Reforming Civil Engineering Education Given the Challenges Related to Infrastructure Engineering and Management

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Outline

- Engineering Education in the 2000’s:
  - Motivations for Change
  - Engineer 2020

- Civil Engineering Education in the 2000’s:
  - Societal needs … infrastructures
  - CEE education reform needs
  - Paradigm needs

- Recommendations
Engineering is designing, constrained by nature, by cost, by concerns of safety, reliability, environmental impact, manufacturability, maintainability, and many other "ilities."

Global competition, subsequent restructuring of industry, shift from defense to civilian work, the use of new materials and biological processes, and the explosion of information technology have dramatically and irreversibly changed how engineers work. If anything, the pace of this change is accelerating.

Curriculum, pedagogy, and diversity. Whether the B.S. should be the first professional degree. The current system of faculty rewards. Faculty should practice what they teach! Formalized lifelong learning, the adequacy of student preparation in grades K-12, and the importance of technological literacy in the general population.
Wulf continued

- The undergraduate curriculum should teach the fundamentals.
- The last major curriculum change in engineering, the move to "engineering science," occurred following WW II. Fundamentals have been seen largely as continuous mathematics and physics.
- The new fundamentals include information technology (IT), which will be embedded in virtually every product and process in the future. Discrete mathematics, not continuous mathematics, is the underpinning of IT. Biological materials and processes are closing fast. Thus, the chemical and biological sciences are also becoming fundamental to engineering.
- In addition, the modern engineer must design under constraints that include global cultural and business contexts, so he or she must understand those constraints at a deep level. We can't just add these new elements to a curriculum that's already too full, especially if we still claim that the baccalaureate is a professional degree. We have to look critically at the current cherished fundamentals and either displace them or find ways to cover them much more rapidly.
The Engineer of 2020: Visions of Engineering in the New Century, National Academy of Engineering

Stephen Director, Provost, Drexel University
Phil Condit, Boeing
Bran Ferren, Disney
Dr. Shirley Jackson, President of RPI and former Director of the Nuclear Regulatory Commission
Peter Schwartz, Global Business Networks

... engaged a diverse group of thought and opinion leaders in a series of activities to gather facts, forecast future conditions, and develop future scenarios for the 2020 engineer..

- Phase I: Visions and scenarios of engineering practice
- Phase II: Action agenda to shape the future of engineering education; Public comment and feedback
Foundational Questions for 2020

- What will the contextual conditions of engineering practice be in 2020 – technological and societal?
- What are your aspirations for engineering and engineers in 2020?
- What will the critical attributes for engineers be in 2020?
Before the World Wide Web, there was the Library of Alexandria, which collected all that had been written.
“Today a 1 gigabit hard drive ships in a package 1’x1’x1/8’’; soon that will be a 10 gigabit drive and computers small enough to fit into trouser pockets will be able to contain information that would fill a modern library (Feldman, 2001)”

"Everything will, in some sense, be 'smart'; every product, every service and every bit of infrastructure will be attuned to the needs of humans it serves and will adapt its behavior to those needs.”
Example of Information Explosion in Healthcare

The Healthcare Big Bang

More Data Over the Next 3 Years Than Previous 40,000 years Combined

Electronic Medical Record Digital Radiology/Cardiology

Pharmacogenomics
Human Genome
Metabolic Pathways
Proteins
MIPs
SNPs

Data Management Requirements [Petabytes]

Combinatorial Chemistry
ESTs
HTS

Moore's Law Curve

Source: UC Berkeley, School of Information Management and Systems
Bioengineering, Biotechnology & Biomedical Technology

- Advances in biotech have already significantly improved the quality of our lives
- More dramatic breakthroughs ahead
- Tissue engineering
- Regenerative medicine
- Drug delivery engineering
- Bio-inspired computing
- Protection from biological terrorism

Korean technique for human DNA extraction.
Micro/Nanotechnology

- **Draws on Multiple Fields**
  - Genetic and molecular engineering
  - Composites and engineered materials
  - Quantum scale optical and electrical structures

- **Potential Applications**
  - Environmental cleaning agents
  - Chemical detection agents
  - Creation of biological (or artificial) organs
  - Ultra-fast, ultra-dense, circuits

*A factory large enough to make over 10 million nanocomputers per day might fit on the edge one of today’s integrated circuits.* - Drexler and Peterson
## Grand Challenges in the National Nanotechnology Initiative

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Strategic Challenges</th>
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</table>
| **Nano-Now** | - Pigments in paints  
| | - Cutting tools and war resistant coatings  
| | - Pharmaceuticals and drugs  
| | - Nanoscale particles and thin films in electronic devices  
| | - Jewelry, optimal and semiconductor wafer polishing |
| **Nano-2007** | - Biosensors, transducers and detectors  
| | - Functional designer fluids, propellants, nozzles and valves  
| | - Flame retardant additives  
| | - Drug delivery, biomagnetic separation, and wound healing |
| **Nano-2012** | - Nano-optical/electronics & power sources  
| | - High-end flexible displays  
| | - NEMS-based devices  
| | - Faster switches and ultra-sensitive sensors |
Materials Science & Photonics

- Smart materials and structures, which have the capability of sensing, remembering & responding (e.g., to displacements caused by earthquakes and explosions; smart textiles provide cooling and heating).

- “As the physical sizes of optical sources decrease, while their power and reliability continue to increase, photonics based technologies will become more significant in engineered products and systems.”

Applications: fiber optics, precision cutting, visioning and sensing; photochromic windows.
Meanwhile: Some Remaining Challenges

- Infrastructures in Urban Settings
- Safety and Security of Information and Communications Infrastructures
- Technology for an Aging Population
- The Environment
- Social Concerns
The engineer of 2020 will need to be conversant with and embrace a whole realm of new technologies, but some old problems are not going to go away. They will demand new attention and, perhaps, new technologies. In some cases their continuing neglect will move them from problems to crises.

Physical Infrastructures in Urban Settings: ... without a sufficient focus on environmental impact and sustainability... victims of pollution, traffic and transportation infrastructure concerns, decreasing greenery, poor biodiversity, and disparate educational services. ... infrastructures are in serious decline, aging water treatment, waste disposal, transportation, and energy facilities are among the top concerns for public officials and citizens alike.
The Environment

- Three quarters of the US population resides in areas with unhealthy air. [American Lung Association]
- In 2020, California will need 40% more electrical capacity, 40% more gasoline, and 20% more natural gas than in 2000.
- 50% of the world’s original forest cover has been depleted [Worldwatch Institute] and global per capita forest area is projected to fall to 1/3 its 1990 value by 2020. [Haque, 2000].
- 48 countries (2.8 billion people) face freshwater shortages in 2025 [Henrichsen, 1997]
- The wealthiest 16% of the world consumes 80% of the world’s natural resources. By the year 2020, there will be 8 billion people who will be further depleting the environment and fuel political instability if the inequity of these resources continues. [CIA 2001].
Guiding Principles in Green Engineering
(NSF, 2003)

- Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.
- Conserve and improve natural ecosystems while protecting human health and well-being.
- Use life cycle thinking in all engineering activities.
- Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.
- Minimize depletion of natural resources; strive to prevent waste.
- Develop and apply engineering solutions, while being cognizant of local geography, aspirations and cultures.
- Create engineering solutions beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability.
Societal, Global and Professional Context of Engineering Practice

- The pace of technological innovation will continue to be rapid (if not escalating).
- The world in which technology will be deployed will be intensely globally interconnected;
- The individuals who are involved with or affected by technology (e.g., designers, manufacturers, distributors, and users) will be increasingly diverse and multidisciplinary;
- Social, cultural, and political forces will continue to shape and affect the success of technological innovation.
- The presence of technology in our every day lives will be seamless, transparent, and more significant than ever before.
- Consumers will demand more and more: higher quality, mass customization, personalization, etc.
The World Population (CIA, 2001)

A mix of 100 people in 2020 would look like the following:

- 56 would be from Asia, including 19 Chinese and 17 Indians
- 13 would be from the western hemisphere, including 4 from the United States
- 16 would be from Africa, including 13 from Sub-Saharan Africa
- 3 would be from the Middle East
- 7 would be from Eastern Europe and the former Soviet Union
- 5 would be from Western Europe

In contrast to the aging of the US, Europe and Japan, the most politically unstable parts of the world will experience a “youth bulge”.

Distribution of World Population in 2020 - In a Mix of 100 People:

- Asia (19-China; 17-India)
- Western Hemisphere (4 from US)
- Africa (13-Sub-Sahara)
- Middle East
- Eastern Europe & Former Soviet Union
- Western Europe
Adapting Engineering Education to the New Century (NAE 2004)

- The BS degree should be considered as a pre-engineering or “engineer-in-training” degree.
- Engineering programs should be accredited at both the BS and MS levels, so the MS degree can be recognized as the engineering “professional” degree.
- Institutions should take advantage of the flexibility inherent in the ABET EC2000 accreditation criteria in developing curricula, and students should be introduced to the “essence” of engineering early in their undergraduate careers.
- Colleges and universities should endorse research in engineering education as a valued and rewarded activity for engineering faculty and should develop new standards for faculty qualifications.
- That, in addition to producing engineers who have been taught the advances in core knowledge and are capable of defining and solving problems in the short term, institutions must teach students how to be lifelong learners.
Adapting Engineering Education to the New Century (NAE 2004) continued

- Engineering education should introduce interdisciplinary learning in the undergraduate curriculum and explore the use of case studies of engineering successes and failures as a learning tool.

- Four year schools should accept the responsibility of working with local community colleges to achieve workable articulation with their 2-year engineering programs.

- Institutions should encourage domestic students to obtain the MS and/or PhD degrees.

- The engineering education establishment should participate in efforts to improve public understanding of engineering and the technology literacy of the public and efforts to improve math, science and engineering education at the K-12 level.

- The NSF should collect and assist collection of data on program approach and student outcomes for engineering departments/schools so prospective freshmen can better understand the “marketplace” of available engineering baccalaureate programs.
Aspirations for the Engineer 2020: Engineering a Sustainable Society

- “It is our aspiration that engineers will continue to be leaders in the movement towards use of wise, informed and economical, sustainable development. This should begin in our educational institutions and be founded in the basic tenets of the engineering profession and its actions.

- We aspire to a future where engineers are prepared to adapt to changes in global forces and trends and to ethically assist the world in creating a balance in standard of living for developing and developed countries alike.
Successful Attributes for the Engineer of 2020

- Possess strong analytical skills
- Exhibit practical ingenuity; posses creativity
- Good communication skills with multiple stakeholders
- Business and management skills; Leadership abilities
- High ethical standards and a strong sense of professionalism
- Dynamic/agile/resilient/flexible
- Lifelong learners
- Ability to frame problems, putting them in a socio-technical and operational context
CEE Education in North America (ASEE, 2004)

- ~240 CE Bachelors Programs in North America
- ~140 CE PhD Programs in North America
- ~40 Construction Technology Programs in North America
- 8142 Bachelors graduated (23.1% Woman)
- 3745 Masters graduated (25.2% Woman)
- 644 Doctoral degrees awarded (19.4% Woman)
- 43,590 CE Bachelors program registered

<table>
<thead>
<tr>
<th>DEGREES AWARDED (2004)</th>
<th>1. Purdue University 176</th>
<th>12. North Dakota State University 103</th>
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<tbody>
<tr>
<td></td>
<td>2. Texas A&amp;M University 157</td>
<td>13. Michigan Technological University 101</td>
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<td></td>
<td>4. Polytechnic Univ. of Puerto Rico 131</td>
<td>14. Univ. of Minnesota, Twin Cities 94</td>
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<td></td>
<td>5. Univ. of Illinois, Urbana-Champ 128</td>
<td>16. Michigan State University 92</td>
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<td></td>
<td>7. Georgia Institute of Technology 121</td>
<td>18. Ohio State University 87</td>
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<td></td>
<td>8. California Polytechnic State Univ. 111</td>
<td>19. University of California, Davis 83</td>
</tr>
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<td></td>
<td>11. Univ. of Puerto Rico, Mayaguez 104</td>
<td>22. University of Washington 77</td>
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<tr>
<td></td>
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<td>23. Iowa State University 72</td>
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ABET and ASCE Outcomes for civil engineering education

Apply knowledge of mathematics, science and engineering.
Design and conduct experiments, as well as analyze and interpret data.
Design a system, component or process to meet desired needs.
Function on multi-disciplinary teams.
Identify, formulate and solve engineering problems.
Understand professional and ethical responsibility.
Communicate effectively.
Understand the impact of engg solutions in a global/societal context.
Recognize the need for, and an ability to engage in, life-long learning.
Knowledge of contemporary issues.
Understand the techniques, skills, and modern engineering tools
Apply knowledge in a specialized area related to civil engineering.
Understand project management, construction, and asset management.
Understand business and public policy and administration fundamentals.
Understand the role of the leader and leadership principles and attitudes.
Civil engineering, the oldest engineering discipline, is facing unprecedented challenges. The world we live in today is vastly different from that of fifty years ago. Information technology has become ubiquitous in our society, new technologies are emerging, and learning paradigms and cognitive psychology are pointing the way to more effective education. Students are searching for an educational experience that prepares them for a variety of jobs, yet the curriculum and educational paradigm for civil engineers remains virtually unchanged over the past half century. Civil engineering technicians are serving in positions that would have been filled by civil engineering graduates in the past, and other professionals are filling some executive positions that had been reserved for civil engineers. The civil engineer has the bottom median salary of all fields of engineering. We have to begin educating tomorrow's civil systems integrators.
The coming Century will bring times of great challenge but also of great opportunity for civil engineers. Civil engineering is losing its luster to fields like biotechnology and information technology. Yet this trend will be forced to correct itself in the coming years as a rapidly growing world population appropriates more of the natural environment for its use; demands more water, energy, waste disposal and transportation resources; produces more pollution; and expands its exposure to natural hazards. In addition, society is about to come abruptly face to face with infrastructure needs and environmental problems that have already been neglected for too long and will grow to crisis levels if left unattended any longer. Yet civil engineering will not be the profession to reap the rewards that will come in meeting these challenges if it clings to old practices and educational paradigms.
Challenges and Opportunity for Civil Engineers

Challenges:

- Civil and Environmental Engineering is slipping in its image, worth and societal standing while many civil engineers are in denial.
- Civil engineers have not been very successful as stewards of infrastructures and constructed systems for safe, effective, sustainable operation, preservation, protection, maintenance, repair, retrofit and replacement.
- Civil engineers should be transforming systems engineering and associated tools to more effectively address large infrastructure systems problems. We need to re-learn civil engineering by scientific observation, identification, simulation and control of actual operating infrastructure systems.

Opportunity:

- Properly educated/trained Civil and Environmental Engineers remain essential for leading and coordinating the multi-disciplinary teams and integrating technology and knowledge essential for effective engineering and management of large infrastructure systems.
Why is civil engineering so different?

- Civil engineers design, construct and manage (operate, preserve, protect) **constructed systems** that are the backbones of many **infrastructure system-of-systems**
- Disconnected design-construction-operation-maintenance
- Lack of a **systems approach, observation and measurement**. We have NOT yet learned how to effectively observe and **measure** such large, complex **system-of-systems**
- Lack of objective valuation and descriptions for **condition, performance and health**
- Complex interactions/interdependency between natural, human and engineered elements of infrastructures defy modeling. **Vulnerability due to hidden intersections between elements and systems are discovered mainly as a result of costly breakdowns**
- Barriers abound hindering effective technology research and integration through multidisciplinary “systems” research on actual infrastructures
- Significant **epistemic uncertainty prevails** most critical decisions
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<tr>
<th>Physics-Based Models</th>
<th>Non-Physics-Based Models</th>
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<tbody>
<tr>
<td><strong>Mathematical Physics Models</strong></td>
<td><strong>Semantic Models</strong></td>
</tr>
<tr>
<td>• F=MA</td>
<td>• Ontologies</td>
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<tr>
<td>• E=MC²</td>
<td>• Semiotic Models</td>
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<tr>
<td><strong>Continua Models</strong></td>
<td><strong>Meta Models</strong></td>
</tr>
<tr>
<td>• Theory of Elasticity</td>
<td>• Rule-based meta Models</td>
</tr>
<tr>
<td>• Field and Wave Eqns</td>
<td>• Mathematical (Ramberg-Osgood, etc.)</td>
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<tr>
<td>• Idealized Diff. Eqns (Bernoulli, Vlasov, etc.)</td>
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<tr>
<td><strong>Discrete Geometric Models</strong></td>
<td><strong>Numerical Models</strong></td>
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<tr>
<td>• Smear-Macro or Element Level Models</td>
<td>• Probabilistic Models</td>
</tr>
<tr>
<td>• FEM-for Solids and Field Problems</td>
<td>- Histograms to Frequency Distribution</td>
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<tr>
<td>• Modal Models:</td>
<td>- Standard Prob. Distributions</td>
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<tr>
<td>- Modal Parameters</td>
<td>- Independent events</td>
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<tr>
<td>- Ritz Vectors</td>
<td>- Event-based (Bayesian)</td>
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<tr>
<td><strong>Numerical Models</strong></td>
<td>- Time-Based (Markov)</td>
</tr>
<tr>
<td>• K,M,C Coefficients</td>
<td>- Symptom-based</td>
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<td><strong>Agents</strong>: Meta + Monte Carlo</td>
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<td><strong>Statistical (Data-Based)</strong></td>
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<tr>
<td></td>
<td>- ARMA, ANN, others</td>
</tr>
<tr>
<td></td>
<td>- Signal/Pattern Analysis, Wavelet, etc</td>
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Uncertainty in Predicted Properties and Performance of Constructed Structures

- **Errors >100%** are common in predicted displacements of idealized reinforced concrete and steel structural models tested in the laboratory.

- Field experiments on bridges indicate a range of discrepancies between predicted and measured:
  - ~2-5 times in service displacements,
  - ~5-10 times in predicted stresses,
  - ~10 -20 times in predicted system load capacities.

- Many intrinsic load mechanisms and the changes these cause in the intrinsic force distributions are unknown.

- **Actual failure modes** of especially aged and deteriorated systems, are often a complete surprise for even experienced engineers.
Types of Uncertainty Affecting Reliability of Scenario Analysis and Predictions Involving Infrastructures

Human Errors (HE)
- Inattention/Thoughtlessness
- Inexperience
- Omission (Forgetfulness)
- Commission (Bad Design)

Random Phenomena (RP)

Epistemic Uncertainty (EU)
- Less Understood Phenomena (LUP)
- Unknown Phenomena (UP)
SYSTEMS MODEL FOR DATA RELIABILITY

**Objectives**

- INTERPRETATION, DECISION MAKING
- NATURAL AND HUMAN SYSTEMS
- CONSTRUCTED SYSTEM
- EXPERIMENT (LOADING, DATA ACQ, COMMUNICATION, COMPUTING)

**Sensor**

- SPATIAL, TEMPORAL
- MULTI-MODAL
- DATA FLOW

**Data**

- RANDOM ERRORS
- BIAS ERRORS

**Data Component Due:**

- UNKNOWN INFLUENCES (EPISTEMIC UNCERTAINTY)
- CHANGES IN INTRINSIC RESPONSE DUE TO NATURAL AND HUMAN INFLUENCES
- RESPONSE DUE TO OBSERVED/CONTROLLED INPUTS
Paradigms That Should Guide Technology Research:

- Systems Engineering
- Structural Identification
- Health Monitoring
- Structural Control
- Integrated Asset Management
- Performance Based Engineering
- Intelligent Processes and Systems
- Sustainability
Why is Education Reform so Difficult?

- Administration, faculty, staff and students of the entire university are an integrated system:
  - Shared vision, mission, values, policies, goals?
  - Coherent strategic plans at each level?
  - Shared definitions for academic values, quality?
  - Shared definitions and commitment to scholarship?

- Create knowledge and serve as its repository
- Transparency of goals, policies, strategies
- Financial success should follow from focus on academic quality and innovative enterprising
DISTRIBUTED EXCELLENCE

- Strive for a **collective and integrative academic quality** of program(s):
  - Define indices for collective excellence as the principal measure of academic quality
  - Provide the leadership, resources and incentives for faculty and students to exceed these indices

- **Choose focal area(s) for excellence**: Emerging area(s) of research in which the program has potential to become a principal node of a Nexus

- **Focal area**: Pressing societal concern that requires integrative, multidisciplinary and coordinated research and education
Intelligent Infrastructure Systems

- Goal: Efficient/safe operation, preservation, protection and asset management of critical infrastructures
- A new discipline **Large Systems Engineering:**
  - Fundamental knowledge on natural, human and engineered elements, their behaviors and interactions
  - Observation, measurement, controlled testing
  - Integrated modeling, identification, control
  - Scenario development and simulations for analyses
  - Valuation, performance, health, decision models
  - Revenue, risk and asset management
- Intelligent system applications become necessary
Kolb’s Cycle for Learning:

- Concrete experience
- Reflective observation
- Abstract conceptualization
- Active experimentation


A Moving Target for Educators:

The student today is greatly different from the student of only a decade ago in being able to take advantage of IT for learning and communicating.
Concepts for an Infrastructures Specialization

Freshmen Design
- Fundamental Sciences: Math, Chem-Bio, Physics
- Material Science Energy Science
- Computation, Measurement, Data Management Skills

SYSTEMS, Linear Algebra and Statistics

Teaming, Productivity and Time Management

Mechanics of Solid and Deformable Bodies, Structural Analysis and Structural Design
- Structural Stability, Ultimate and Failure Limit State Analysis
- Uncertainty, Risk Reliability

Computer-Aided-Integrated Analysis, Design, Construction, Operation and Maintenance of Constructed Systems

Law, Ethics, Professionalism

Geotechnical Engineering, Foundations, Pavements
- Evaluation and Design of Constructed Systems

Engineering of Natural Systems: Environmental and geo-environmental

Application of Technical and Management Skills

Structural Dynamics, Earthquake and Multi-Hazards Engineering
- Operational and Maintenance Management of Infrastructure Systems
Summary: Critical Drivers for Reform

- Technology Leaps
- Globalization and Demographics
- The Changing Roles of Engineers
- Rapid Knowledge Growth
- New Fundamentals and Curriculum
- Practice What you Teach
- Pedagogy
- Diversity
- Scholarship and Value System