The Role of Empirical Study in Software Engineering

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Setting the Context

- Software engineering is an engineering discipline
- We need to understand products, processes, and the relationship between them (*we assume there is one*)
- We need to experiment (human-based studies), analyze, and synthesize that knowledge
- We need to package (model) that knowledge for use and evolution
- Recognizing these needs **changes how we think**, what we do, what is important

Motivation for Empirical Software Engineering

Understanding a discipline involves observation, model building, and experimentation

Learning involves the encapsulation of “knowledge”, checking our “knowledge” is correct, and evolving it over time

This is the empirical paradigm that has been used in many fields, e.g., physics, medicine, manufacturing

Like other disciplines, software engineering requires an empirical paradigm

The nature of the field influences the approach to empiricism.

Motivation for Empirical Software Engineering

Empirical software engineering involves the scientific use of quantitative and qualitative data to understand and improve the software product, software development process and software management

It requires real world laboratories

Research needs laboratories to observe & manipulate the variables

- they only exist where developers build software systems

Development needs to understand how to build systems better

- research can provide models to help

Research and Development have a synergistic relationship that requires a working relationship between industry and academe

Motivation for Empirical Software Engineering

For example, a software organization needs to ask:

- What is the right combination of technical and managerial solutions?
- What are the right set of process for that business?
- How are they tailored?
- How do they learn from their successes and failures?
- How do the demonstrate sustained, measurable improvement?

More specifically:

- When are peer reviews more effective than functional testing?
- When is an agile method appropriate?
- When do I buy rather than make my software product elements?

Examples of Useful Empirical Results

"Under specified conditions, …"

Technique Selection Guidance

- Peer reviews are more effective than functional testing for faults of omission and incorrect specification (UMD, USC)
- Functional testing is more effective than reviews for faults concerning numerical approximations and control flow (UMD, USC)

Technique Definition Guidance

- For a reviewer with an average experience level, a procedural approach to defect detection is more effective than a less procedural one. (UMD)
- Procedural inspections, based upon specific goals, will find defects related to those goals, so inspections can be customized. (UMD)
- Readers of a software artifact are more effective in uncovering defects when each uses a different and specific focus. (UMD)

Basic Concepts
for Empirical Software Engineering

The following concepts have been applied in a number of organizations

Quality Improvement Paradigm (QIP)

An evolutionary learning paradigm tailored for the software business

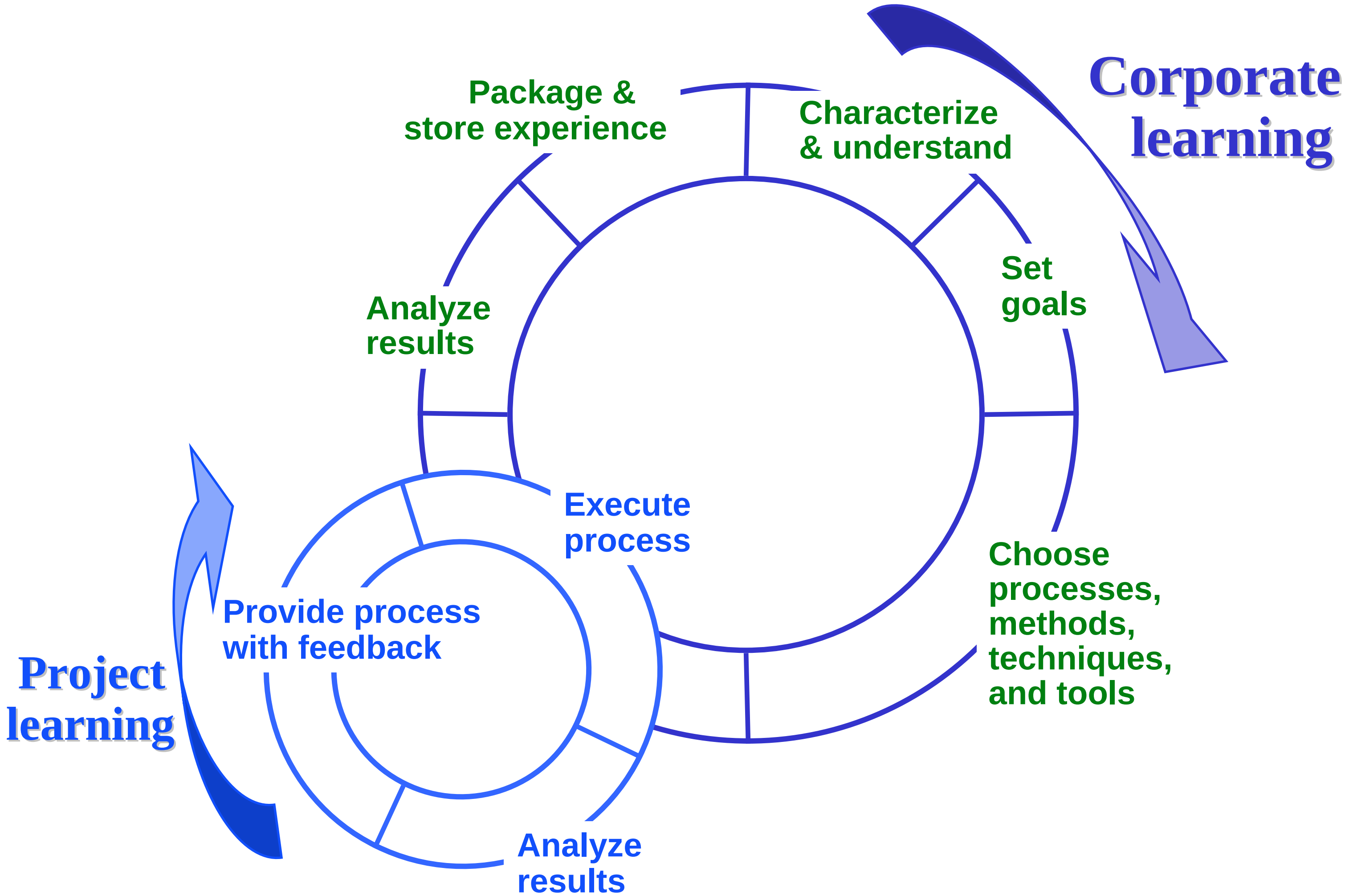
Goal/Question/Metric Paradigm (GQM)

An approach for establishing project and corporate goals and
a mechanism for measuring against those goals

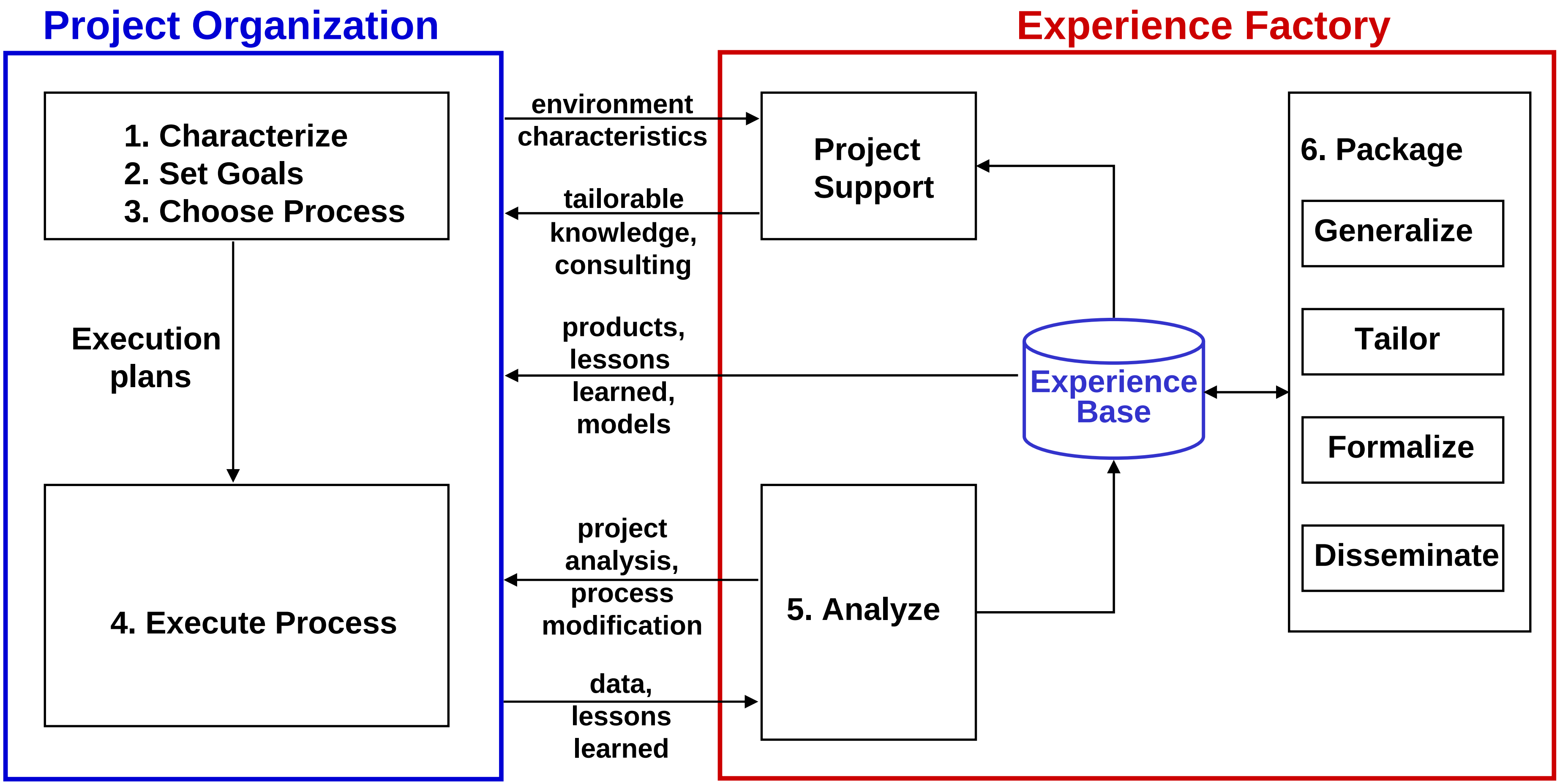
Experience Factory (EF)

An organizational approach for building software competencies and
supplying them to projects

Quality Improvement Paradigm



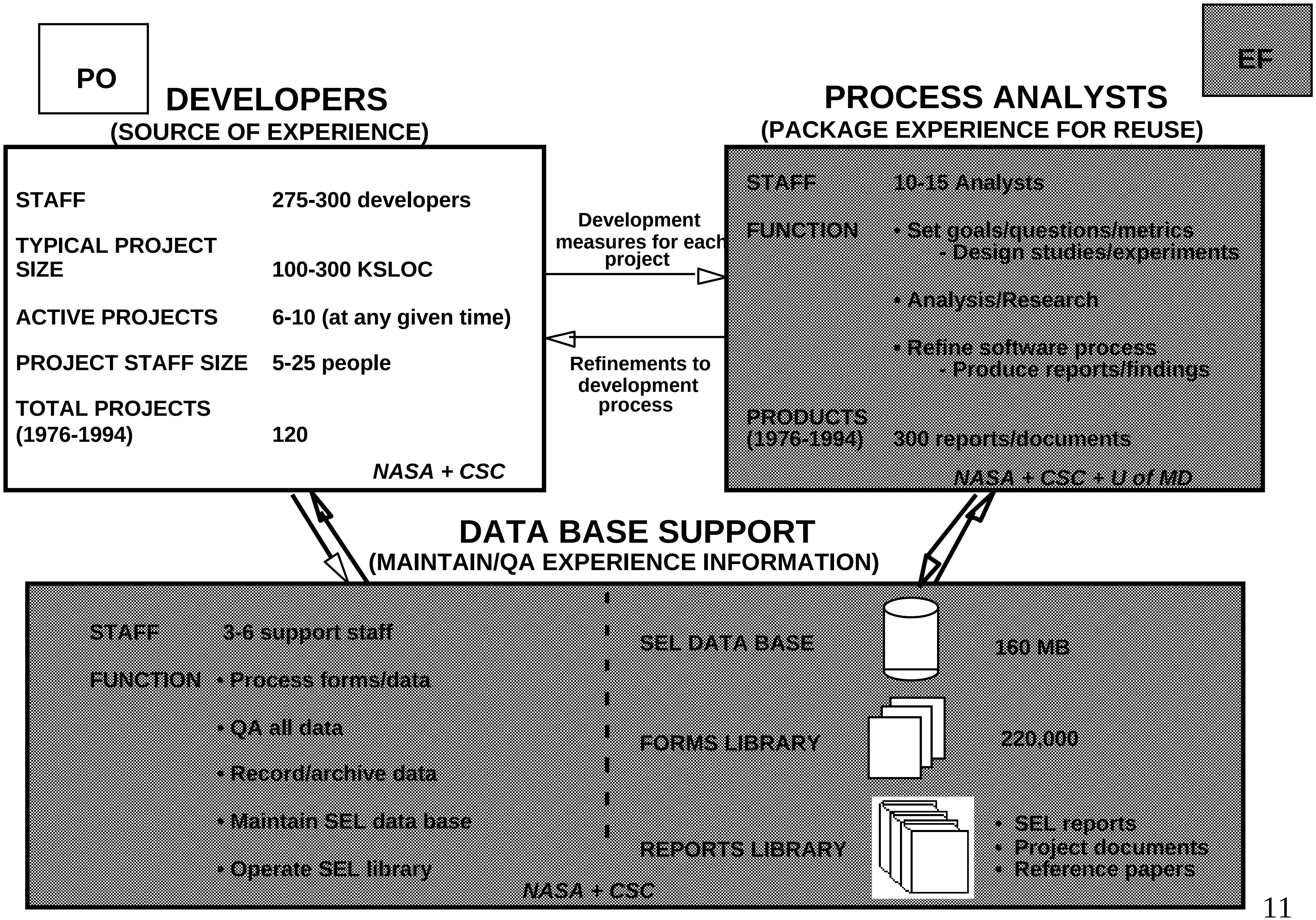
The Experience Factory Organization



The Experience Factory Organization
A Different Paradigm

Project Organization Problem Solving	Experience Factory Experience Packaging
Decomposition of a problem into simpler ones	Unification of different solutions and re-definition of the problem
Instantiation	Generalization, Formalization
Design/Implementation process	Analysis/Synthesis process
Validation and Verification	Experimentation
Product Delivery within Schedule and Cost	**Experience / Recommendations Delivery to Project**

SEL: An Example Experience Factory Structure



Using Baselines to Show Improvement 1987 vs. 1991 vs. 1995

Continuous Improvement in the SEL

Decreased **Development Defect rates** by
75% (87 - 91) **37%** (91 - 95)
Reduced **Cost** by
55% (87 - 91) **42%** (91 - 95)
Improved **Reuse** by
300% (87 - 91) **8%** (91 - 95)
Increased **Functionality** five-fold (76 - 92)

CSC officially assessed as CMM level 5 and ISO certified (1998), starting with SEL organizational elements and activities

These successes led to

Fraunhofer Center for Experimental Software Engineering - 1997

CeBASE Center for Empirically-based Software Engineering - 2000

CeBASE
Center for Empirically Based Software Engineering

CeBASE Project Goal: Enable a **decision framework and experience base** that forms a basis and infrastructure needed to evaluate and choose among software development technologies

CeBASE Research Goal: Create and evolve an **empirical research engine** for building the research methods that can provide the empirical evidence of what works and when

Partners: Victor Basili (UMD), Barry Boehm (USC)

CeBASE NSF Center for Empirically Based Software Engineering

University of Maryland • Fraunhofer Center-MD • University of Southern California • University of Nebraska • Mississippi State University

CeBASE Approach

Observation and Evaluation Studies of Development Technologies and Techniques

Empirical Data

Predictive Models

(Quantitative Guidance)

General Heuristics

(Qualitative Guidance)

E.g. COCOTS excerpt:

Cost of COTS tailoring = f(# parameters initialized, complexity of script writing, security/access requirements, …**)**

E.g. Defect Reduction Heuristic:

For faults of **omission** and **incorrect specification, peer reviews** are more effective than functional testing.

CeBASE
Three-Tiered Empirical Research Strategy

Technology maturity	Primary activities	Evolving results
Practical applications (Government, industry, academia)	Practitioner use, tailoring, and feedback. Maturing the decision support process.	Increasing success rates in developing agile, dependable, scalable applications.
Applied Research	Experimentation and analysis with the concepts in selected areas.	Partly filled EB, more mature empirical methods, technology maturation and transition.
Basic Research	Building a SE Empirical Research Engine and Experience base structure	Empirical methods for SE, Experience Base definition, decision support structure

CeBASE Basic Research Activities

Define and improve methods to

- Formulate evolving hypotheses regarding software development **decisions**
- Collect empirical **data** and experiences
- Record **influencing variables**
- Build **models** (Lessons learned, heuristics/patterns, decision support frameworks, quantitative models and tools)
- Integrate models into a **framework**
- Testing **hypotheses** by application
- **Package** what has been learned so far so it can be evolved

Applied Research

NASA High Dependability Computing Program

Problem: How do you elicit the software dependability needs of various stakeholders and what technologies should be applied to achieve that level of dependability?

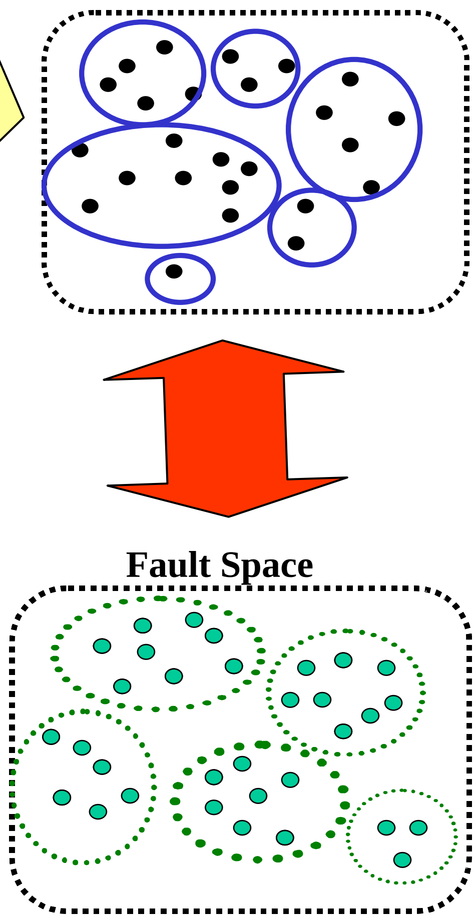
Project Goal: Increase the ability of NASA to engineer highly dependable software systems via the development of new technologies in systems like Mars Science Laboratory

Research Goal: Quantitatively define dependability, develop high dependability technologies and assess their effectiveness under varying conditions and transfer them into practice

Partners: NASA, CMU, MIT, UMD, USC, U. Washington, Fraunhofer-MD

What are the top level research problems?

System Users



Research Problem 1
Can the quality needs be understood and modeled?

Technology Developers

Research Problem 2
What does a technology do?
Can it be empirically demonstrated?

Research Problem 3
What set of technologies should be applied to achieve the desired quality? (Decision Support)

System Developers

System User Issues

How do I elicit quality requirements?
How do I express them in a consistent, compatible way?

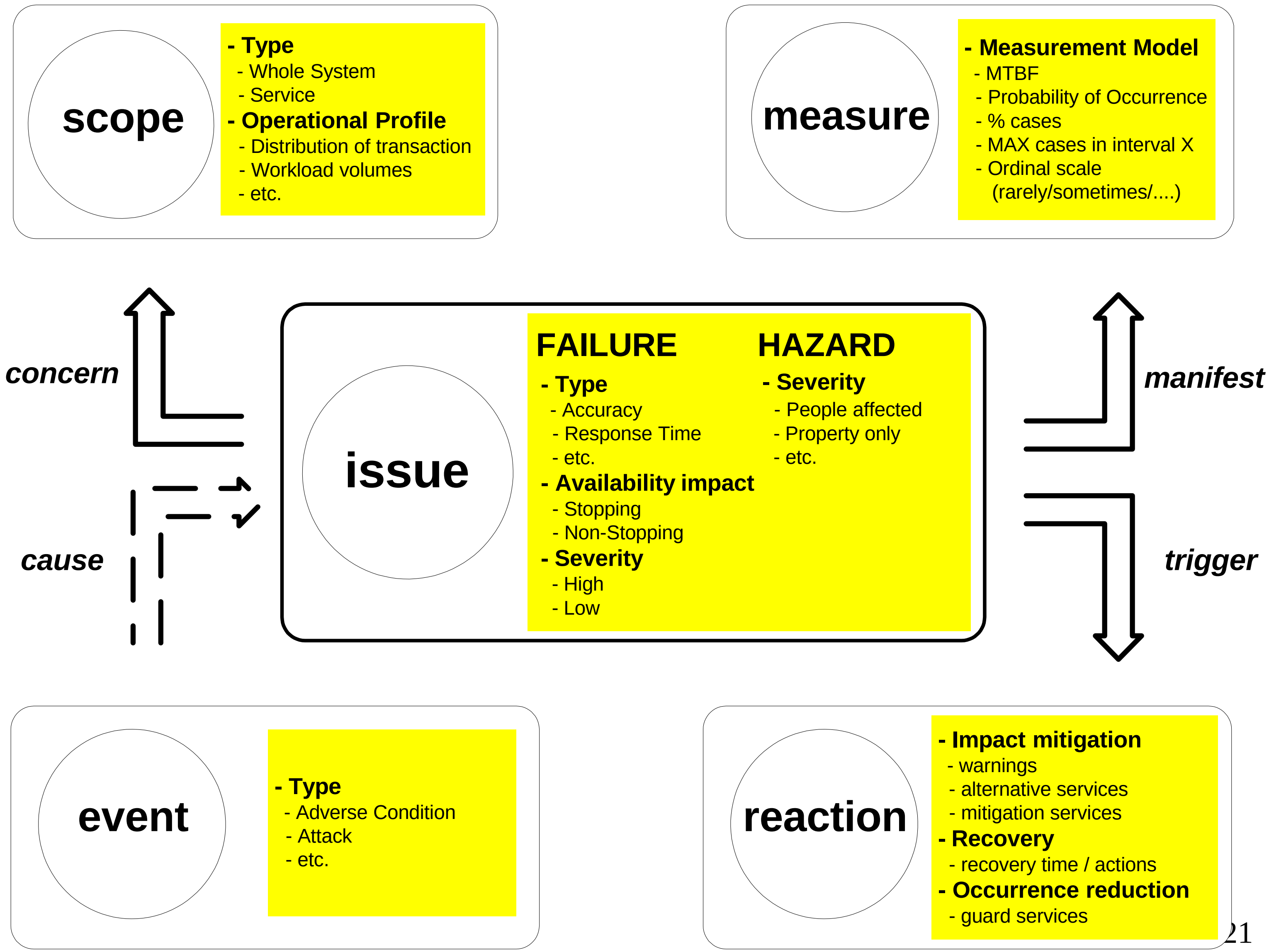
- How do I identify the non-functional requirements in a consistent way?
  - Across multiple stakeholders
  - In a common terminology (Failure focused)
  - Able to be integrated
- How can I take advantage of previous knowledge about failures relative to system functions, models and measures, reactions to failures?
  - Build an experience base
- How do I identify incompatibilities in my non-functional requirements for this particular project?

UMD - Unified Model of Dependability

- The **Unified Model of Dependability** is a requirements engineering framework for eliciting and modeling quality requirements
- Requirements are expressed by specifying the actual **issue** (failure and/or hazard), or class of issues, that should not affect the system or a specific service (**scope**).
- As issues can happen, tolerable manifestations (**measure**) may be specified with a desired corresponding system **reaction**. External **events** that could be harmful for the system may also be specified.
- For an on-line bookstore system, an example requirement is:

  "The book search service (scope) should not have a response time greater than 10 seconds (issue) more often than 1% of the cases (measure); if the failure occurs, the system should warn the user and recover full service in one hour".

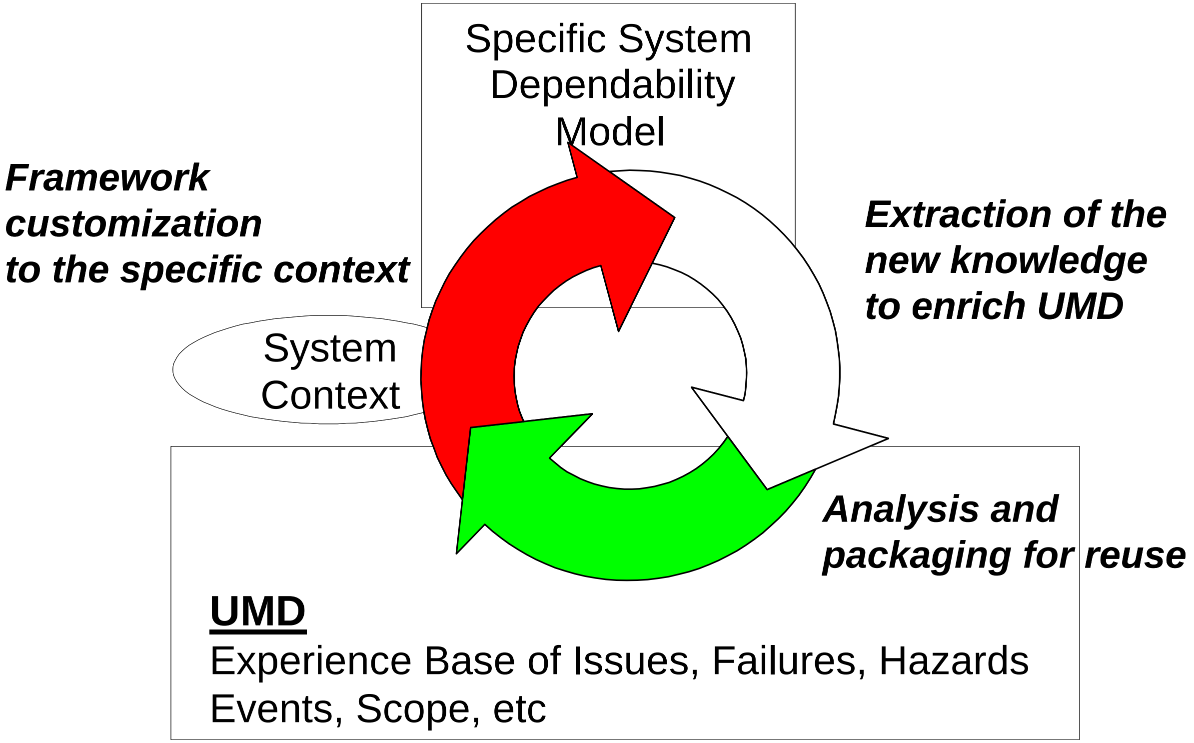
UMD is a model builder



UMD assimilates new experience

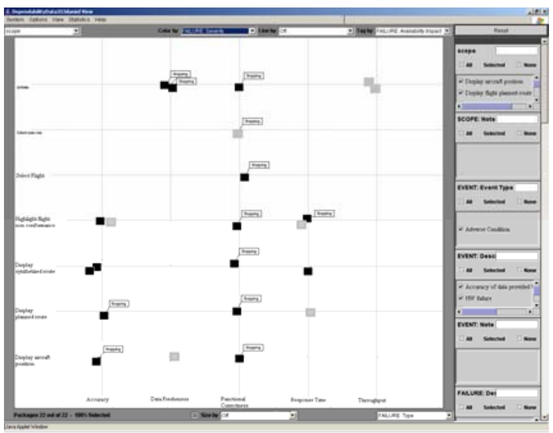
Characterizations (e.g., types, severity, etc.) of the basic UMD modeling concepts of issue, scope, measure, and event depend on the specific context (project and stakeholders).

They can be customized while applying UMD to build a quality model of a specific system and enriched with each new application

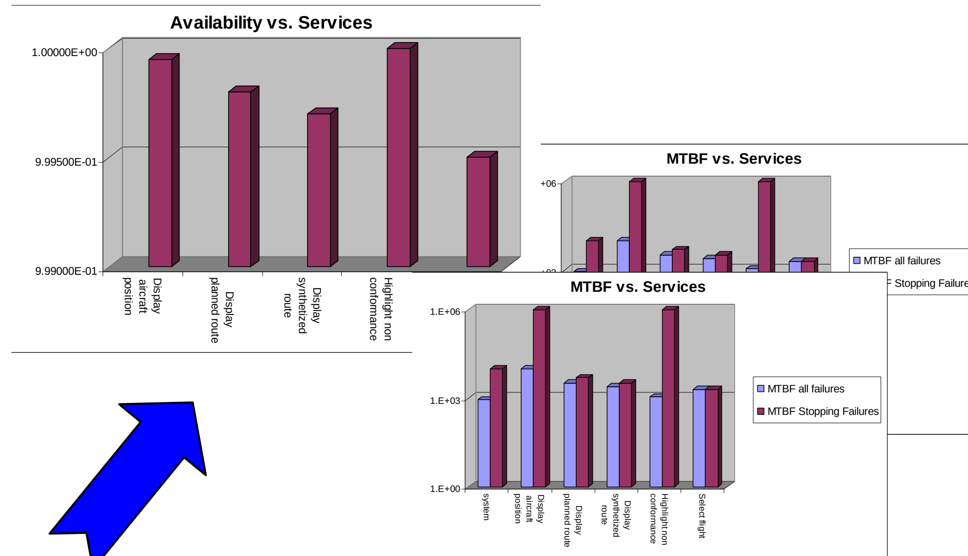


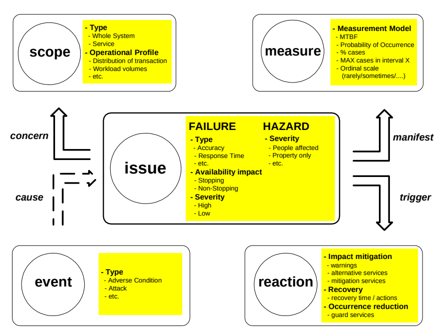
UMD: a framework for engineering decisions

UMD support engineering decisions at requirements phase for quality validation, negotiation, trade-offs analysis



Requirements Visualization





Computation of aggregate values of dependability

(availability, MTBF per service, etc)

UMD

Technology Developer Issues

How well does my technology work?
Where can it be improved?

- How do I articulate the goals of a technology?
  - Formulating measurable hypotheses
- How do I empirically demonstrate its goals?
  - Performing empirical studies
  - Validate expectations/hypotheses
- What are the requirements for a testbed?
  - Fault seeding
- How do I provide feedback for improving the technology?

Example Technology Evolution

A process for **inspections of Object-Oriented designs** was developed using multiple iterations through this method.

Early iterations concentrated on **feasibility**:

- *effort required, results due to the process* in the context of *offline, toy systems.*

Is further effort justified?

Mid-process iterations concentrated on **usability**:

- *usability problems, results due to individual steps* in the context of *small systems in actual development.*

What is the best ordering and streamlining of process steps to match user expectations?

Most recent iterations concentrated on **effectiveness**:

- *effectiveness compared to other inspection techniques previously used by developers* in the context of *real systems under development.* **Does the new techniques represent a usable improvement to practice?**

Using testbeds to transfer technology

- A **testbed** is a set of artifacts and the infrastructure needed for running experiments, e.g., evaluation support capabilities such as instrumentation, seeded defect base; experimentation guidelines, specific features to monitor faults, …

- **Used to**
  - Conduct empirical evaluations of emerging technology
  - Stress the technology and demonstrate its context of effectiveness
  - Help the researcher identify the strengths, bounds, and limits of the particular technology at different levels
  - Provide insight into the integration of technologies
  - Reduce costs by reusing software artifacts
  - Reduce risks by enabling technologies to mature
  - Assist technology transfer of mature results

Example Technology and Testbed Evolution

- **Testbed**: a safety critical air traffic control software component (FC-MD's TSAFE III)
- **Technology**: Tevfik Bultan's model checking design for verification approach applied to concurrent programming in Java
- **Technology goal**: Eliminate synchronization errors techniques
- **Empirical Study Goal**: investigate the effectiveness of the design for verification approach on safety critical air traffic control software
  - Applied the design for verification approach to a safety critical air traffic control software component (FC-MD's TSAFE III)
  - TSAFE III software was reengineered based on the concurrency controller design pattern

Example Technology and Testbed Evolution

- **Testbed** :
  - 40 versions of TSAFE source code were created via fault seeding
  - The faults were created to resemble possible errors that can arise in using the concurrency controller pattern such as
    - making an error while writing a guarded command or
    - forgetting to call a concurrency controller method before accessing a shared object
- **Results**:
  - The experimental study resulted in a
    - Better fault classification
    - Identified strengths and weaknesses of the technology
    - Helped improve the design for verification approach
  - However, there was one type of fault that was difficult to catch
    - Three uncaught faults were created to test this

System Developer Issues

**How can I understand the stakeholders dependability needs?
How can I apply the available techniques to deliver the required dependability?**

- How do I identify what dependability properties are desired?
  - Stakeholders needs, dependability goals and models, project evaluation criteria
- How do I evaluate the effectiveness of various technologies for my project?
  - What is he context for the empirical studies?
- How do I identify the appropriate combinations of technologies for the project needs?
  - Technologies available, characterization, combinations of technologies to achieve goals
- How do I tailor the technologies for the project?

Applied Research

DoE High Productivity Computing Systems

Problem: How do you improve the time and cost of developing high end computing (HEC) codes?

Project Goal: Improve the buyers ability to select the high end computer for the problems to be solved based upon productivity, where productivity means

Time to Solution = Development Time + Execution Time

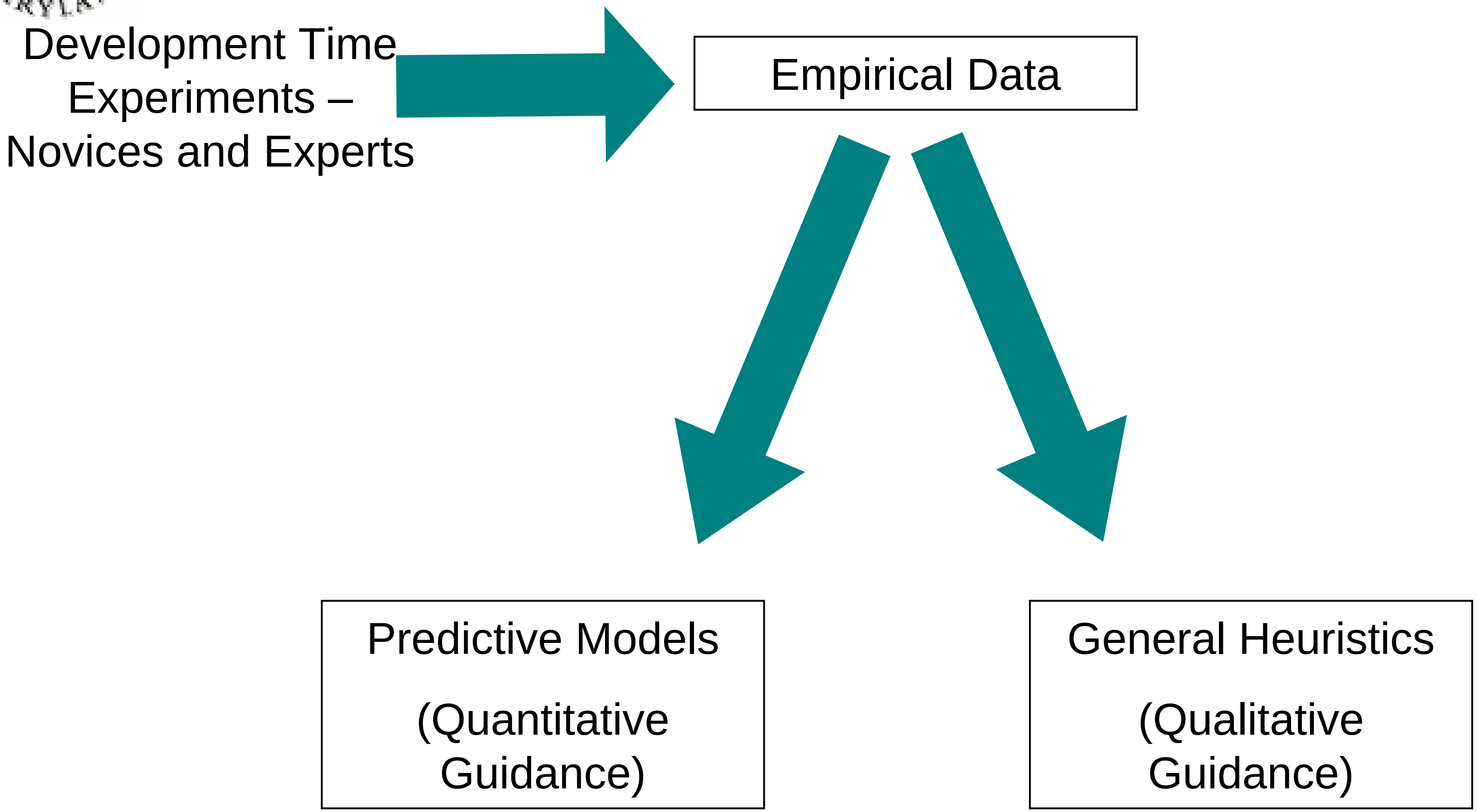
Research Goal: Develop theories, hypotheses, and guidelines that allow us to characterize, evaluate, predict and improve how an HPC environment (hardware, software, human) affects the development of high end computing codes.

Partners: MIT Lincoln Labs, MIT, UCSD, UCSB, UMD, USC, FC-MD

HPCS Example Questions

- **How does a HEC environment (hardware, software, human) affect the development of an HEC program?**
  - What is the **cost** and **benefit** of applying a particular HPC technology (MPI, Open MP, UPC, Co-Array Fortran, XMTC, StarP,…)?
  - What are the **relationships** among the technologies, the work flows, development cost, the defects, and the performance?
  - What **context variables** affect the development cost and effectiveness of the technology in achieving its product goals?
  - Can we build **predictive models** of the above relationships?
  - What **tradeoffs** are possible?
  - …

HPCS Research Activities



E.g. Tradeoff between effort and performance:

MPI will increase the development effort by y% and increase the performance z% over **OpenMP**

E.g. Experience:

Novices can achieve speed-up in cases X, Y, and Z, but not in cases A, B, C.

HPCS Testbeds

We are experimenting with a series of testbeds ranging in size from:

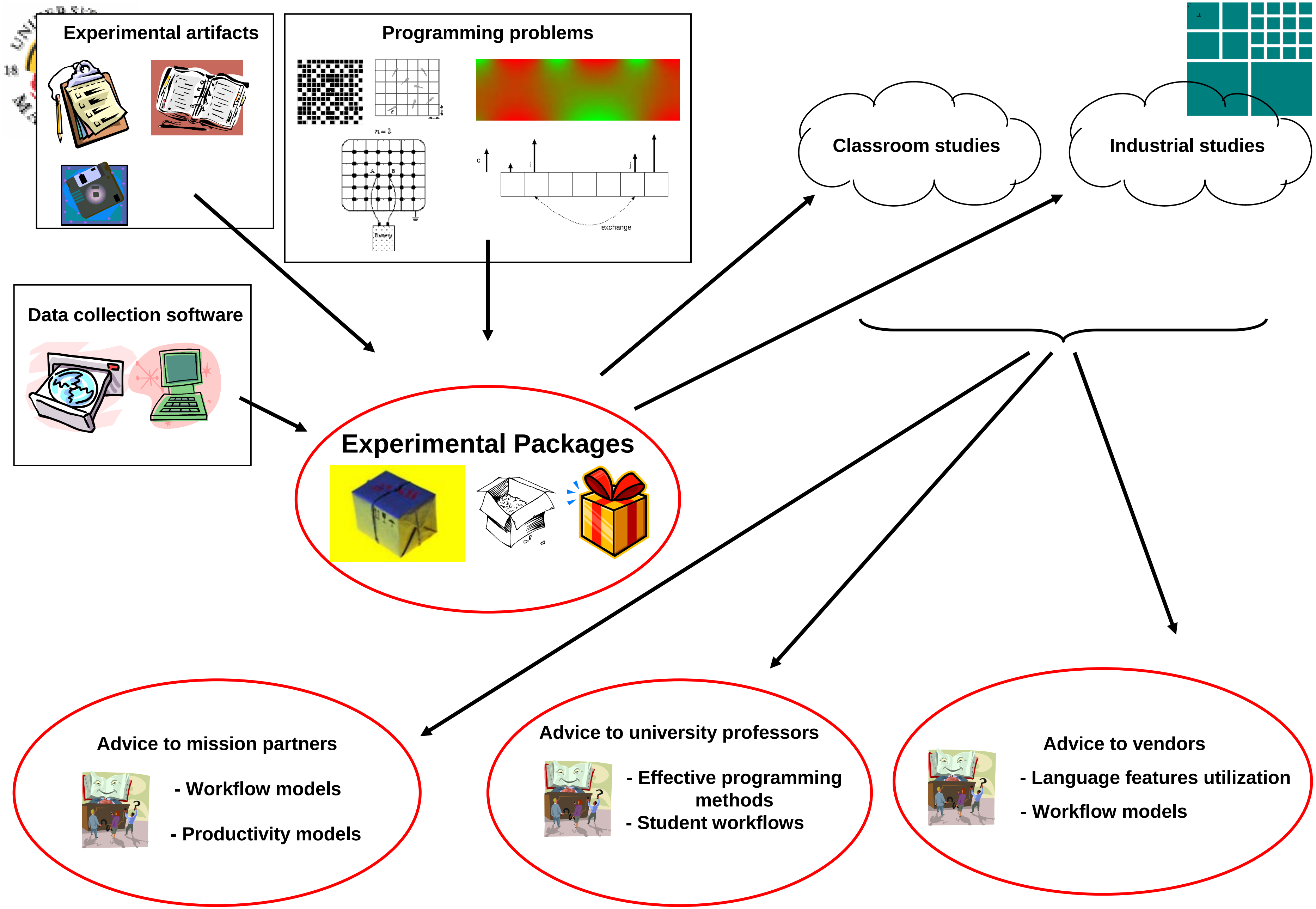
– Classroom assignments (Array Compaction, the Game of Life, Parallel Sorting, LU Decomposition, …

to

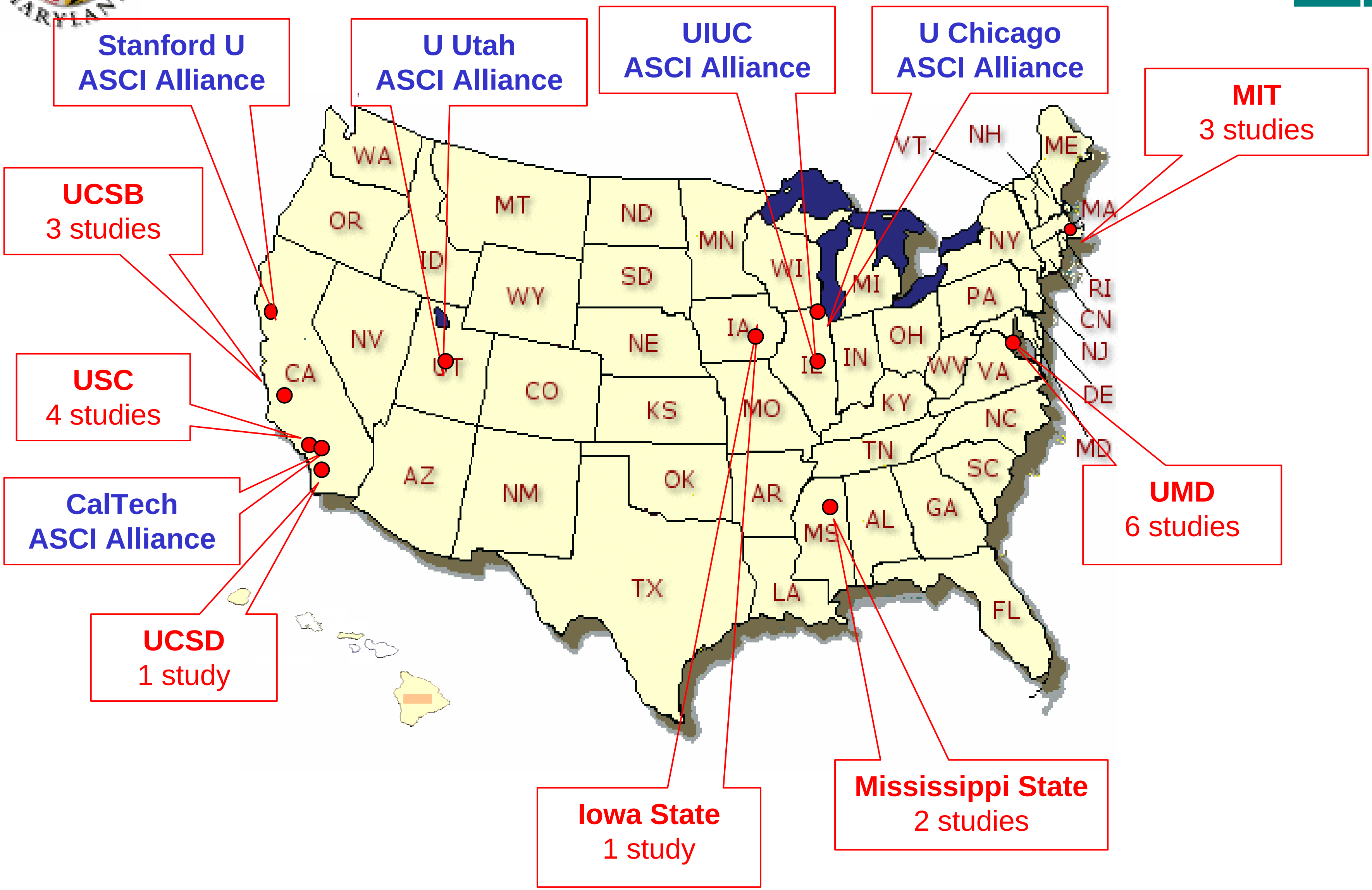
– Compact Applications (Combinations of Kernels, e.g., Embarrassingly Parallel, Coherence, Broadcast, Nearest Neighbor, Reduction)

to

– Full scientific applications (nuclear simulation, climate modeling, protein folding, ….)


Experimental artifacts
Programming problems
n = 2
Battery
exchange
Classroom studies
Industrial studies
Data collection software
Experimental Packages
Advice to mission partners
- Workflow models
- Productivity models
Advice to university professors
- Effective programming methods
- Student workflows
Advice to vendors
- Language features utilization
- Workflow models

Studies Conducted



Clearinghouse Project

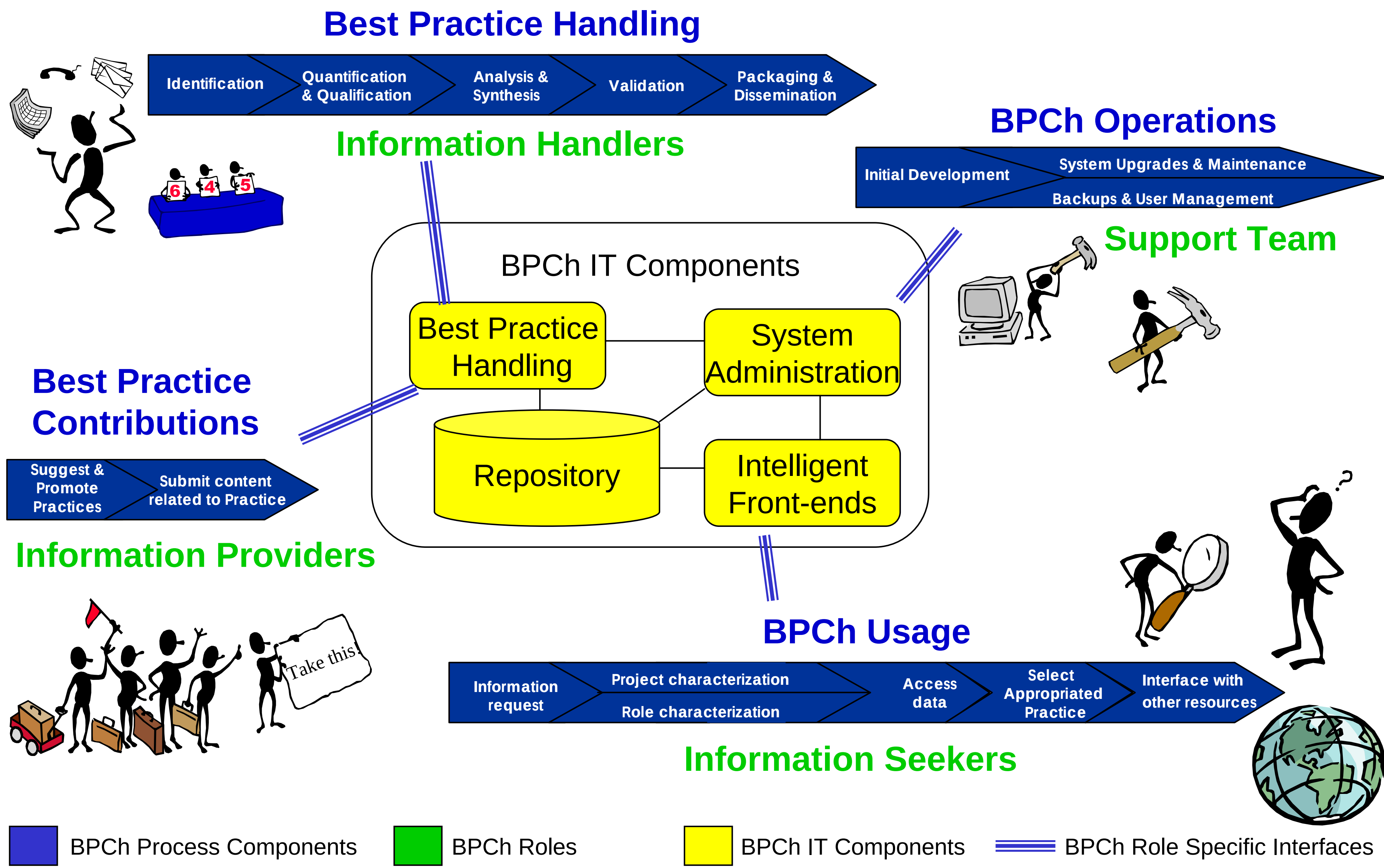
Problem: How do I pick the right set of processes for my environment.

Project Goal: Populate an experience base for acquisition best practices, defining **context and impact** attributes allowing users to understand the effects of applying the processes based upon the best empirical evidence available

Research Goal: Define a repeatable model-based empirical evidence vetting process enabling different people to create profiles consistently and the integration of new evidence

Partners: OSD, UMD, FC-MD, DAU, CSC, …

Operational Concept

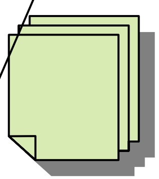


Behind the Scenes

BPCh recommendations based on ***evidence*** from real programs.

Evidence

- Source: *How trustable?*
- Context: Used by a *safety critical* program? In a *DoD environment*? On a *warfighter*?
- Results: Did it *increase or reduce* cost, quality, and schedule?



Evidence 1

Source
Context
Results

Evidence 2

Source
Context
Results

Evidence 3

Source
Context
Results

Evidence 4

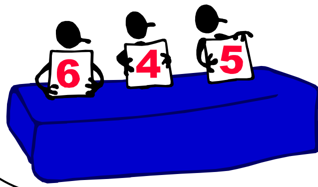
Source
Context
Results

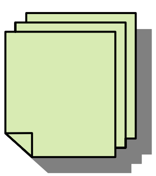
Behind the Scenes

Summary

The summary says
where the practice was successful
what it helped and cost
how to get started

Practices are vetted for accuracy and usefulness





Evidence 1

Source
Context
Results

Evidence 2

Source
Context
Results

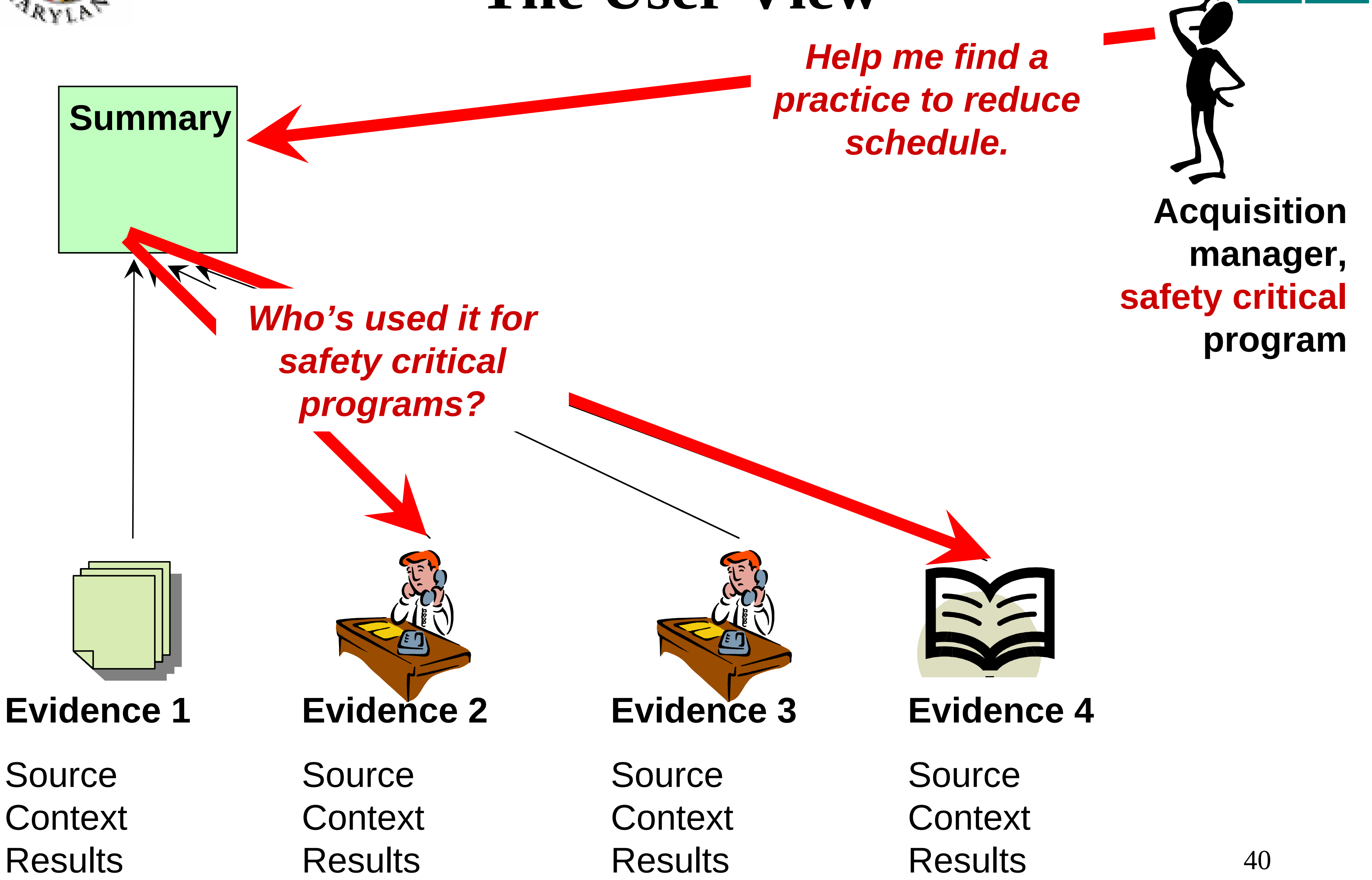
Evidence 3

Source
Context
Results

Evidence 4

Source
Context
Results

The User View



Summarizing

• Measurement is fundamental to any engineering science

• User needs must be made explicit (measurable models)

• Organizations have different characteristics, goals, cultures; stakeholders have different needs

• Process is a variable and needs to be selected and tailored to solve the problem at hand

• We need to learn from our experiences, build software core competencies

• Interaction with various industrial, government and academic organizations is important to understand the problems

• To expand the potential competencies, we must partner

Where do we need to go?
Propagating the empirical discipline

Build an empirical research engine for software engineering

- Build testbeds for experimentation and evolution of processes
- Build product models that allow us to make trade-off decisions
- Build decision support systems offering the best empirical advice for selecting and tailoring the right processes for the problem
- **Use empirical study to test and evolve technologies for their appropriateness in context**