SYSTEMS ENGINEERING
Research Center

Systems Engineering Advancement Research Initiative

Interactive Model-Centric Systems Engineering (IMCSE)

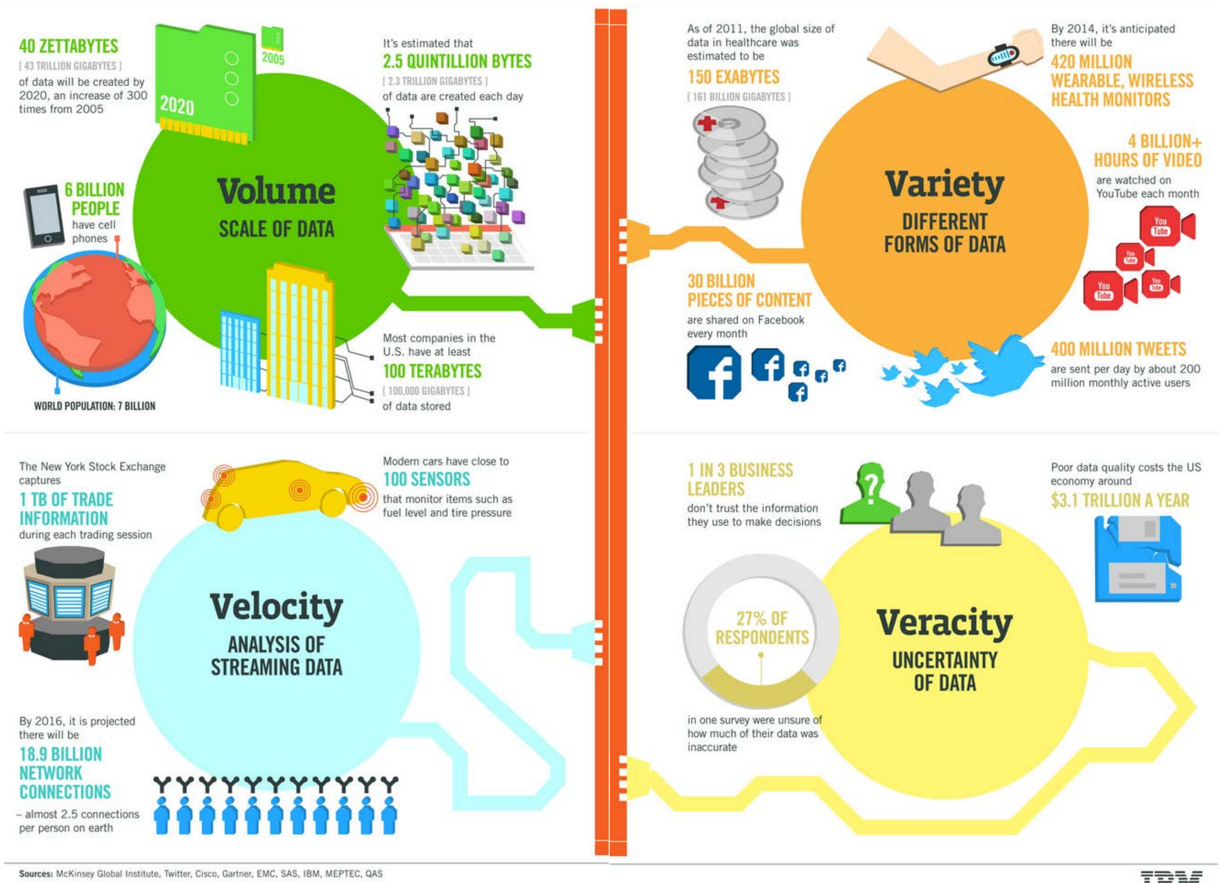
Dr. Adam M. Ross, MIT

5th Annual SERC Sponsor Research Review
February 25, 2014
Georgetown University
Hotel and Conference Center
Washington, DC

www.sercuarc.org

Collecting Vast Information: Big Data

We live in a world with big data…



http://www.ibmbigdatahub.com/sites/default/files/infographic_file/4-Vs-of-big-data.jpg

The impact of big data is felt across many fields, and will only increase…

http://bigdata.csail.mit.edu/Big_Data_Privacy

Application Areas

- transportation, consumer products, entertainment, banking, life sciences, physical sciences, …
- communications, education, sports, insurance, manufacturing, retail, healthcare, utilities, dating …

Big data is being leveraged in many ways to gain insights into phenomena and to create predictive models…

Big data provides a foundation for large scale analytics to predict the future

Making Sense of the Data: Visual Analytics

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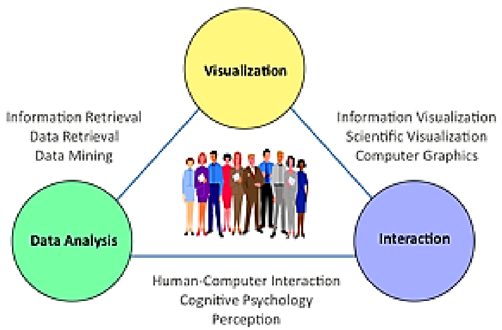
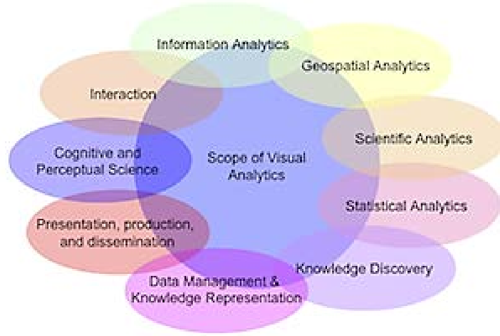
What is Visual Analytics?





www.visual-analytics.eu/faq/

…It is a collaboration between human and computer

Enabling Software Tools

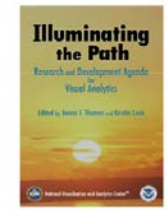
GI 1.3, www.graphinsight.com

Starlight Visual Information System, www.futurepointsystems.com

SAS Visual Analytics Software, www.sas.com/en_us/software/business-intelligence/visual-analytics.html

Visual Analytics Definition

Visual analytics provides the last 12 inches between the masses of information and the human mind to make decisions



"Visual analytics is the science of analytical reasoning facilitated by interactive visual interfaces"

People use visual analytics tools and techniques to

- Synthesize information and derive insight from massive, dynamic, ambiguous, and often conflicting data
- Detect the expected and discover the unexpected
- Provide timely, defensible, and understandable assessments
- Communicate assessment effectively for action.

Jim Thomas, Director, USDHS National Visualization and Analytics Center, "*Visual Analytics: An Agenda in Response to DHS Mission Needs*," 2007.

Application Areas

- homeland security, intelligence community, law enforcement, financial markets, anti-fraud
- banking, communications, education, insurance, life sciences, manufacturing, retail, utilities, …

Visual analytics is resulting in a transformative capability, bridging human and computer analysis for **natural*** data

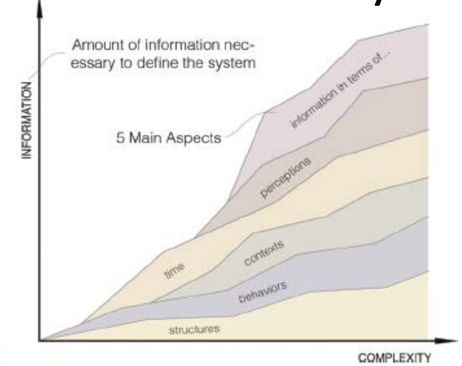
*observable "ground truth" possible

Our Domain: Complex Systems

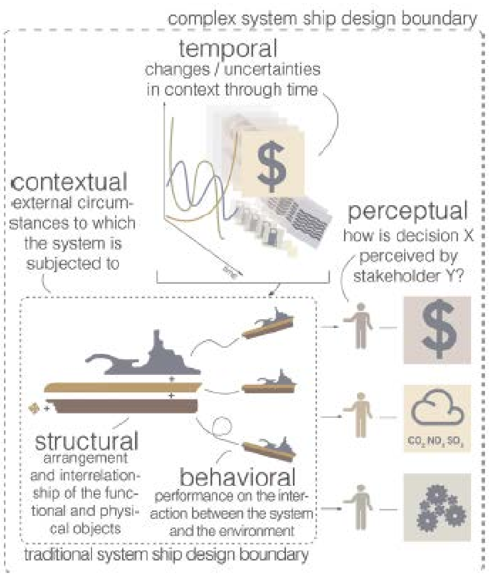
Our application domain is the development of (*artificial*) systems that serve the purpose of delivering value to stakeholders…

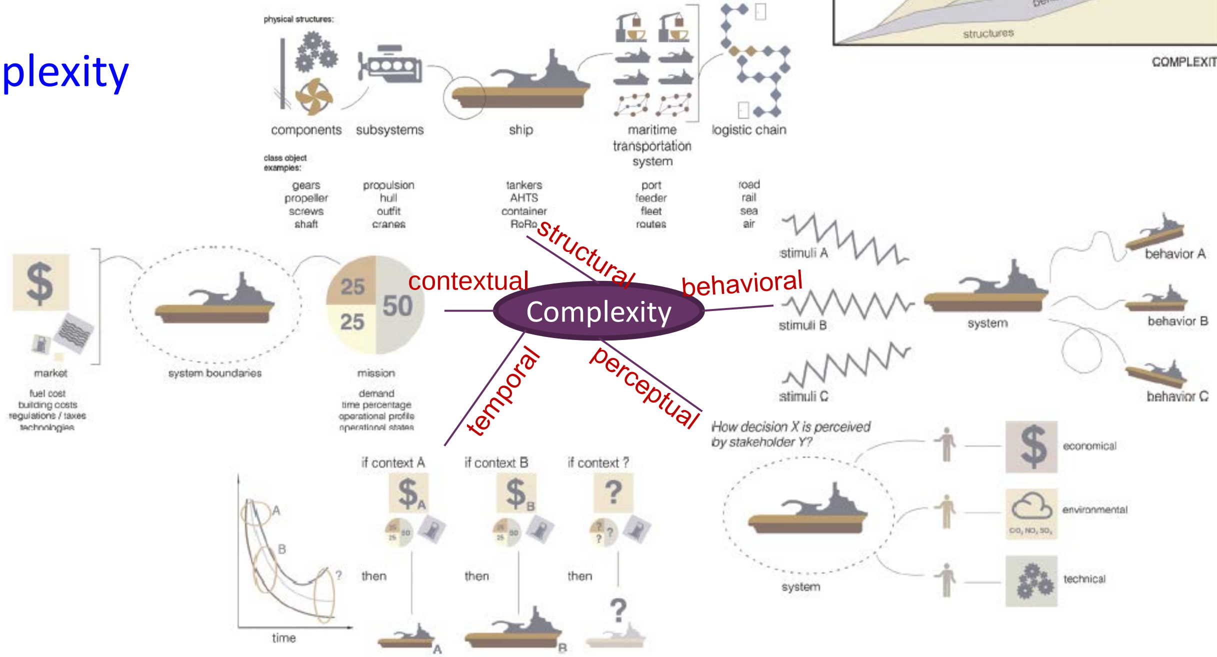
The complexity of our systems has been growing over time, not only due to scale and interconnectedness, but also due to increased scope in our ability to describe the system

Complexity grows with the amount of information needed to define a system



Five aspects of system complexity



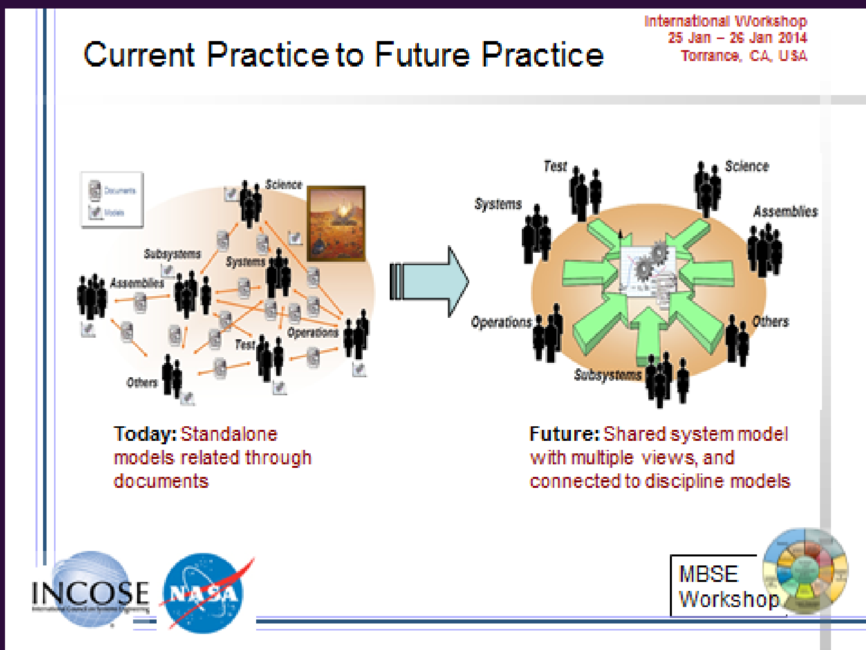


Developing complex systems necessitates an approach to generate, manage, and analyze artificial data across these five aspects

Model-based Systems Engineering

"Model-based systems engineering (MBSE) is the *formalized application of modeling* to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."

INCOSE SE Vision 2020 (INCOSE-TP-2004-004-02, Sep 2007)



NDIA SE Division: Model-Based Engineering (MBE) Subcommittee Report (2011)

- Reduce acquisition time of first article systems and solutions
- Reduce time to implement planned and foreseen changes
- Enhance reliability
- Enhance interoperability

…each of these benefits enhance affordability

Model-based systems engineering generates "artificial data" about our systems which we use to make decisions that impact the future/continuing success of that system

Merging the Four:
Interactive Model-Centric Systems Engineering

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- Big Data + Visual Analytics…
  + Complex Systems + MBSE = IMCSE
  — Volume, variety, velocity, and veracity of data
  — Collect data, visualize, interact, model, find patterns, generate insights, repeat
  — Structural, behavioral, contextual, temporal, and perceptual complexities
  — Integrated models including requirements, structure, behavior, parametrics

- Potential use for this merged capability for decision support within and across systems engineering throughout lifecycle

On the power of humans with computers:

"statistics (computing) + humans is much more powerful than statistics alone or humans alone"

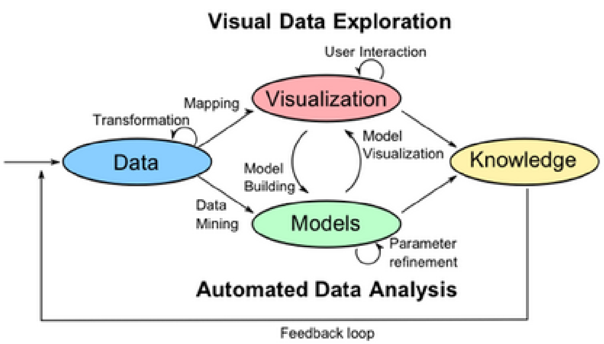
– Professor Remco Chang, Tufts University Visual Analytics Lab, Aug 2013

Interactive Model-Centric Systems Engineering				
	MBSE	STRUCTURAL	form of system components and their interrelationships	**Existing "state of practice"** systems architecting and model-based systems engineering
	MBSE	BEHAVIORAL	function/performance, operations, and reactions to stimuli	
		CONTEXTUAL	circumstances in which the system or enterprise exists	**Emerging "state of art"** *Epoch Modeling* *Multi-Epoch Analysis* *Epoch-Era Analysis* *Dynamic Tradespace Exploration* *Multi-Stakeholder Negotiations* *Comprehension of Complex Datasets* *Studies of Decision Making* *and more….*
		TEMPORAL	dimensions and properties of systems over time	
		PERCEPTUAL	stakeholder preferences, perceptions and cognitive biases	

Developing complex systems necessitates an approach to generate, manage, and analyze artificial data across these five aspects, which result in improved SE decision making

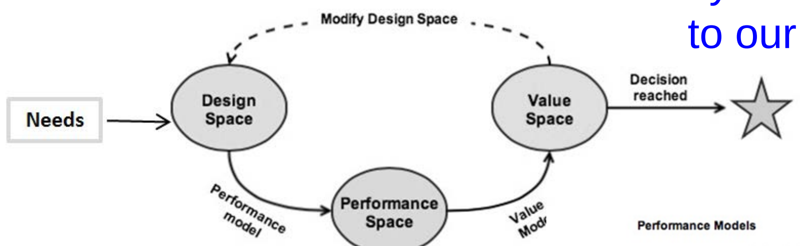
What is IMCSE?

More than just visual analytics…

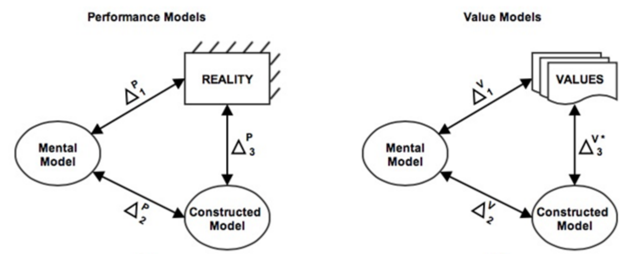


www.visual-analytics.eu/faq/

Our data is generated by models (e.g. "M" of MBSE)…



In SE, our job is to make decisions that result in systems that deliver value to our stakeholders...



Mental Model v. Values

Constructed Model v. Mental Model		Low Δ_1 (truthful)	High Δ_1
	Low Δ_2 (trust)	Correct Trust (d)	(a) Type I Error
	High Δ_2	Type II Error (c)	(b) Justified Mistrust

Two critical gaps in current approaches:

1. **Visual analytics of artificial (model-generated) data**
2. **Active tradeoffs of the models themselves**

Key questions:

- How can techniques from VA result in better model-enabled SE decisions?
- How can we determine proper trust and truthfulness for various types of models?
- Ultimately, how can this approach help to manage complexity in modern SE and deliver more affordable and valuable systems?

IMCSE Goal: leveraging visual analytics applied to model-generated "big data," develop a rigorous framework, with associated MPTs, that results in transformative new capabilities for SE decision making

Interaction between Humans and Models Enables Anticipatory Capacity

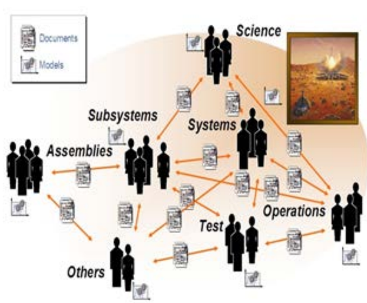
Systems scientists have long recognized that humans possess unique abilities for anticipation rather than simple reactive response

- Anticipation (ability to look forward in order to take a future decision or action)
- Pattern recognition skills
- Subject to cognitive limits, preferences, and biases…

Interactive Model-Centric Systems Engineering
Decision Science – Visual Analytics – MBSE

Anticipatory Capacity Key Enablers

- Mindset – systems thinking
- Methods – model-based
- Environment – hw/sw enhanced



- Complex, integrated models
- Varied levels of fidelity
- Large artificial data sets

Anticipatory Capacity is the capacity to continuously develop and apply knowledge acquired through a structured approach to anticipate: (1) changing scenarios as stakeholder needs and systems context change over time; (2) to consider their consequences; and (3) to formulate design decisions in response.

Rhodes and Ross 2008

IMCSE Role in Decisions

- Make portfolio decisions using discovered capability gaps and synergies
- Select resilient concepts by anticipating and evaluating future uncertainties
- Determine proactive resourcing adjustments to accelerate development schedule
- Select optimal prior program models for reuse with trade-off of alternative models
- Reach agreement on change impact assessments through interactive model-based sessions

IMCSE will leverage many of the benefits of MBSE and Visual Analytics

Discoverer II 1998

24 satellites, IOC: ?? cost: $10B

Cancelled in 2000

- High costs, **lack of stated req'ts** or CONOPs, trade-off analyses
- Would overtax existing systems

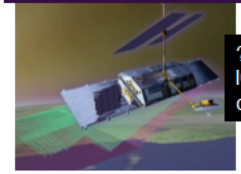
Space-Based Radar (SBR) 2001

9 satellites, IOC: 2008 cost: $34B

Effectively cancelled in 2005

- **Lack of agreement among stakeholders**, no approved CONOPs
- No plan for downstream acquisition issues

Space Radar (SR) 2005



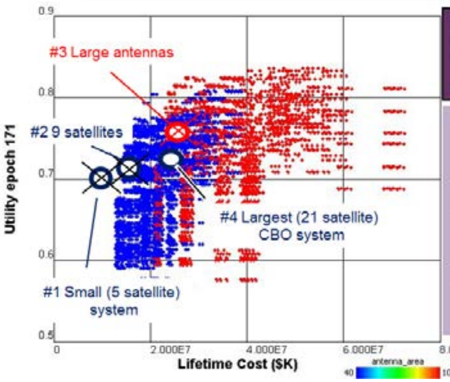
? satellites, IOC: 2015 cost: $??B

Cancelled in 2008

- **Failed to meet req'ts oversight**
- Lacked long-term funding plan

Alternative Space Radar Architectures Examined by CBO

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Number of Satellites	5	9	9	21
Aperture Dimensions	16 x 2.5 m	16 x 2.5 m	25 x 4 m	16 x 2.5 m
Aperture Area	40 m²	40 m²	100 m²	40 m²
Orbital Configuration[a]	Walker 5/5/1	Walker 9/3/2	Walker 9/3/2	Walker 21/7/3



Epoch 171
No AISR avail, WGS avail
No jamming, TRL 9 tech
TARGETS: Mideast med, Asia large, Imaging mission (primary)

- Performance of 4 designs studied by CBO calculated using our model
- Good agreement with CBO analysis
- 3 of 4 systems did not meet the maximum target acquisition time requirement for epoch 171 (X'ed)
- The largest system (21 satellites) did, but is not a Pareto efficient design

Key mission for the US government, but programs repeatedly cancelled mostly due to inability to effectively characterize cost and benefits of program under uncertainty

*Congressional Budget Office, *Alternatives for Military Space Radar*, January 2007.

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Vision for IMCSE Research Program

MIT SEAri Systems Engineering Advancement Research Initiative

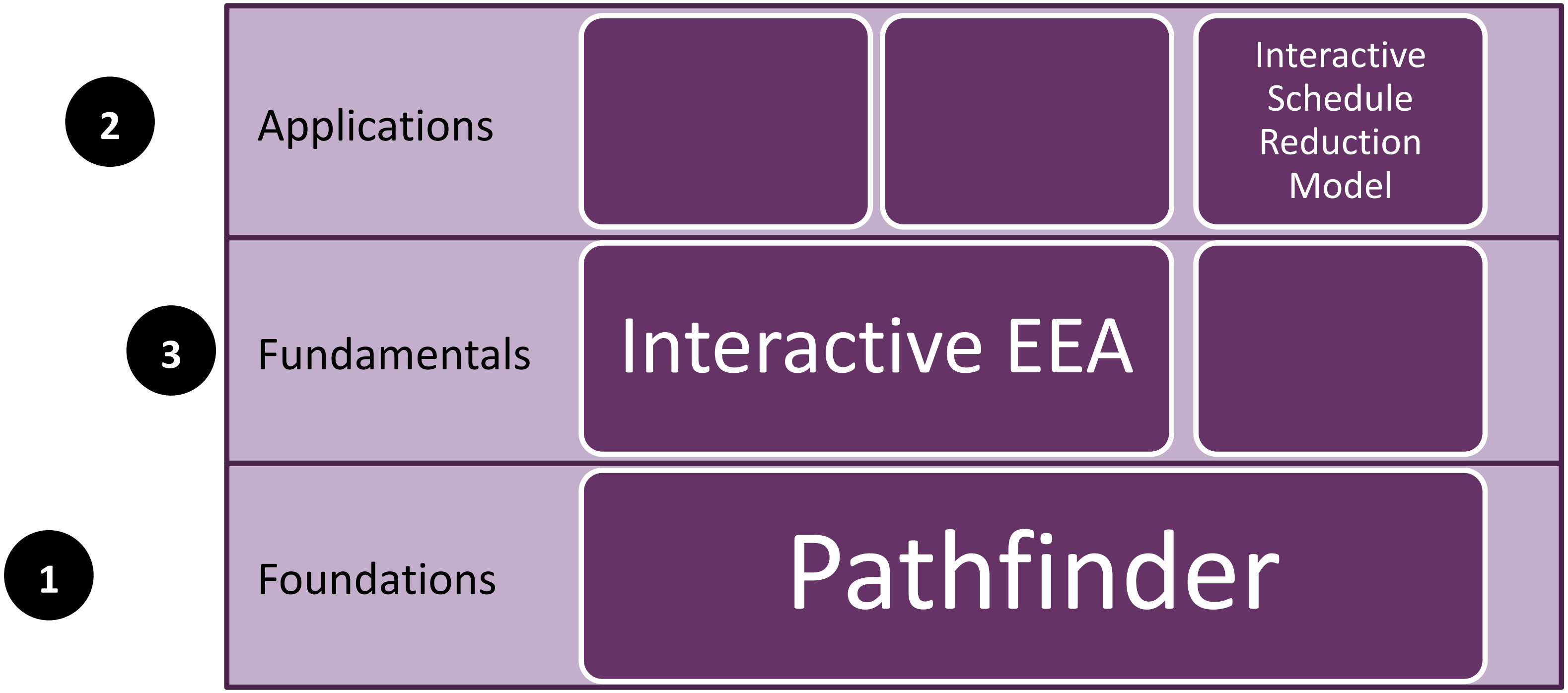
- IMCSE will pursue a balanced basic and applied research approach
  - leveraging strengths of academic environment (e.g. fundamentals, rigor, neutral party view of problem), and
  - keeping the research relevant to the sponsor community, and
  - enabling opportunities for knowledge and MPT transfer to sponsors
- As the program matures, collaborations inside and outside of SERC

Knowledge Transfer Opportunities

Workshops, teleconferences and meetings, reports, papers, collaboration with other SERC activities, prototypes, MPTs, government partner applications, potential student internships

The IMCSE research program aims to develop transformative results through enabling intense human-model interaction, to rapidly conceive of systems and interact with models in order to make rapid trades to decide on what is most effective given present knowledge and future uncertainties, as well as what is practical given resources and constraints.

Approach in Three Thrusts



- To have most impact, IMCSE uses three complimentary thrusts with different timescales for impact
  1. Foundations: 1 year, set the stage for IMCSE
  2. Applications: 1 year, short timescale impact, deployment opportunities
  3. Fundamentals: multi-year, medium timescale impact, potentially broad applicability

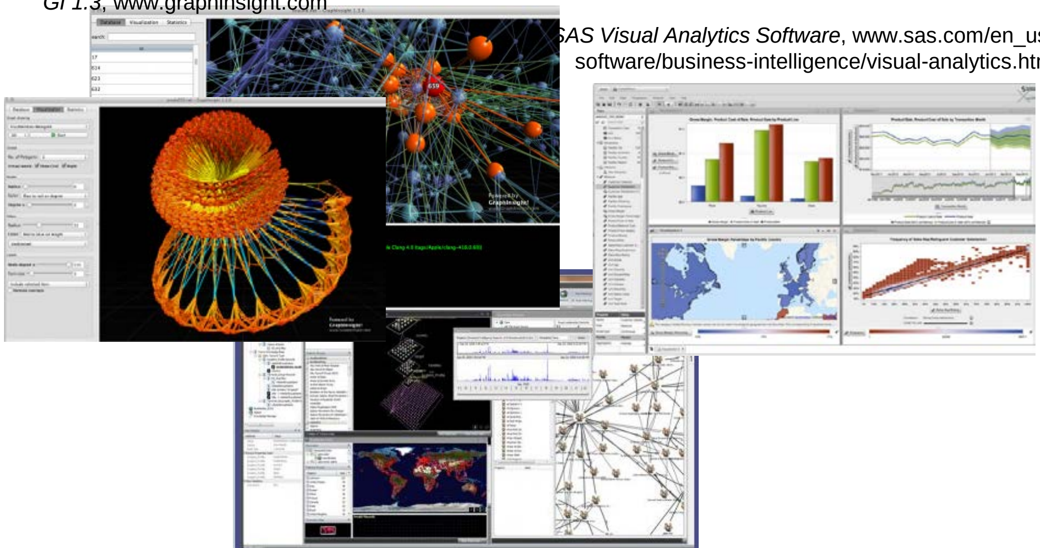
- Following year one, we anticipate additional projects within applications and fundamentals, plus updates to foundations

Thrust 1: Foundations
IMCSE Research Pathfinder

Enabling Software Tools

GI 1.3, www.graphinsight.com

SAS Visual Analytics Software, www.sas.com/en_us/software/business-intelligence/visual-analytics.html



Starlight Visual Information System, www.futurepointsystems.com

Georgia Tech — MBSE Model-Based Systems Engineering Center
http://www.mbse.gatech.edu/

http://www.lboro.ac.uk/research/avrrc/

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

[v]alt Visual Analytics Laboratory @ Tufts
http://valt.cs.tufts.edu/

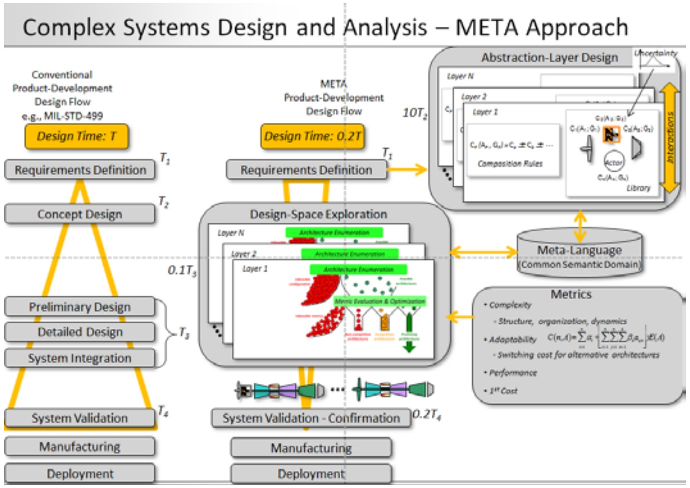
Visual Analytics Community — NVAC National Visualization and Analytics Center
http://vacommunity.org/tiki-index.php

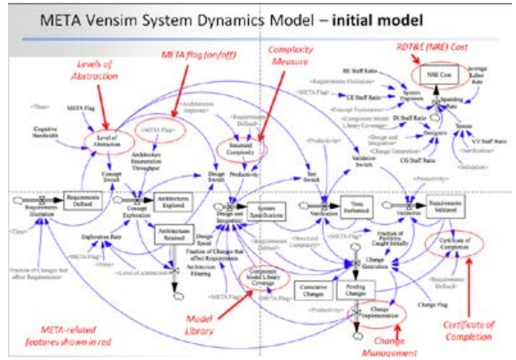
The Pathfinder project will focus on identification of past and present related state of art and practice, and will begin to build a community of interest around IMCSE

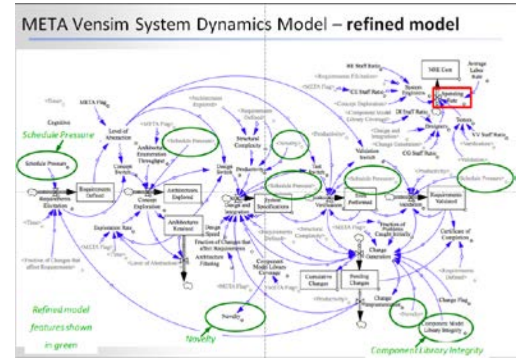
- **Lead**: Dr. Donna H. Rhodes, Dr. Adam M. Ross
- **Summary**: Investigation of state of art and practice, conduct of an invited workshop including SERC and selected outside entities
- **Example Anticipated Outcomes**: Workshop summary report, literature review, research agenda report

Thrust 2: Applications

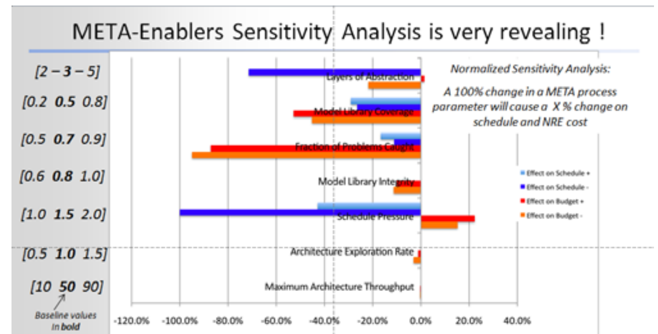
Interactive Schedule Reduction Model



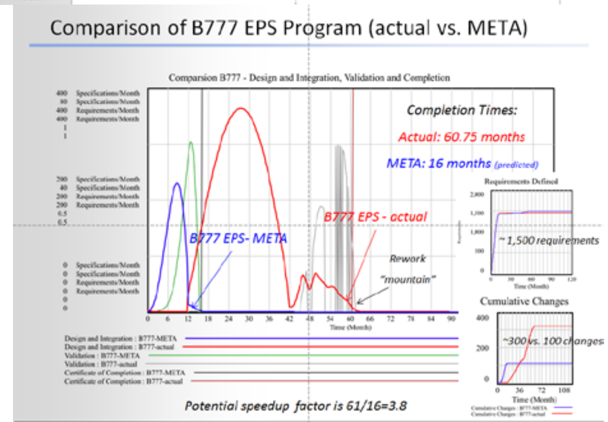




de Weck, O., "Feasibility of a 5x speedup in system development due to META design", ASME 2012 IDETC, Chicago, IL, Aug 12-15, 2012, paper DETC2012-70791.



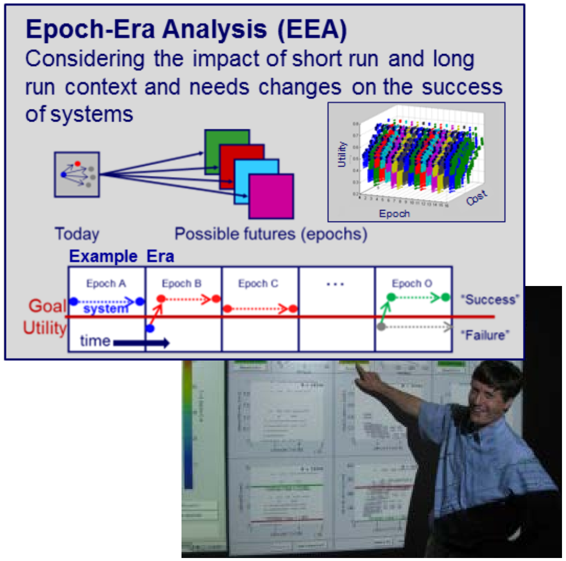
Leveraging prior work from DARPA META, the Schedule Reduction Model will be extended with interactivity as a central aspect, promoting sensitivity analyses and benchmarking to be the central use case

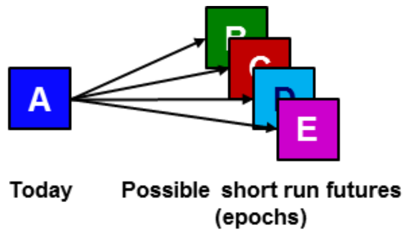


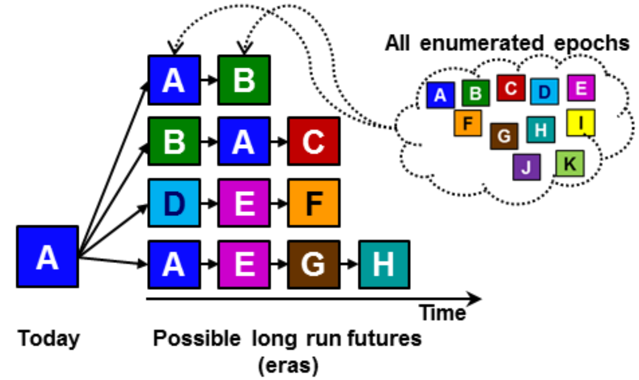
- **Lead**: Professor Olivier de Weck
- **Summary**: Exploratory extension of system dynamics-based Schedule Reduction Model, w/prototype model for pilot application
- **Example Anticipated Outcomes**: Report, Demo, Prototype, Potential Deployment Partner

Thrust 3: Fundamentals

Interactive Epoch-Era Analysis



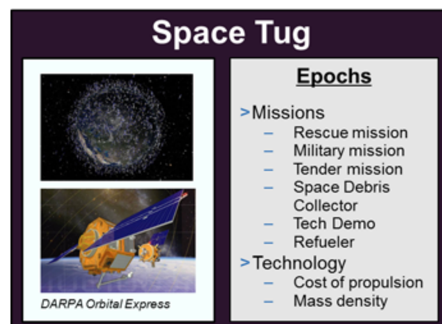


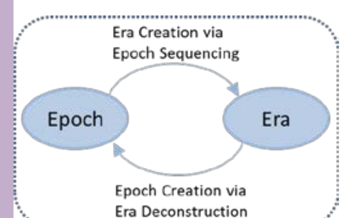


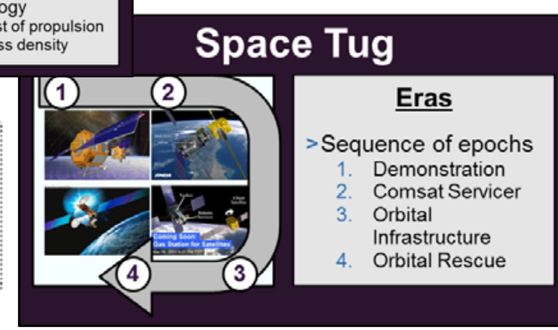
IED attacks in Iraq: (*Wired*)

EEA is a framework that supports narrative and computational scenario planning and analysis for both short run and long run futures

- **Lead**: Dr. Adam M. Ross, Dr. Donna H. Rhodes
- **Summary**: Exploratory development of interactive Epoch-Era Analysis, including human interface and reasoning considerations for epoch and era characterizations, as well as single and multi- epoch/era analyses
- **Example Anticipated Outcomes**: Report, Papers, Proof of concept demo via mission planning support





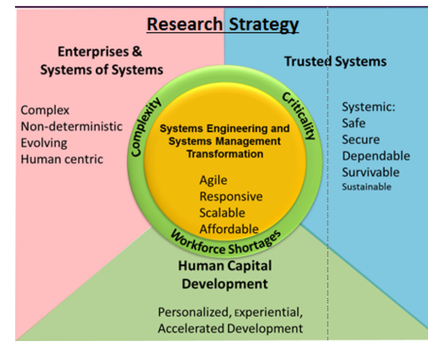


IMCSE Going Forward

- Looking forward to beginning this research program soon…
- This program is just a start with clear growth opportunities
  - E.g. Leverage MIT initiatives

bigdata @CSAIL

  - E.g. Leverage other SERC initiatives
    - Full lifecycle MBSE, including Concept Engineering



- IMCSE has applicability across DoD and government in general
  - Looking for additional collaborators within SERC
  - Looking for additional government partners for case applications and field testing
- While starting in defense-oriented applications, IMCSE can be leveraged for use in government more generally

Future of SE Decision Making

- In the future, SE decisions must be more rapid, holistic, and better than "good enough"…
  - Q: How to manage system and program given dynamic uncertainties through the lifecycle?
  - A: IMCSE will enable more rapid and transparent decision making that will result in more affordable and valuable system solutions
- How could IMCSE turn out in 5-10 years?
  - Current visual analytics research shows how interaction reveals domain knowledge, which could then be used for learning systems (e.g. intelligent systems that further augment humans by anticipating queries and pre-fetching large data sets)
- Future IMCSE will show its value by enabling systems and programs to be more anticipatory and empowered to discover superior dynamic strategies, resulting in transformative capabilities

This type of capability could be used to address a host of questions, such as:

Programmatic

- How to write source selection criteria in RFP?
- How to implement changes to save the program today without killing the program in five years?
- How to trade changing requirements for building a "better" yet delayed system with building a less-capable system on schedule?

Infrastructure

- How to assess the impact of infrastructure improvements on program performance and cost?

Systems-of-Systems

- How to assess the impact of other asset availability to augment primary system performance during operations?

Dynamic Acquisition Strategies

- What are the implications of a staged deployment strategy vs. single deployment?

"Models can easily become so complex that they are impenetrable, unexaminable, and virtually unalterable."

– Donella Meadow (1980) "The unavoidable a priori" in: Randers J. ed., *Elements of the system dynamics method,* p.27

"Essentially, all models are wrong, but some are useful."

– George E.P. Box, Norman R. Draper (1987) *Empirical Model-Building and Response Surfaces,* p. 424

"There are many specific techniques that modellers use, which **enable us to discover aspects of reality that may not be obvious to everyone**... but they are not as important as the ability to **understand the underlying dynamics of a complex system** well enough to **assess whether the assumptions of a model are correct and complete**. …whether a model **reflects reality, and to identify and deal with divergences between theory and data**"

– William Silvert (2001) "Modelling as a Discipline" in: *Int. J. General Systems*. Vol. 30(3), p. 261

*"Artificial things are synthesized (though **not always and usually** with full **forethought**) by human beings"*

– Herb Simon (1996) *The Science of the Artificial,* third ed., p. 5

How can we enable more deliberate forethought in our systems throughout their lifecycle using interactive models?

Back up slides

Using an “Epoch”-based Framework is Not New…

Era

Variable:

- Environment
- “Systems”
- Value

Epoch Shift

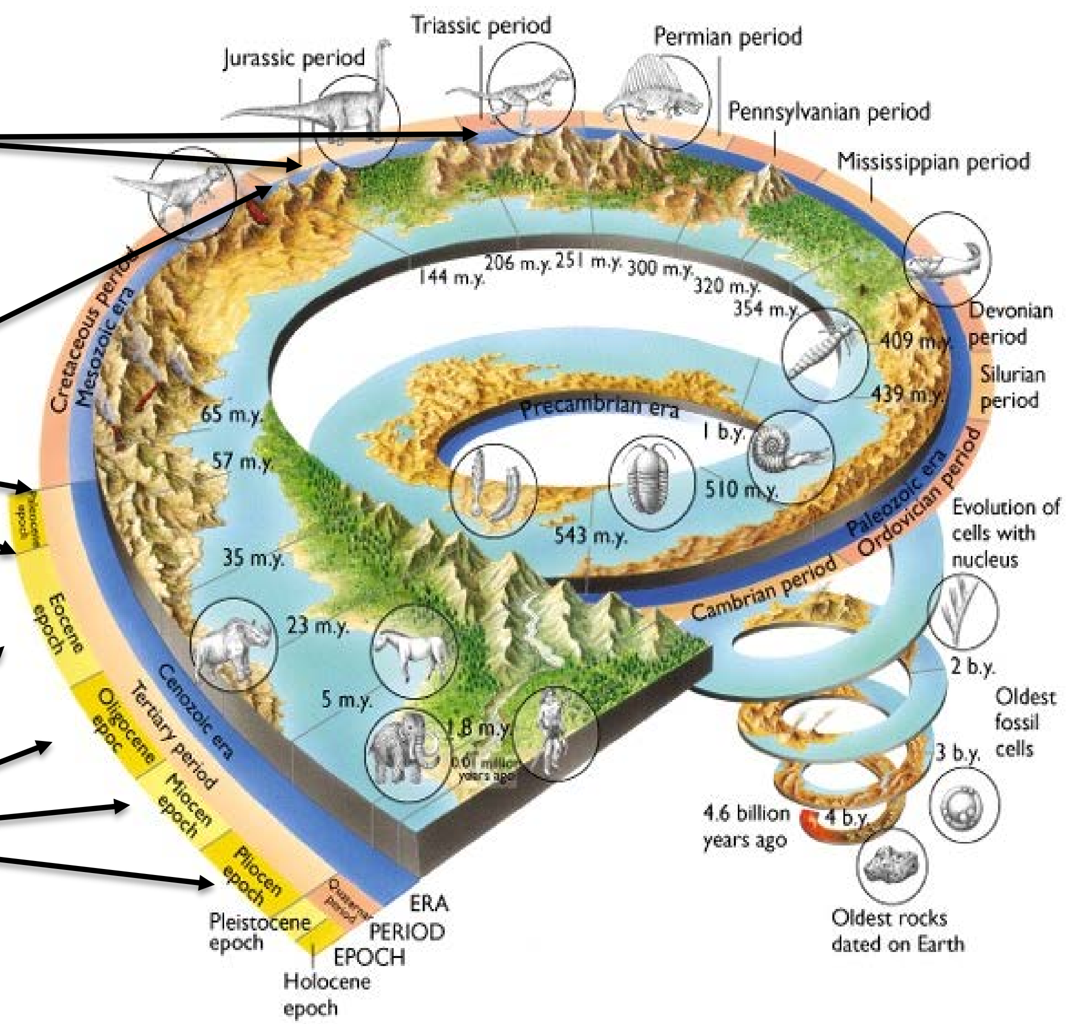
Change in:

- Environment
- “Systems”
- Value

Epoch

Fixed:

- Environment
- “Systems”
- Value



(EEA example slide courtesy of Andrew Long, 2010)

Various Epochs Define the World for our Systems…

(EEA example slide courtesy of Andrew Long, 2010)

… and Can be Assembled into Possible Eras (Futures)

(EEA example slide courtesy of Andrew Long, 2010)

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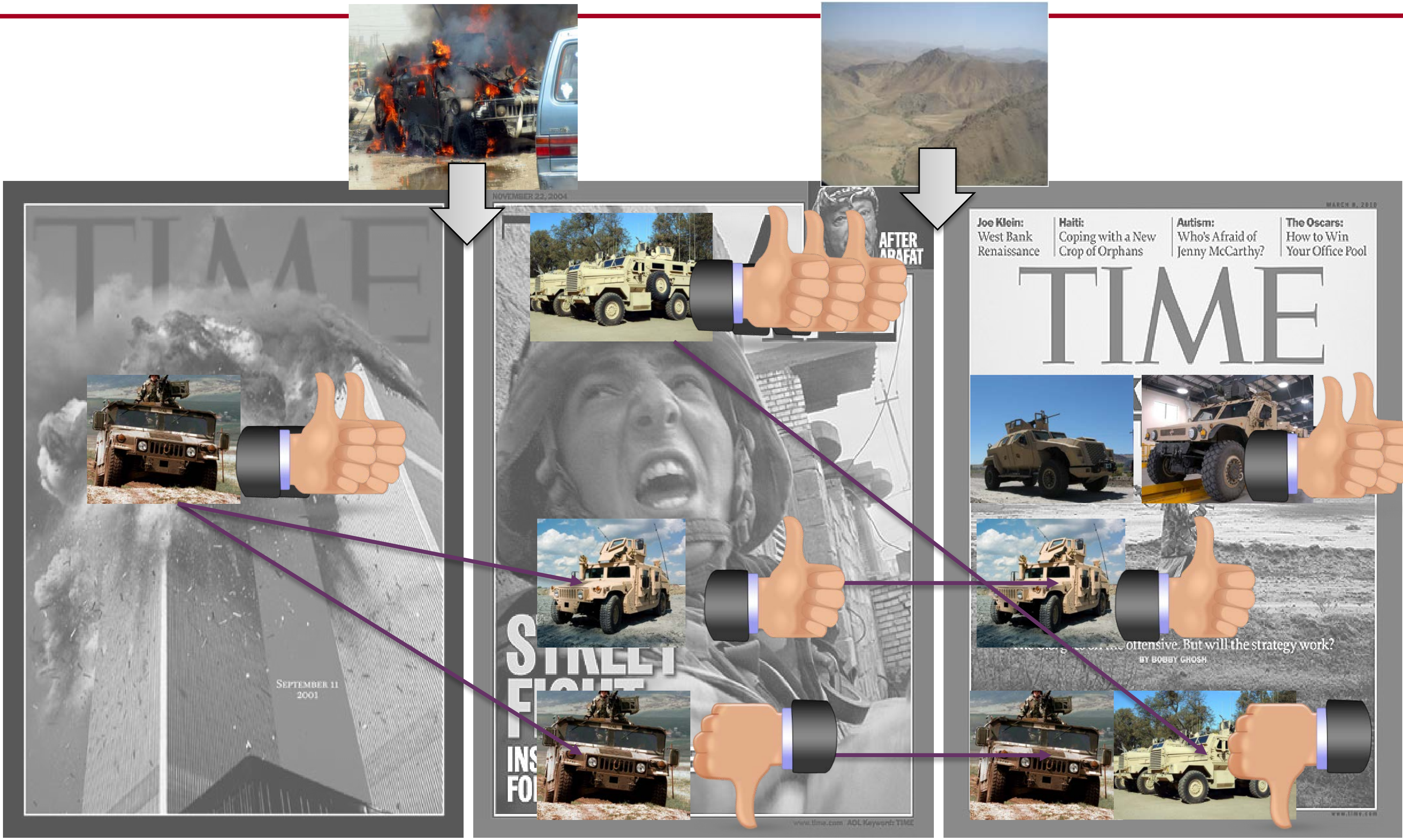
Example: Modern HMMWV

SEAri MIT Systems Engineering Advancement Research Initiative

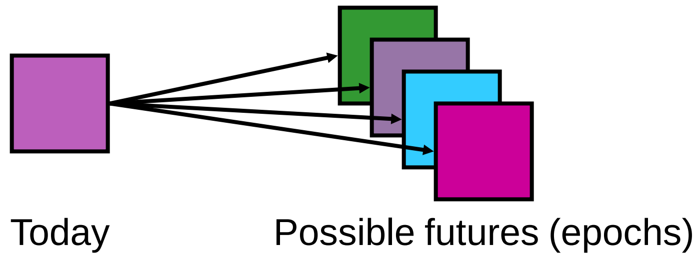


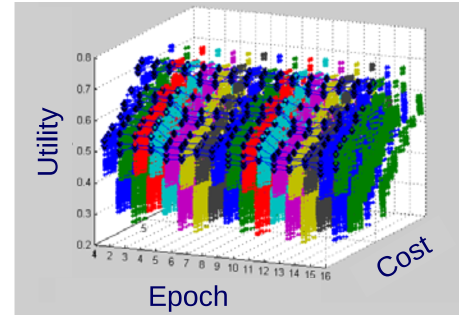
(EEA example slide courtesy of Andrew Long, 2010)

Generating Epochs

Many possible contexts and needs may unfold in the future, impacting actual and perceived system utility and cost

"Epoch-based thinking" can be used to structure anticipatory scenario analysis





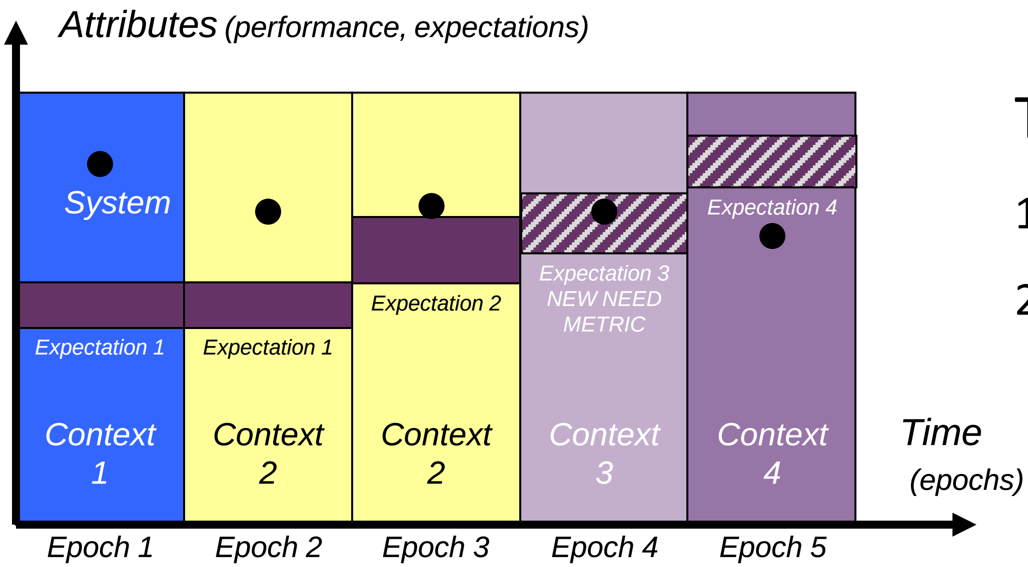
Example triggers for epoch shifts impacting a system

- Change in political environment
- Entrance of new competitor in market
- Emergence of significant new or changed stakeholder need(s)
- Policy mandate impacting product line, services or operations

<u>Categories of epoch variables can aid in thinking about key changing factors</u>

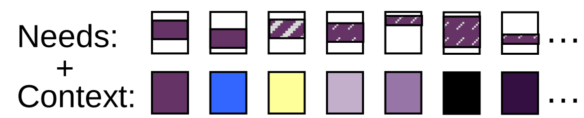
E.g., Resources, Policy, Infrastructure, Technology, End Uses ("Markets"), Competition, etc.

Storyboarding with Epochs

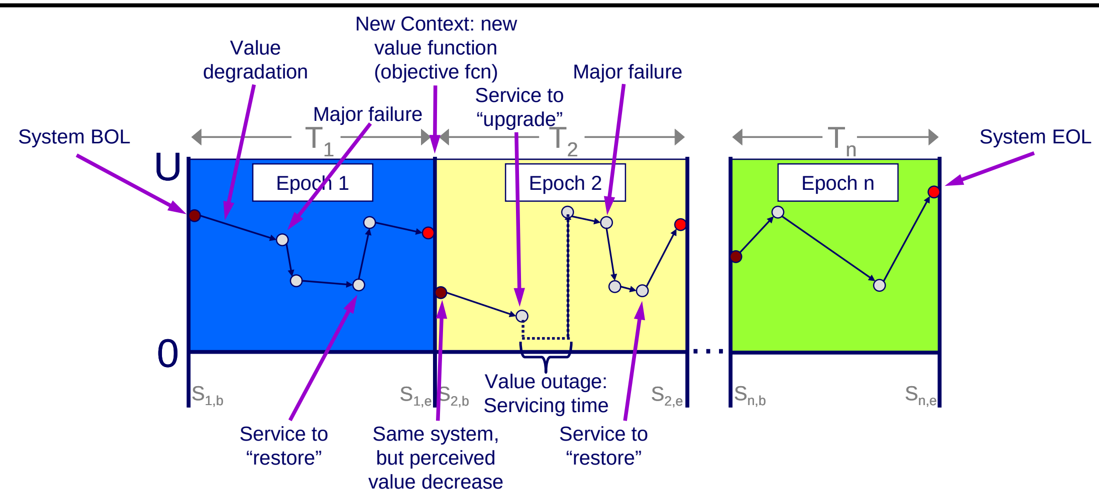


Two aspects to an ***Epoch***:

1. Needs (expectations)
2. Context (constraints including resources, technology, etc.)

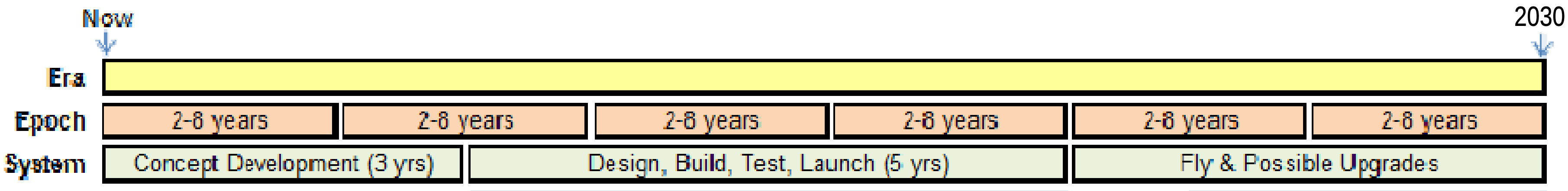


Example system:
Serviceable satellite



Epochs and Eras to Consider Long Run Uncertainties

- System Development Lifecycle (SDLC) is a crucial organizing construct for managing system design activities, but does not facilitate management of uncertain contexts and mission needs



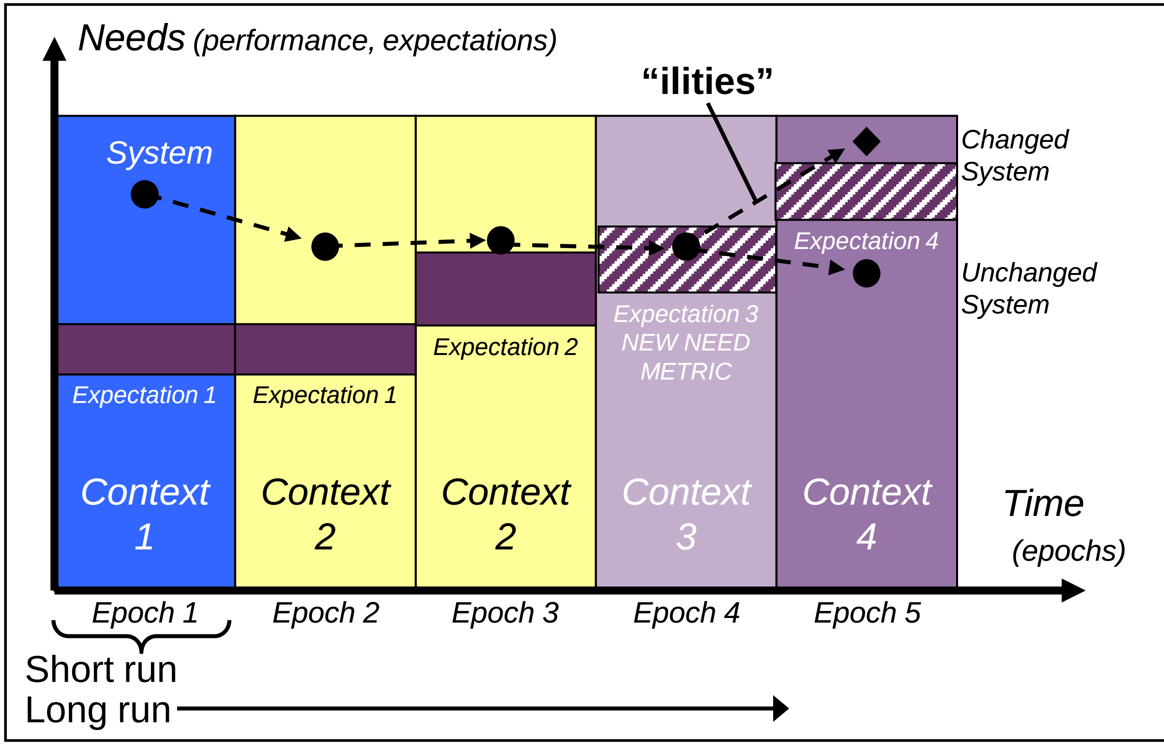
(Ross and Rhodes 2008)

- Epoch
  - A period of time during which the context and mission needs are static
  - Duration is determined by underlying dynamics of contextual factors considered
- Era
  - Spans the total lifecycle of a system
  - Constitutes an integrated set of epochs
  - Allows analysis of system evolution strategies

Epoch-Era Analysis provides a structured way to consider the impact of context changes and mission needs over the SDLC

Using Epochs for Proposing Time-Based Strategies across Eras

Discretization of change timeline into short run and long run enables analysis



Epoch:

Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated needs

Era:

Time-ordered sequence of epochs

Legend
- ● System
- ▬ ► System Trajectory
- ▨ Expectations

(Ross and Rhodes 2008)

In order to pursue dynamic strategies, a system must have temporal properties, i.e., "-ilities" such as flexibility, evolvability, or survivability

SYSTEMS ENGINEERING Research Center

IMCSE Summary

MIT Systems Engineering Advancement Research Initiative

Summary: Catalyze human-model interaction capabilities and MPTs to rapidly conceive of systems, and to accelerate rapid trades for deciding on what is most effective, given present knowledge and future uncertainties, and what is practical, given resources and constraints.

- Project 1: IMCSE Pathfinder
  - — Investigation of state of art and practice
  - — Invited research workshop with report
  - — Pathfinder project report
- Project 2: Interactive Schedule Reduction Model
  - — Exploratory extension w/prototype model for pilot application, and project report
- Project 3: Interactive Epoch-Era Analysis
  - — Exploratory development of interaction capability w/ demo case via mission planning support, and project report
- Build community and publish several papers

Prior Related Work

- Prior SERC research: RT-30: Graphical CONOPS
- Prior/ongoing MIT research under other sponsors:
  - Research lab with interactive tradespace exploration capability (prior-NRO, foreign gov'ts)
  - Prototype schedule reduction model (prior-DARPA)
  - Epoch-Era Analysis (EEA)
    - Method development for considering alternative futures (prior-NRO)
    - Method refinement (prior-AFOSR, NPS, foreign gov'ts)
    - Method application cases within multiple domains (prior-NRO, AFOSR, NPS, USCG, Army, foreign gov'ts)
  - Development and transition of MPTs embodying research outcomes (prior-foreign gov'ts)