach included evening sessions focused on commercial fishing, using our own computer simulation, and an exploration of community strategies in the face of a hypothesized outbreak of influenza for which we had inadequate supplies of vaccine.
3. CIESD: Also at VCS, as a novel way to engage the students, we presented ourselves as SD consultants in guiding a "group model building" project to explore two issues of particular concern to them: one concerned with physiological and psychological dependencies associated with underage drinking, the other focused on issues of time-management.

CIESD: Going Forward

Remaining engaged with the K-12 community is one of CIESD's greatest desires, but two primary barriers restrict the time we can devote to that and the benefit that that time can realize. First, there seems to be little reward for educators to seek out and develop innovative and effective ways to accomplish high-level, collaborative, self-directed, problem-solving, interdisciplinary learning on the part of their students whether or not that directly involves SD. "What is measured is what is valued," and, despite language in state standards and frameworks that advocates for such learning, the standardized tests that constitute the true public measure of educational success do not typically address those higher-level learning objectives. We need to find tools and directions to allow us to bring the benefits of SD in 'under the radar' and have it visibly contribute to, or at least not distract from, those test-based aspirations. Reinforced by that focus on test results is an unwillingness to commit the time and invest the financial resources needed for SD-competent educators to create the curricular materials and training opportunities needed for growth in these SD applications. Without that focused and effective outreach to new educators, the current crop of SD innovators have little opportunity to bring new participants into the fold, create effective applications, or create of such powerful educational opportunities, That suggestion of a reinforcing loop makes a depressing story when it operates in its 'death spiral' mode. On the other hand, if it can once be turned around, such a reinforcing loop creates powerful growth dynamics. What's the policy that will allow that fundamental and crucial change of direction?

Conclusions: What Have We Learned?

Without a doubt, all of the innovative pioneers represented here would agree that infusing system dynamics into K-12 education has been an enriching experience for them and, especially, for their students. Teachers are always impressed by the depth of understanding that students can achieve when they are engaged in viewing problems through a system dynamics perspective. Anecdotal evidence shows us that system dynamics can "offer a framework for giving cohesion, meaning, and motivation to education at all levels from kindergarten upward" (Forrester, 1992, 1), as Forrester foresaw fifteen years ago.

However, although we have all been encouraged and inspired by student performance using system dynamics/systems thinking in some classrooms and by the benefits of learning organization principles in some schools, we have not yet seen widespread adoption of system dynamics in the curriculum or culture of schools. In fact, there may be less system dynamics in these schools now than there was when the Essex meeting convened in 2001. Unfortunately, most of the programs described (and several others not represented here) have not been able to maintain initial momentum after major outside funding ended. Why is that? What can we learn from our experience so that we can continue to fulfill the promise of system dynamics in education and provide students with the skills and perspective they will need?

Certainly the obstacles to implementing change have been more formidable than any of us expected. K-12 education is a large institution with built-in resistance to change. Because teachers are most comfortable teaching what they themselves were taught, usually in a teacher-centered way, system dynamics and learner-centered learning are not always easy to embrace.

When schools are challenged by the public to improve their performance, they naturally redouble policies and practices that seemed to work in the past, like the current No Child Left Behind emphasis on rote "basics skills" testing. As several of the educators reported, this testing program leaves no time, energy or money for innovation beyond what is tested. Therefore, K-12 SD will not spread just because it is a great idea for students. To succeed, K-12 SD will need to find better ways to work within the system to slowly change it, such as by designing curriculum materials that help students meet the testing standards (until such time as the testing movement proves that redoubling current policies cannot effect fundamental improvement in schools, allowing other models to rise).

Many institutional obstacles lay outside our control, but as systems thinkers we also need to look at how our own policies may have shaped our progress and hindered our success. Some clues come from the cautionary advice Forrester gave in his 1992 paper and in our own assessments at the Essex meeting. Some of the issues facing K-12 system dynamics reflect concerns in the broader system dynamics community as well.

For example, we struggle with how best to integrate system dynamics modeling skills with the broader systems thinking tools. Some of the schools represented here have focused almost exclusively on computer modeling, while others have focused more on using systems thinking tools that do not involve simulation. In both cases, teachers have been impressed with their students' creative insight into problems. In 1994 Forrester said, "I believe that confining student learning to systems thinking and to discussion about systems will convey very little understanding of the nature and behavior of the systems in which we live (Forrester, 1994, 20)." But, as all the programs reported, learning to build computer models can be difficult for teachers and requires considerable time, support and perseverance. As Forrester noted, students will not build the knowledge of complex systems necessary to competently address complex social, environmental and economic problems without learning the principles of system dynamics and practicing with simulations. But how do we get them there? Experience has shown that systems thinking tools are easily accessible, and they open minds to exciting new ways of seeing things. Is there a way to harness that enthusiasm to lead teachers and students into more rigorous system dynamics? This is a worthy challenge that we have not yet met. It will require working together to combine the lessons learned in both model-building and systems thinking approaches to give students the full benefit of both – because they will need it.

A related issue concerns the purpose of system dynamics in education. Is it a set of systems thinking or simulation tools for representing and understanding elements of the current curriculum? Is it a learner-centered teaching approach aligned with other promising education innovations? Is it a set of principles that shapes school organization, culture and management? Forrester would say that it is all three. Our educators would all agree, although each program has come to emphasize them differently, sometimes exclusively. The goal now is to learn from each experiment and find ways to integrate all the objectives for their greatest impact, lest programs diverge further.

Another big challenge facing K-12 SD is maintaining the quality of the work. Forrester cautioned educators to hold high standards because "erroneous concepts" can easily creep into a systems education and undermine its credibility and acceptance (Forrester, 1992, 18). In the early days of K-12 SD when no teachers had any system dynamics background and there were no other options, we relied on short occasional workshops for training. While that was a good start, it inadvertently planted misunderstandings because system dynamics is a very big idea that cannot be fully conveyed so briefly. Unfortunately, because we still do not have better system dynamics training options for teachers, our level of system dynamics understanding remains, for the most part, at the very beginning introductory levels – elevating that risk of erroneous concepts creeping into our work. We recognized this dilemma at the Essex meeting by making better training opportunities our highest priority. Unfortunately, accomplishing that goal has been elusive due to time, money, and limited system dynamics background constraints. Several of the authors suggest the need to move forward with improved system dynamics training. Not every teacher needs to study system dynamics in depth, but a few should in order to guide the rest, so that students can eventually learn more too.

Related to training is the need to develop quality curriculum materials, an equally high priority in the Essex report. Every educator stressed this need. We have found that it is a lot to expect teachers to learn system dynamics and develop their own classroom materials. Teachers should always be directly involved in creating curriculum because they have the expertise to distill sophisticated concepts into effective age-appropriate lessons, but teachers with more system dynamics training working with professional system dynamicists as consultants should always be involved to ensure quality. As contributors noted, lessons should be well-integrated into the current curriculum to enhance its pedagogy, not to teach system dynamics as an end in itself. Lessons should be interdisciplinary and learner-centered. Again, systems thinking tools should be integrated into the lessons as bridges to better system dynamics understanding. In both training and curriculum development, it will be essential to set high standards, improve our quality, and guard against goal erosion.

To summarize a few common themes:

1. It is easier for students than teachers to learn new ideas. There is a steep learning curve; it takes a long time for adults to assimilate the paradigm shift that system dynamics engenders. Mentoring helps teachers learn and keep going.
2. Students easily and eagerly engage in system dynamics/systems thinking. Younger and younger students are able to grasp basic system dynamics concepts like behavior over time graphs and stocks and flows. While, fourth grade may be best age for early model-building, students at all ages easily make connections and transfer their understanding to other settings. Students are also our best ambassadors; their insights speak volumes.
3. Institutional change is difficult, but not impossible. Innovation diffusion works best when students, teachers and community members work together in teams. It is necessary to find ways to work within the system to change it by working with receptive, innovative teachers and their students.
4. There are many ripe places to infuse system dynamics and systems thinking into the current curriculum, especially through topics that are taught universally. Math and science are the easiest entrees, but the social sciences are equally important.
5. A vibrant synergy is created when system dynamics in the curriculum is supported by an administration that also values the principles of a learning organization.

Challenges and resources needed:

1. We need support for time to study, collaborate, and use SD/ST tools in the classroom and organization.
2. We need training at every level, beginning to advanced, conducted by instructors with classroom experience and strong system dynamics backgrounds.
3. We need sequential curriculum materials at all levels and in all subjects that are well-designed, well-integrated into the current curriculum, well-founded on system dynamics principles and easily adopted by teachers who do not have extensive systems training.
4. We need to formally assess the efficacy of our work to gain credibility in a standards-based system and to inform our own improvement and growth.

Looking back, we can take pride in the considerable accomplishments of K-12 system dynamics in spite of obstacles and set-backs. Forrester's early vision and the Essex recommendations are still relevant today as a guide for moving forward. Forrester's time frame encompasses "the next several decades;" thus, we have only just begun. Moving forward, we must work together and learn from our successes and mistakes "to sustain the hope and promise of a more effective education." (Forrester, 1992, 18)

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