Systems’ approach to Physics Education

Accepted 2nd May, 2018

ABSTRACT

Learning is training the brain to create. Systems are the brain’s playground – nature systems, human creation and mental constructs. The essence of learning is matching the keys to the secrets of systems to the characteristics of our brain. These are discussed, based on recent broadly published multiple brain researches, published novel physics education practices and ongoing experiences. As complexity of life staggers – education moves from rote memorizing encyclopedic knowledge and shear computing – to sorting information and solving complex problems.

Keywords: Learning, systems, physics laws, physics education.

INTRODUCTION

Learning has a purpose to enable the learner to successfully cope and strive in his environment. Pedagogy aims at effectively developing and preparing the student to meet the challenge. As the human wisdom has ever been a mystery, visible only through his explicit behavior, pedagogical ideas and methods span a broad range of theories and practices. This system is facing a revolutionary challenge now. The information and ubiquitous communication revolutions, concurrent with a tremendous technological development – create a whole new life environment. Technology relieves the student from rote learning of facts and procedures but challenges him with harnessing the exponentially increasing complexity to his benefit – in manipulating and in creating. Man, machine and complexity at large have never been closer before.

The culmination of advances in brain research, successes in machine learning (“Deep Learning”) that might hint to the human thinking processes – and the staggering need for expertise in resolving complexities in science, engineering and daily life, entices a research on the nature of the match between the complexity of systems and the human learning process. This approach is explored in the following. Seven topics are discussed:

1. Physics education – shift of focus from rule learning and exercising to system inquiries and modeling.
2. Machine learning and human learning – review of relevant characteristics of the brain as a “learning machine”.
5. Design of learning for expertise – the three axes of expertise: conceptual knowledge, experimentation and analysis tools, and competence for coping with complexity.
6. The new pedagogy – summarizing the pedagogy for developing expertise.
7. Programs in Israel – review of pioneering programs in Israel.

PHYSICS EDUCATION: SHIFT OF FOCUS

Modern physics constructs closed models, consistently interweaving towards a complete picture of the world. The modern science education, prevailing since the 19th century, is aimed at teaching the present state of knowledge – physics laws and their interaction. The language is the rigor language of the models, different from the daily spoken one in terms and their interpretation. The
purpose is learning the laws – the tools for analyzing and interpreting nature. These are the physics educational book and the training physics teachers obtain.

Students are sucked into the science world–abstract and compatible with mathematical formulation. They have to interweave this world into their umwelt, the world of their experience and emotions. The ensuing conflicts are called "misconceptions", and a major part of the curriculum is aimed at rooting them out.

Most of the physics laws are mental evolutions of observations and experimentations with phenomena and structures of nature. They are cognitive concepts whose validity and accuracy are tested by many peers' agreement on examples. Their accuracy and the validity of the representation are limited to the range of measurements and the environment of observations. This is typical to the academic and innovative engineering research.

These are two separate trails of physics: one continuously builds and strengthens an integrated rational fortress of generic models ("physics laws"), while the other conceives integrated models explaining authentic researched phenomena utilizing the physics laws as building blocks and seeking their balance in the model by guess, analogy, approximation and imagination. The higher the complexity of the phenomena, such is the iterative process of guess and test.

Technologies’ development during the past decades created an environment whose complexity grows exponentially along with the ubiquitous information accessibility. Computability, software flexibility and availability of digital subsystems - span a broad space of opportunities and creation of increasingly complex systems. This environment finds the graduate unprepared: his training is in building blocks ("laws"), while his engagement is in systems.

The education system is undergoing a change and seeks to redefine itself and its objectives. Data accumulation and computation-rich education needed for the developing technologies and occupation in an era when these could not be satisfied by machines and communication, now clear the way to creative problem solving and coping with complexity. Expert thinking is sought - the competence to quickly identify the scope and parameters of the problem and converge to its optimal solution. It is an intuitive process, partly cognitive, whose structure is yet to be fully unveiled (https://www.youtube.com/watch?v=aBEPxY7Elw, 2014).

**MACHINE LEARNING AND HUMAN LEARNING**

Machine learning was first developed by trying to imitate human neural networks as per observations of brain activity. It is a process of repeatedly reducing the error in identifying a pattern or an object by training on a myriad of examples. Deep learning, the acronym for its successful version, serves in all search machines in the internet, and its successful application in robot learning brings futurists to discuss implications of the coming superior robot intelligence. Recent interpretation in terms of information theory (https://youtu.be/ekUWO_pl2M8, 2017) identifies two parameters dominating the accuracy and rate of convergence: the number of examples used for calibration and the number of processing layers, that accrue relevance to the desired concise concept while discarding excess information.

The success of deep learning entices to inquire similarity to brain learning processes. Observations from deep learning showed:

1) The brain is the sentinel of self and its purpose is survival and breeding;
2) The brain interprets inputs from the body sensors by applying them to an umwelt, a "world picture" developed and stored from past experiences and their relevance to survival or opportunity (predator, pray and sex);
3) The sensors are not linear and sample space and time according to the threat or opportunity;
4) The brain processes and remembers feelings and activates emotions. Every fact in the memory is related to a feeling;
5) The brain reacts fast. It estimates – accurate enough for resolving between alternatives. It does not seek perfection;
6) The active memory is limited to 5 to 7 items, thus, limiting the cognitive processing;
7) The brain is energy-limited (oxygen supply, heat) and manages energy resources:
   - Motivation is a chemical trigger for action;
   - Filters and controls memory and its retrieval by chemical triggers;
8) The brain is slow and manages its sensor sampling patterns. Concentration and ultimately "flow", suppresses other sensors.

Consequences, according to deep learning indicate the following:

1) The brain as a learning machine processes a multivariate scene by sequential correlation/association through multiple layers of memory patterns to identify a cognitive concept;
2) The layered memory patterns accrue and develop through relevant experiences and inferences thereof, self or learned. Rich life experiences broaden the range of expertise and creativity;
3) Experiences are created in the sensory space and are focused on the self-well-being from sensing through imprinting and retrieving memories. Relevance and self-need, emerging from authenticity of the problem at hand...
to the self-Umwelt create the needed motivation;
4) The self-sensory space creates its unique space time reference frame according to its circumstances. A transformation is required between the personal experience space and the universal scientific reference space where measurements are made and concepts are formulated. A transformation between the spoken language, describing live event and rigorous scientific language of the model is required.

These have implications to the learning process:
- Learning is motivation-supported when it expands the self “control zone”. Learning in the self-space and relevant to self is imprinted in the memory and enriches the cognitive patterns. Concepts are brewed and tested in authentic scenes/systems – and generalized and mathematically formulated therefrom;
- Active learning involves challenge and commitment that increase motivation, persistence and memory solidification;
- Space and motion perception of self are mainly visual. Visual presentation, imaging and simulations are effective in linkage to memory and development of physical concepts;
- Expert thinking excels in mission orientation and system perception that hops between alternatives by analogy, imaging and inference, striving for sufficient accuracy of the system model to resolve between them.

According to Albert Einstein “Things should be made as simple as possible, but not any simpler”. Accessible physics of daily life is the ideal learning clinic: the living space is familiar and experiences expand the “control zone/comfort zone”. Only few rules dominate the tangible physics enabling experimentation, inference, testing and verifying and even creative development. All other sciences rely on physics, they are more complex and their research requires a lot more a priori knowledge. Physics is therefore a platform for the development of inquisitive, mission-directed system thinking which, together with mastering the physics concepts, constitute the basis for academic and engineering expertise.

**NATURE SYSTEMS AND SYSTEM THINKING**

Nature is a system of systems. Every collision of two particles in space is a system, embedded in a bigger one, and so on to the edge of the universe. A two-particle collision in space is a simple closed system, fully characterized by a physical/mathematical model. The arsenal of canonical models that may serve to build a suitable model to fully characterize a scene is depleted fast as the complexity of the system increases, and deciphering the system model becomes iterative and creative through guess, imagination and comparison – and is dependent on the interaction with the surrounding environment. A projection of the model of the whole onto a desired aspect/point of view reduces the complexity to manageable dimensions and may be the best achievable.

An important issue involved here is the physics-learning process and development of research and development competencies. Inquiry of nature systems serves as a tool for this purpose, while our interest is in the dynamic interaction of a nature system with the human learning system and its development to an expert system. We have to dwell on the interface between the systems – what does nature show and what does the brain interpret, and the mapping transformation between the mental picture and the scientific map.

A system is an aggregate of interrelated objects/items that respond to an excitation with a typical/unique behavior. This relation is the system function for which the inquiry seeks a model. Nature systems are interrelated and open systems affect each other. System inquiry seeks to reduce the complexity of the research by setting boundary conditions that close the system, seeking its dominant function (Eigen function), and then revisiting the inter-systems interaction. The process entails converging guesses of involved basic concepts of physics and other constrains and balancing between them by searching back and forth along the structural (space) and logical/ causal (time) axes.

Mission oriented system thinking incorporates iterative conception, analysis and test, involving both linear and divergent thinking. It is holistic and seeks the balanced interactions between system constituents that drive its characteristic behavior (function). The number of search iterations for the optimal model grows exponentially with the system’s complexity, precluding a structured algorithmic process and resorting to iterative guess, comparison, imaging – processes involving intuitive deep learning.

**MATCHING SYSTEMS’ INQUIRY TO HUMAN LEARNING**

System thinking at large is a powerful virtue for a modern citizen. Our interest here, however, is physics education and developing expert thinking competencies. Inquiring nature systems serve this purpose as a clinic and their success is a gratifying acknowledgement of endeavor and achievement. Two objectives are interwoven in an inquiry project: searching the unknown and developing the expert competencies. The optimal design of the inquiry has to be adjusted to the features of human learning. Transformations are required between the scientific research space and the human sensing and processing space. These have to be reflected in the structure of the inquiry. Thus:
- Observation has to conform with perception by properly (mentally) transforming between the measurements reference frame and the self point-of-view;
- Measurements of phenomena out of human sensing range in scale and time have to be (mentally) scaled into range;
- Complexity should be split into simpler scenes/models to suit the limits of the human working memory and enable the learner to examine hypotheses. This is obtained by seeking the topology of the event;
- The translation between the scientific languages to spoken one should be exercised in relevance to the inquiry at hand (https://www.researchgate.net/publication/316831883, 2017).

The ensuing inquiry process is portrayed in the following plots: the search order in Figure 1 and the search iterations in Figure 2. Topology seeks sequential/parallel structural and logical subsystems, feedback and enhancement affecters that control stability or change. The structural axis reflects the spatial inter-relations and unveils correlations, not necessarily causal, while the logical axis ties up functional and causal relations.

An inquiry project is bound in time and resources and has to be designed to optimize the educational objective while considering the constraints. The student’s motivation is of prime importance. However, the choice of inquiry topic has to consider both students wish, mentors expertise, pre-assessment of the complexity and needed knowledge and resources. Young students are easily enthused by a challenging topic if properly introduced (http://harvardmagazine.com/2008/09/the-teen-brain.html, 2008). A generic wisdom is plotted in Figure 3, strategizing the project so as to reduce risks early in both the prime research and of its enabling resources/ phases. The project phases have to be identified and their series/parallel ordering designed by assessing their conditional validity.

DESIGN OF LEARNING FOR EXPERTISE

The choice and design of the educational inquiry project is guided considering the triad: Knowledge, skills and complexity.

i) Background knowledge in the research area:
- Conceptual acquaintance with physical laws and generic order rules: patterns, symmetry and stability, etc;
- Exercised examples of these laws and rules in a variety of contexts.

ii) Experimentation and analysis skills:
- Measurements and measurement equipment, and its principle of operation;
- Recording, processing and presenting tools, including relevant mathematical tools and techniques.

iii) Complexity;
- Multiple-layered logical inference;
- Creative divergent thinking.

The project may thus be bound by proper weighting of these three axes – in the design and assessment, as depicted in Figure 4.

THE NEW PEDAGOGY

This is the new pedagogy: effectively matching the system challenge to the student’s mind (http://www.nap.edu/catalog.php, 2013).

1) From bulk transfer of knowledge and grading the products (students), to catalyzing the matching process of the students minds to the system challenge.
2) From rote frontal teaching to active involvement of students in formulating questions, discussing concepts and discovery inquiries.
3) From rules teaching and exercising to concepts learning, building and exercising on a broad range of situations, and intimating dialog/feedback along the process – with peers and mentors.
Figure 2: The inquiry search iterations in both axes.

Figure 3: Effort assessment and risk reduction in inquiry planning and execution.
Though key features of the brain are typical, as discussed above, it's “wiring” is unique to the individual, differing in sensitivities and imprinted by his past experience that formed his “comfort zone” and perceptions (https://www.youtube.com/watch?v=5_6fezBz9IA, 2015).

It is the mentor's role to “check the wiring” by challenging relevant processes and concepts. This cognitive mentoring art is geared towards building the mental structure of the expert by guided training. It is a context-dependent interaction, converging from broad patterns of estimation, comparison, imagination and selective attention to specific inquiry. The mentor has to master the scientific discipline to lead his challenges toward student's clear understanding of his own arguments (Carl, 2017).

The pedagogy transformation shakes the entire education system, as it involves change in syllabus, teachers' education, restructuring classes, laboratories and organizations. Such transforms are discussed (Carl, 2017; https://www.youtube.com/watch?v=5_6fezBz9IA, 2015; 2016; http://www.researchgate.net/publication/321292372_The_STEMLab_SL_platform_and_applications, 2015)).

Programs in Israel

Our focus is on the K-12 education system in Israel. Whereas a nationwide shift is yet to move, two initiatives are described.

RoboPhysics

ROBOPHYSICS is a program for inquiry projects in STEM through the sensors of a manipulated robot. The robot is designed, assembled and implemented per mission, emulating scientific research. Observations through the robot's sensors imitate the human's point of view and bridge the gap between the scientific frame of reference and the human perception. This is exemplified in Figure 5 (www.researchgate.net/publication/292047086, 2015; 2016; http://www.researchgate.net/publication/321292372_The_STEMLab_SL_platform_and_applications, 2015))

The program, conceived, developed and operated by Ofer Danino since 2012, runs in various schools 6-12, endorsed by the ministry of education and by the Technion. A special training program accommodates teachers and interested engineers. An ongoing teachers' workshop vitalizes its further development. Students are highly motivated (robots are perceived as extending human limbs, empowering and extending the human control zone).
INQUIRY PHYSICS

Moshe (2006) initiated the ACHERET center (www.acheret.org.il, 2017) and this led to guided discovery-oriented inquiry projects in physics, whereby a high school student teams with a mentor to research a phenomenon unfamiliar to both. Successful record over 10 years led to a nationwide official program “Inquiry physics”, now spanning 10 regional clusters and growing. The program encapsulates the triad: knowledge, skills and complexity over a two-year project.

The intimacy of the student, or a couple of, with a mentor through the lengthy discovery process – is exhilarating and mind-changing. It benefits the teacher, enriching his system-inquiry thinking and creativity and developing his career and opportunities. A new seminary – The Archimedes Point, running a two-year mentors training program, provides the necessary education for inquiry-expert teachers (Figure 6).

REFERENCES

Eric Mazur Memorization or understanding: are we teaching the right thing?
http://www.nap.edu/catalog.php?record_id=18312
https://www.researchgate.net/publication/316831883_Colliding_worlds
https://www.wired.com/story/new-theory-deep-learning/
https://www.youtube.com/watch?v=5_6ezBz9IA
https://www.youtube.com/watch?v=aBEFPY7Ehr
https://www.youtube.com/watch?v=n1DLFnb6Go
https://youtu.be/ekdW0_pl2M8
Undergraduate Physics Education (2013).
www.acheret.org.il
www.researchgate.net/publication/315972424_DEVELOPING_SYSTEMS_THINKING.SKILLS.A_HIGH-SCHOOL_COURSE_ON.EngineERING_DESIGN
www.researchgate.net/publication/318828031_Colliding_worlds._acceleration_as_a_key
www.researchgate.net/publication/321292372_The_STEMLab_SL_platform_and_applications.

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