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Verification, Validation and Quantification of Margins and Uncertainties for Electrical Systems

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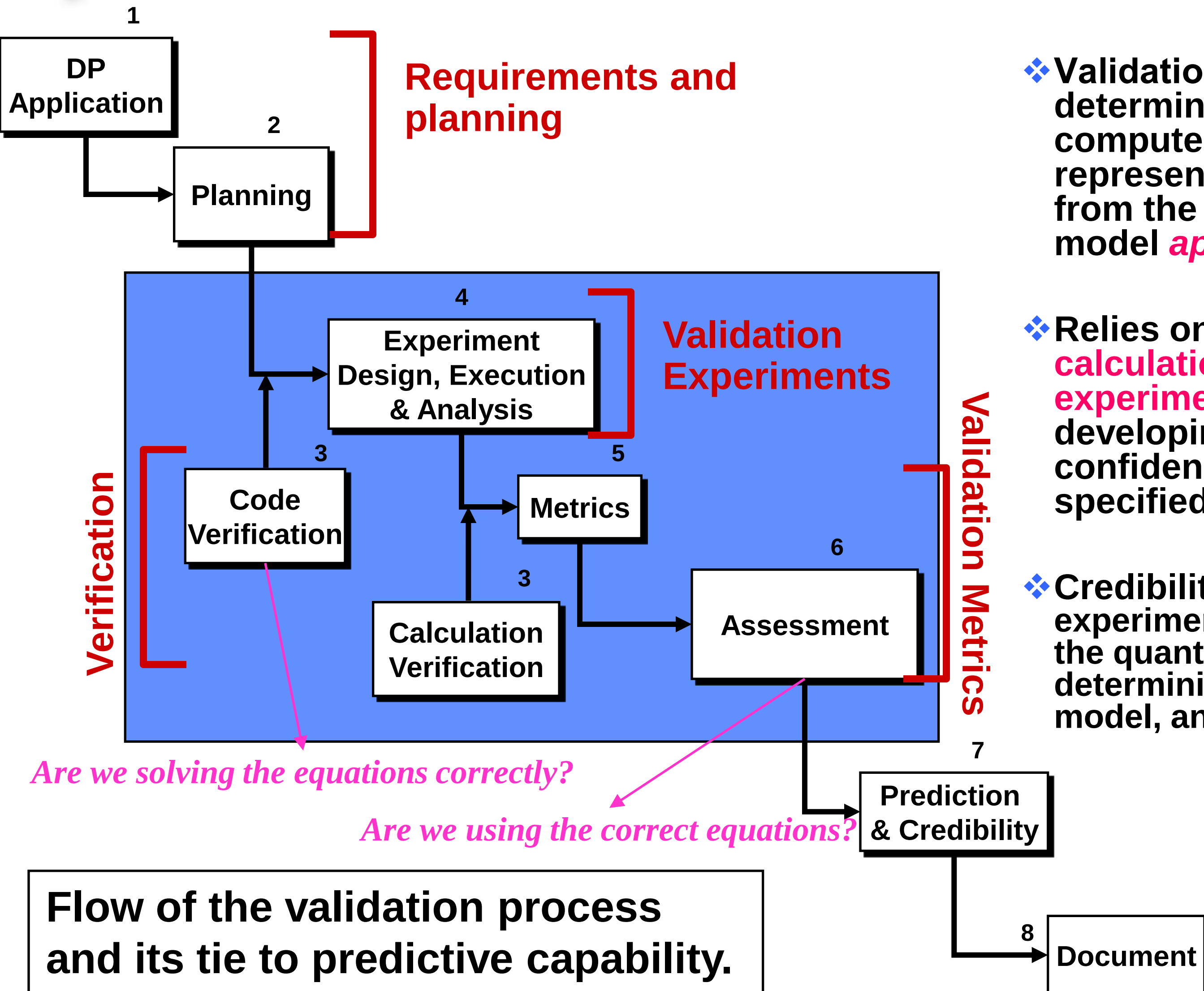
Outline

1. **Motivation**
2. **Why M&S?**
3. **Sandia Model of V&V**
   1. DP Application: Electrical Modeling & Simulation
   2. Planning
   3. More Planning & Prioritization (PIRT)
   4. Verification (if time allows)
   5. Electrical Hierarchical Validation Approach
   6. Aspects of Validation
4. **Summary**
5. **Paths Forward**

Sandia Model of Verification & Validation

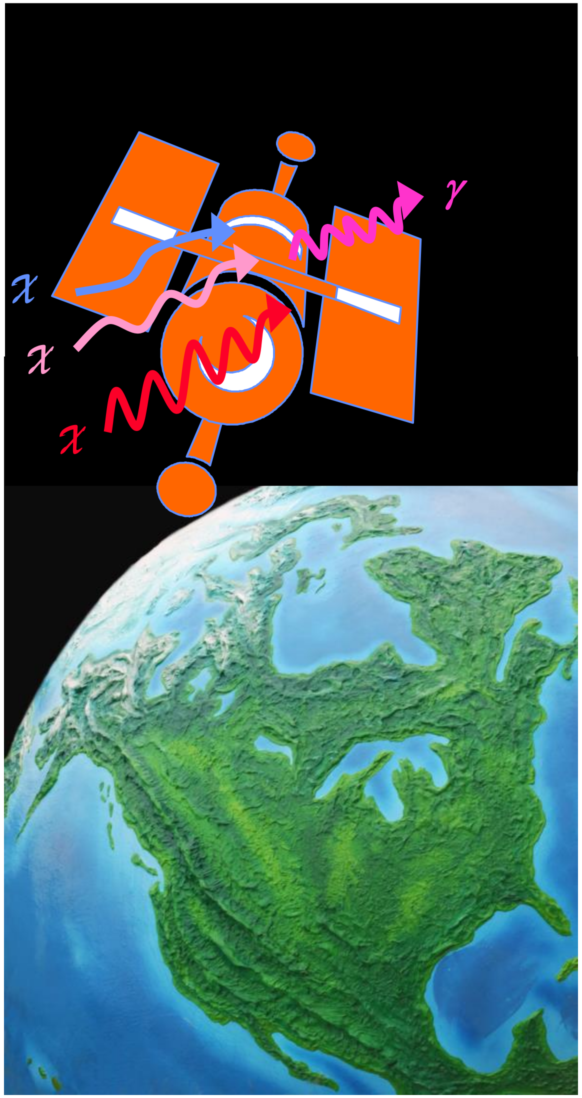


Flow of the validation process and its tie to predictive capability.

Trucano et al; SAND Report 2002-0341

- **Validation is "the *process* of determining the degree to which a computer model is an accurate representation of the real world from the perspective of the intended model *applications*."**
- **Relies on comparing code calculations to results of physical experiments, with the goal of developing and quantifying confidence in codes to predict a specified problem result**
- **Credibility assesses the relevance of experimental database to application, the quantification and capture of non-deterministic components in the model, and the adequacy of the model.**

Example of an Electronics Application



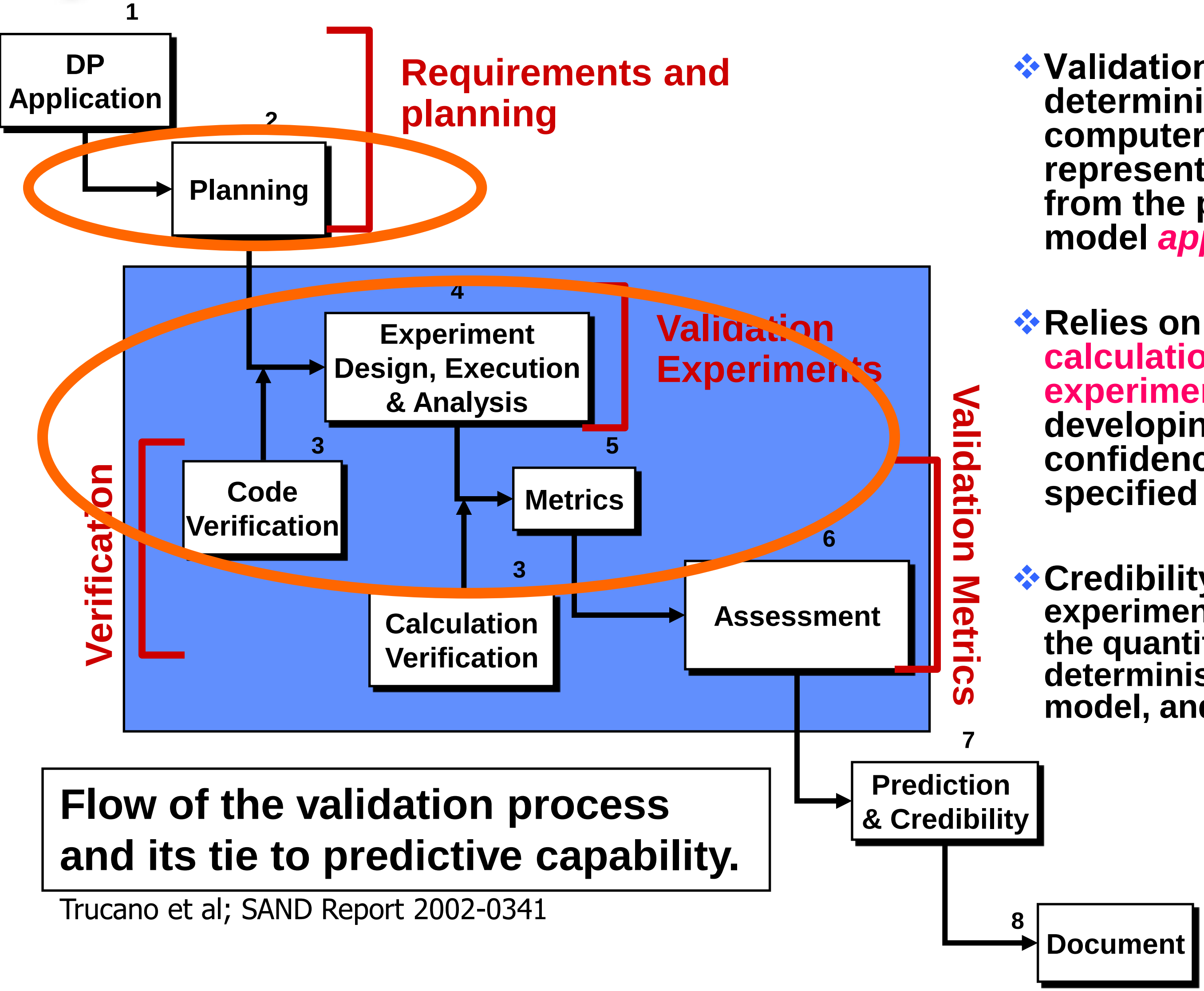
Modeling & Simulation of Electronics has Multiple Drivers

The spirit of ASC is to support Programs of interest

Shift from only ***test-based*** confidence to inclusion of ***simulation-based*** confidence…why?

- Resource-limited test climate → Fewer (radiation) tests
  - Tests are expensive (30K/test at some facilities)
  - Less resources: ↓ time, ↓ money
  - Regulations/treaties/laws prohibit particular types of testing (underground)
  - Fewer operational test facilities
  - Test facilities cannot duplicate realistic environment
- *Simulation* provides a compelling alternative
  - Simulate environments that cannot be reproduced or controlled in a lab/field test
  - Gain higher visibility into circuits
  - Assess design margins to provide increased confidence in design.
- But *Simulation* also has its detractors
  - Is it truly Cost-effective? (← depends on who you ask)
  - Is it really Predictive? (← trying to assess)
  - Augment/complement test program (← where/how?)

Sandia Model of Verification & Validation



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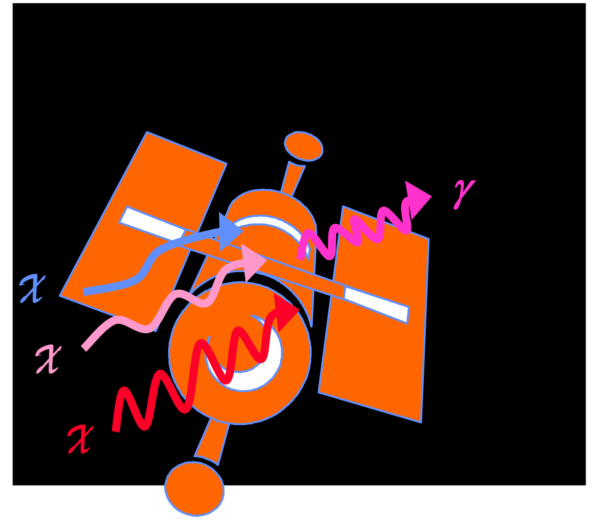
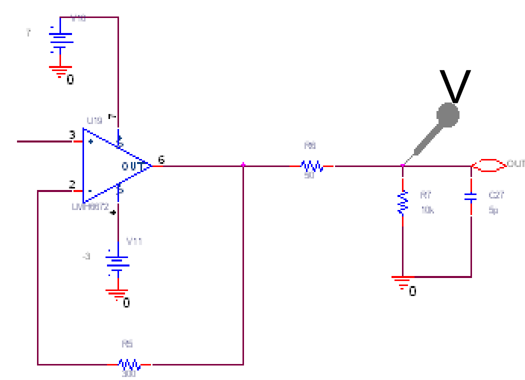
V&V Planning & Requirements: Project Scoping for Electrical System

- Relevant circuit models

- What are model requirements?
  - Phenomena of interest
    - Behavior in radiation (x-/γ-ray environment) → Photocurrent generation
  - Results desired (e.g. inputs/outputs, internal measures)

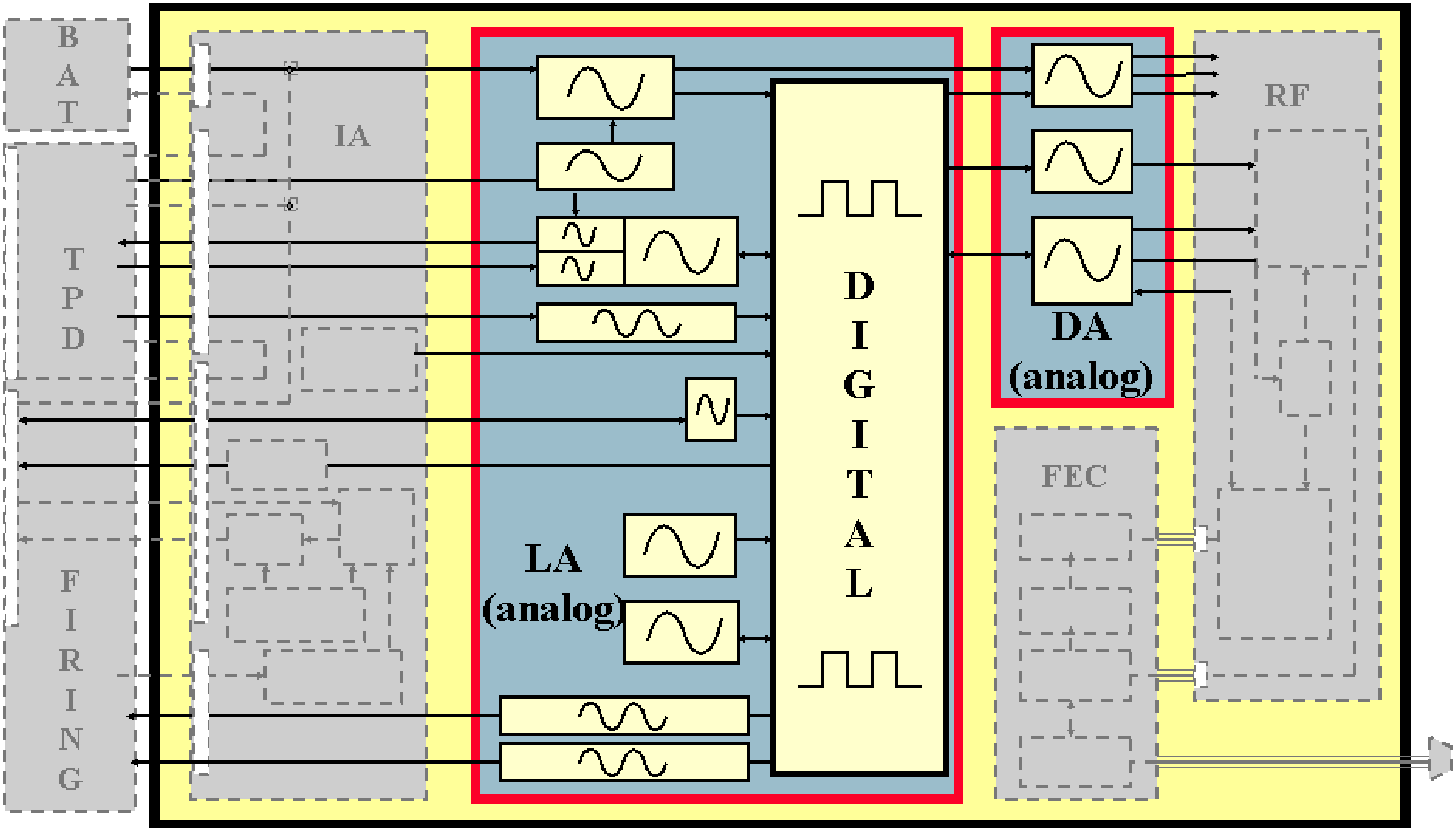


- Environmental/Functional scenario selection
  - Radiation level (dose rate)
  - Pulse shape (pulse width and amplitude)
  - Temperature
  - Function of circuitry



- Adequate coverage

Circuits of interest



V&V Planning &Requirements: Xyce Parallel Electronic Simulator

Sandia's SPICE-like analog circuit simulation code

Radiation-Aware Device Models
•x/γ–ray effects
•Neutron effects

Large-scale complex system model
(Massively-parallel simulations)

- Radiation (x/γ–ray) aware Xyce models represent improvement over current PSPICE capability (used by design engineers & analysts)
  - Physics-based radiation models (as opposed to empirical/behavioral models used in PSpice)
  - Allows for input of exact radiation pulse
- Massively parallel code allows:
  - Simulation of very large-scale complex system model
    - Investigate circuit interaction
    - Simulate large digital components

V&V Planning & Prioritization
Phenomena Identification & Ranking Table

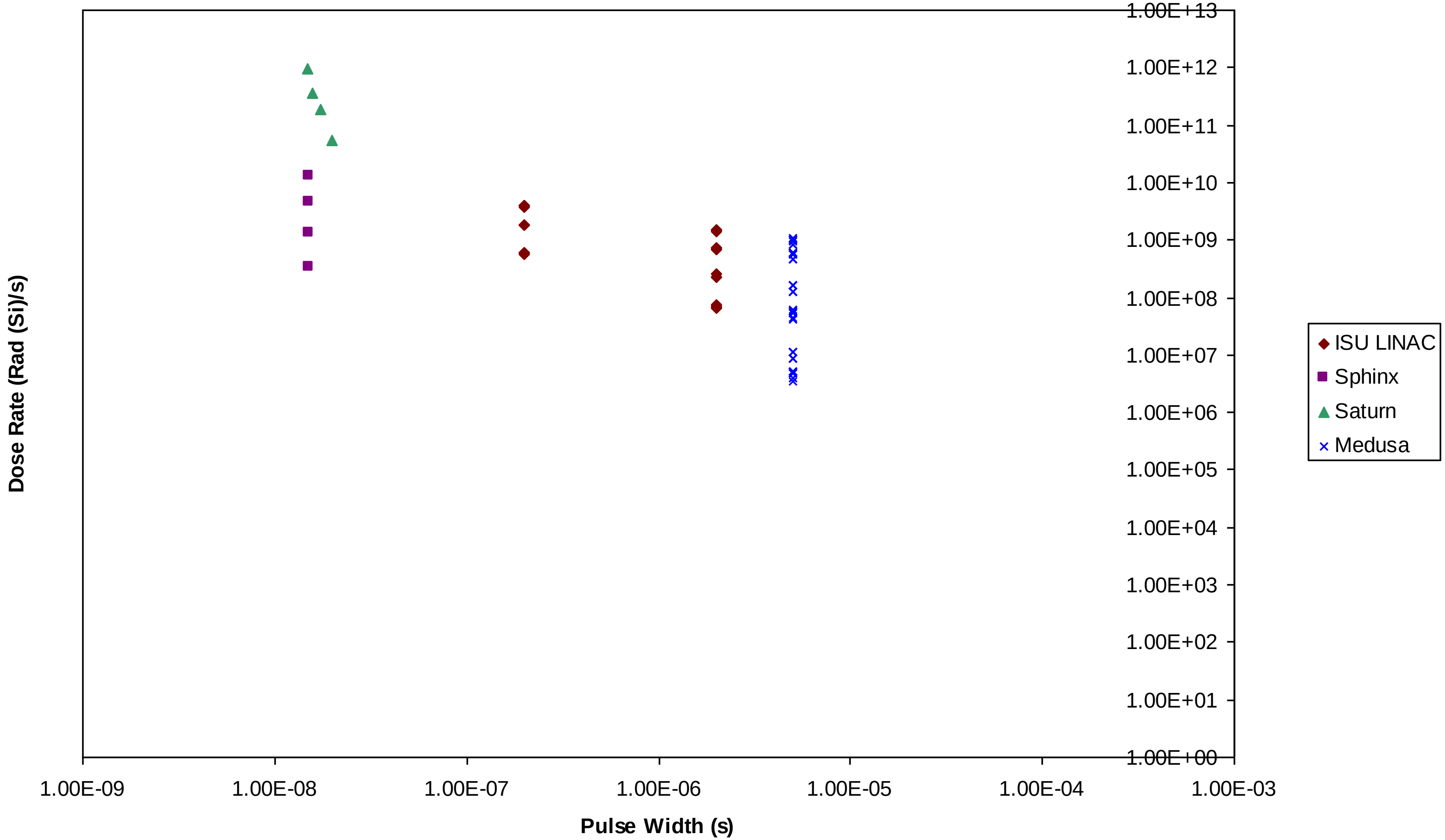
Modeling Hostile Photocurrent Effects in Active Devices		Importance of effects on System Electronics (Application)			Adequacy			
					Modeling			Validation
Device Level Effects (A)								
BA-1	Total transient photocurrent generation	H	H	H	M	M	M	M
BA-2	Individual device region (e.g. each junction) photocurrent generations	H	H	H	M	M	M	L
Sub-Circuit Level Effects (B)								
BB-2	Circuit photocurrent generation by MOSFET	H			M			M
BB-2	Circuit photocurrent generation by MOSFET	H			L			L
ASIC Level Effects (C)								
BC-1	Change in expected logic output	H			M			M
BC-2	Change in expected analog output	M			M			L

Roomful of VIPs + 1 large chalk board = Let's Make A Deal: What do we test?

Rank		Hierarchy Level	When?	Facility	Model Status	Experiment Status
1.	SOI Test Structure	Single device (for SOI ASIC)	Not planned – Test Series 2 or FY07 possible; Originally planned for Apr-May'06 (Test Series 1) – But will not be ready in time (!)	• Short pulse → Sphinx is cheap (and easier to schedule) option • Long pulse	Have all photocurrent models.	MDL Delay – no silicon till mid-June (earliest!); If Test Series 2 reinstated, might be ready (depends on MDL schedule); Otherwise, wait till FY07
2.	Single Devices: • BJTs – all (npn/pnp) • Standard diodes – all (except nc104) • Zener diodes – choose 5 or 11 • MOSFETs	Single Device	April/May 06 (Test Series 1)	• Short pulse @ ISIS (ISU) – week of 10 Apr • Long pulse @ Medusa or ISU (TBD) – week of 15 May	Have most photocurrent models (MOSFETs & 2 zeners missing)	PCBs sent to fab; Developing Test Plan; Will field for Test Series 1 (starting 10 Apr)
3a.	QASPR Complex Prototype	Subcircuit	April/May 06 (Test Series 1)	• Short pulse @ ISIS (ISU) – week of 10 Apr • Long pulse @ Medusa or ISU (TBD) – week of 15 May	Have most photocurrent models (FET missing)	PCBs sent to fab; Developing Test Plan; Will field for Test Series 1 (starting 10 Apr)
3b.	Trigger Circuit	Subcircuit	Not planned	• Short pulse • Long pulse	No photocurrent models for FS devices (FETs, diodes, BJTs okay) (Substitute?)	Possible FY07
4.	PA2 w/ oscillator • diff locations for oscillator circuit • additional analog probes	ASIC	July/Aug 06 (Test Series 2)	• Short pulse • Long pulse	Have all photocurrent models.	Test Series 2 cancelled due to RES funding shortfall
5.	Classified circuit	Full System	FY07	??	Will depend on circuit.	

Decision Point: 03/2006

Facility Capabilities



What Devices do We Need to Test?

- Single Device
  Facilities:
  - ISU LINAC – completed prior to FY06
  - Sphinx – completed prior to FY06
  - Saturn – completed prior to FY06
  - Medusa
  - ISIS
  - Sphinx – *early FY07*

  Devices
  - **BJTs**
    Bfs17a
    Bft92
    Mmbt2222alt1
    Mmbt2369alt1**
    Mmbt2907alt1**
  - **Standard Diodes**
    Bas16lt1
    Bas40lt1
    nc104
  - **MOSFETs**
    Mtb30p06v
    Ntb5605p**
  - **Zener Diodes**
    Mmsz5228bt1 (3.9V)
    Mmsz5229bt1 (4.3V)*
    Mmsz5231bt1 (5.1V)**
    Mmsz5236bt1 (7.5V)**
    Mmsz5238bt1 (8.7V)*
    Mmsz5241bt1 (11V)*
    Mmsz5243bt1 (13V)*
    Mmsz5244bt1 (14V)
    Mmsz5245bt1 (15V)*
    Mmsz5250bt1 (20V)**
    Mmsz5256bt1 (30V)
  - **SOI Test Structure *– pending MDL fab***
    - **Medusa *– early FY07***

- Subcircuit
  - **QASPR Complex Prototype**
    - Medusa
    - ISIS
    - **Sphinx *– early FY07***
  - X-switch
    - WSMR LINAC

- Single ASIC (PA2)
  - Crane LINAC

- System Level
  - **Classified circuit**
    - **Saturn*– early FY07***
  - Combined AFS/FS Circuit – *Tentative; pending model development*
    - Sphinx– *early FY07*
    - Medusa– *early FY07*

→ Use Design of Experiments to Create feasible experiment plan!

Electrical Hierarchical Validation: Validation (& confidence) at increasing levels of system complexity

Provide comprehensive validation activity

- Using Xyce, a parallel SPICE-like analog circuit simulation code
- Physics-based models (as opposed to empirical/behavioral models used in Spice)
- Gain higher visibility into circuits (Internal measures not available in test)
- Verify design margins → Provides increased confidence in design

Complexity/Fidelity ↑

Number of Tests ↓

Uncertainty Propagation ↑

Simulation/Testing Cost ↑

Circuit Board

↑

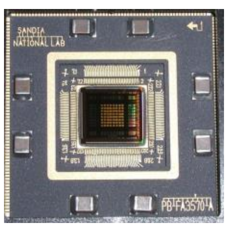
Single ASIC

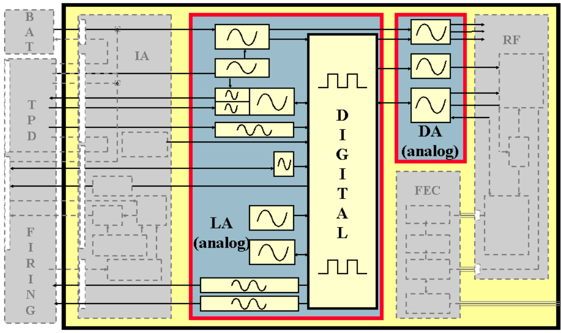
↑

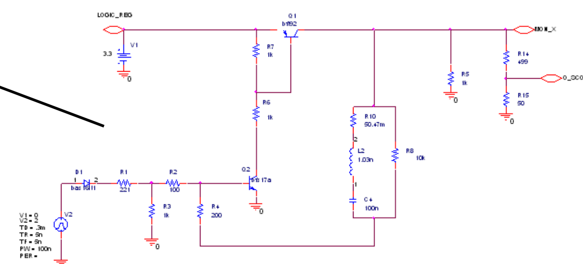
Subcircuit

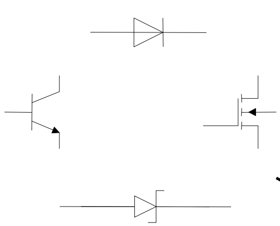
↑

Single Device









Courtesy: G. Gray, C. Lam, R. Mariano, M. Martinez-Canales, B. Owens

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Types of Uncertainties Present

- The goal of Uncertainty Quantification (UQ) is to facilitate confidence assessments for the predictive capability of our models:
  - "Best Estimate + Uncertainty"
- Two main types of uncertainty
  - aleatory uncertainty
    - variability, irreducible uncertainty, inherent uncertainty, stochastic uncertainty
    - has probabilistic representation (if have enough samples to generate pdf)
    - Usually MC-type analysis
  - epistemic uncertainty
    - uncertainty, reducible uncertainty, subjective uncertainty, model form uncertainty
    - results from lack of knowledge
    - Dempster-Schafer belief theory

Uncertainties (of which we are aware):

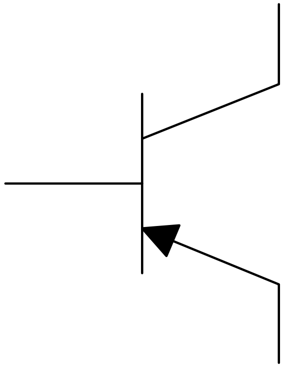
1. Simulation
   - Model (uses mostly physics except where don't)
   - Uncertainties in constitutive model parameters
   - Variation in data used to fit (temperature) model parameters
   - Model error and other model form uncertainties
   - Convergence (of solution with different solver tolerances)
2. Experimental
   - Origin of lot samples unknown
   - Shot-to-shot variation
   - Description may be unavailable.
   - Incomplete database
3. Real-life Use conditions
   - Variable/uncertain environment conditions
4. Validation Data
   - Few data (if any)
   - Incomplete or imperfect data
5. Margin Requirement

Validation Analysis

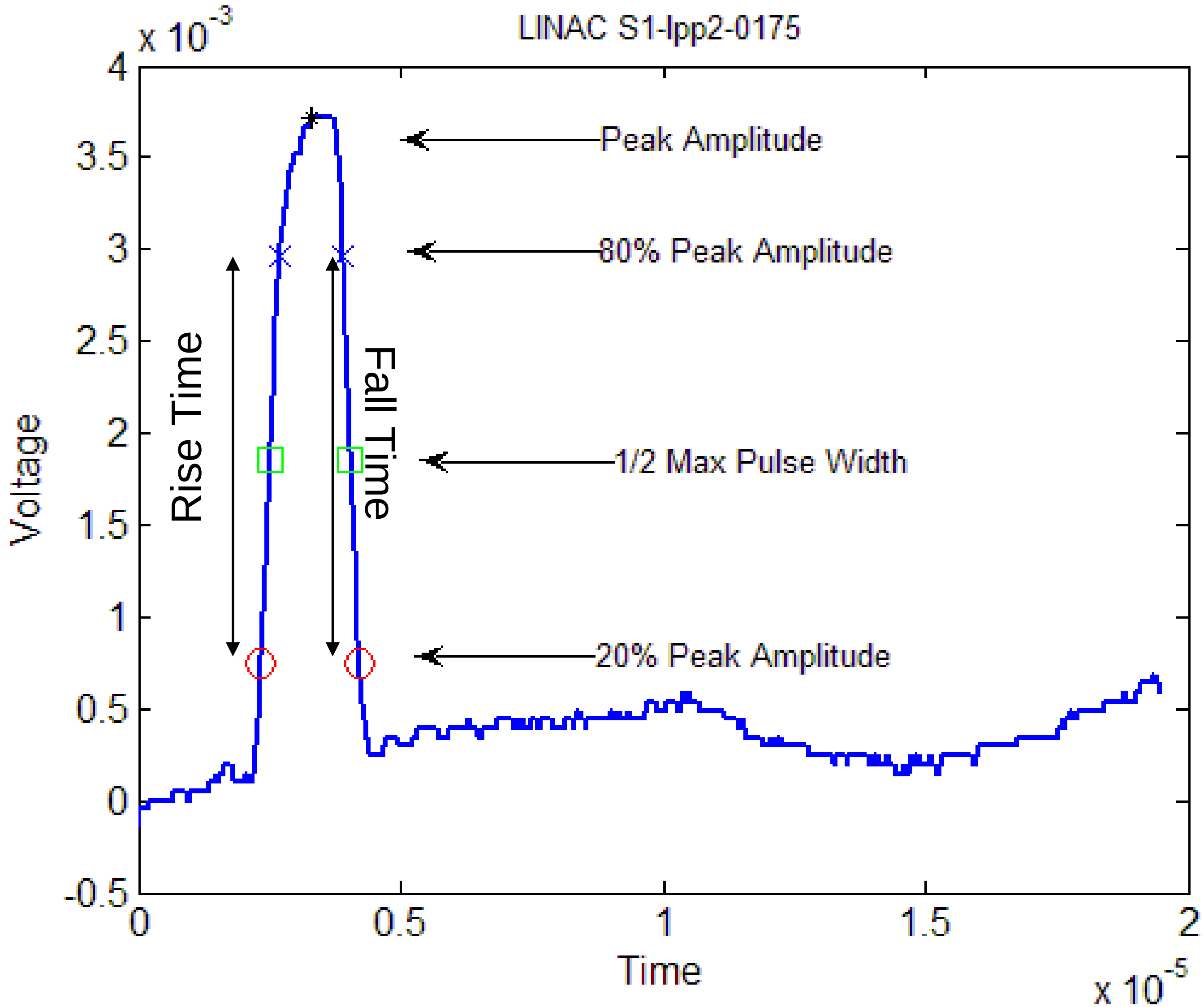
Examine photocurrent generation in single transistor

- PNP Bipolar Junction Transistor (BJT)

- Maps to PIRT element BA-1

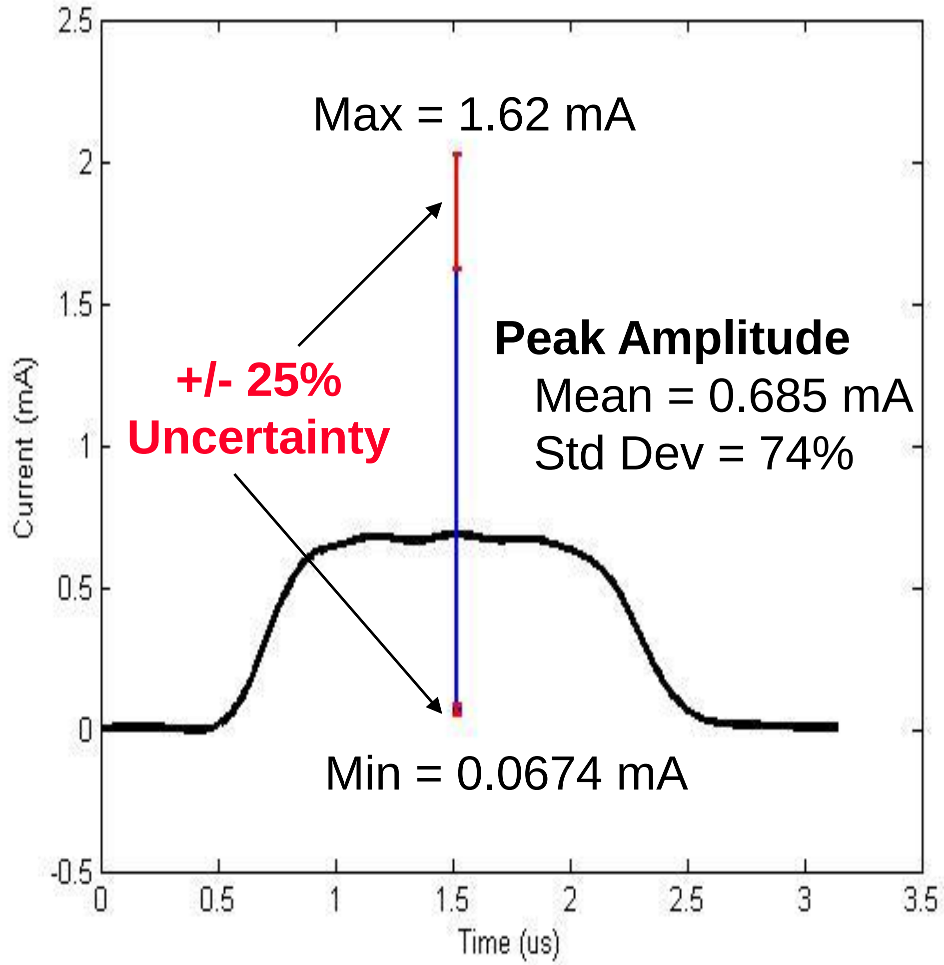


Single Device Model Validation Measures of Response

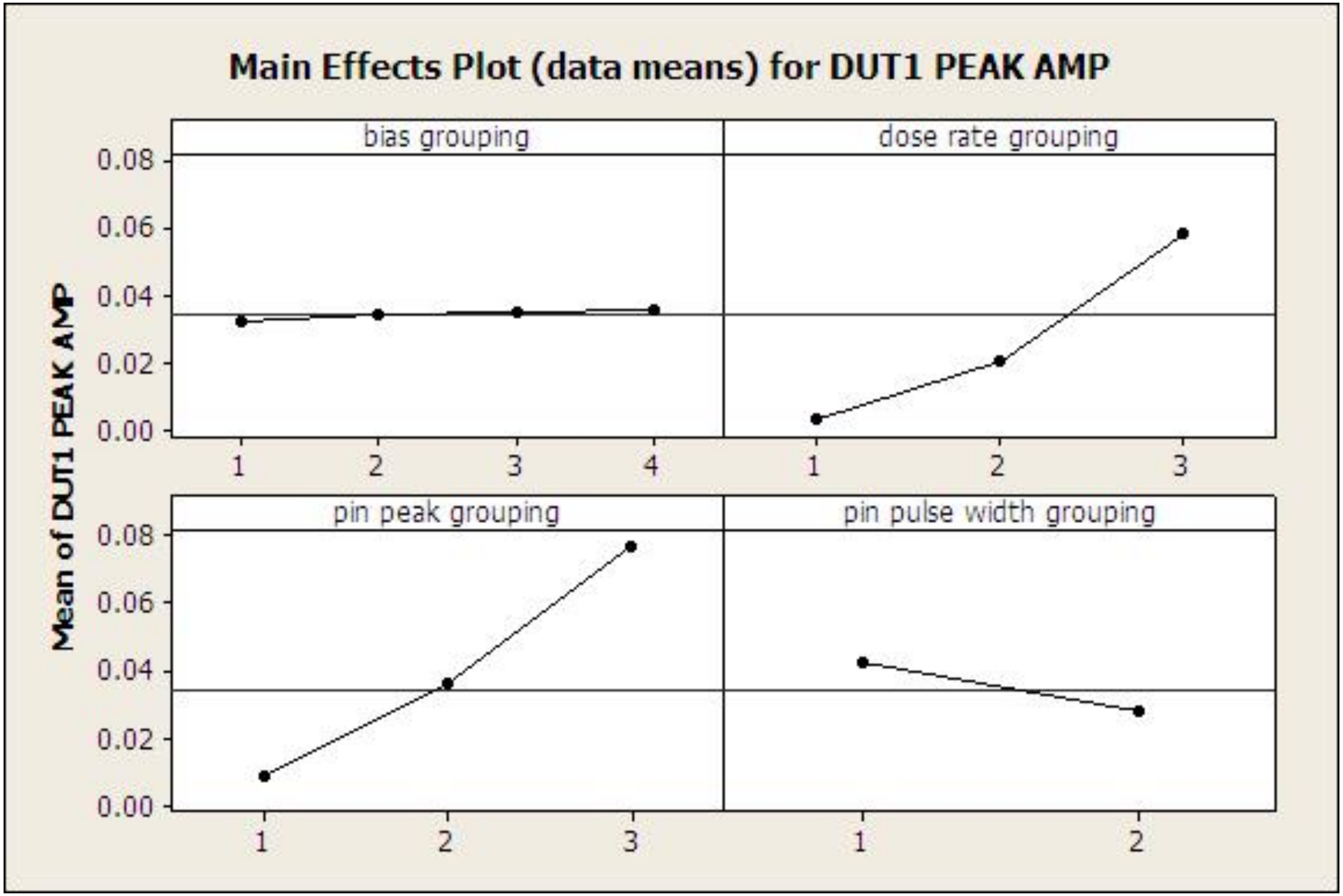


Experimental Data Analysis & Uncertainty Quantification

- Measurement Uncertainty/Error:
  - Use "guess" of +/- 25%
  - Not well characterized
- Several Devices Under Test (DUTs) for each shot
  - Need to characterize variation across DUTs
- Analyze single DUT across range of ~30 LINAC shots

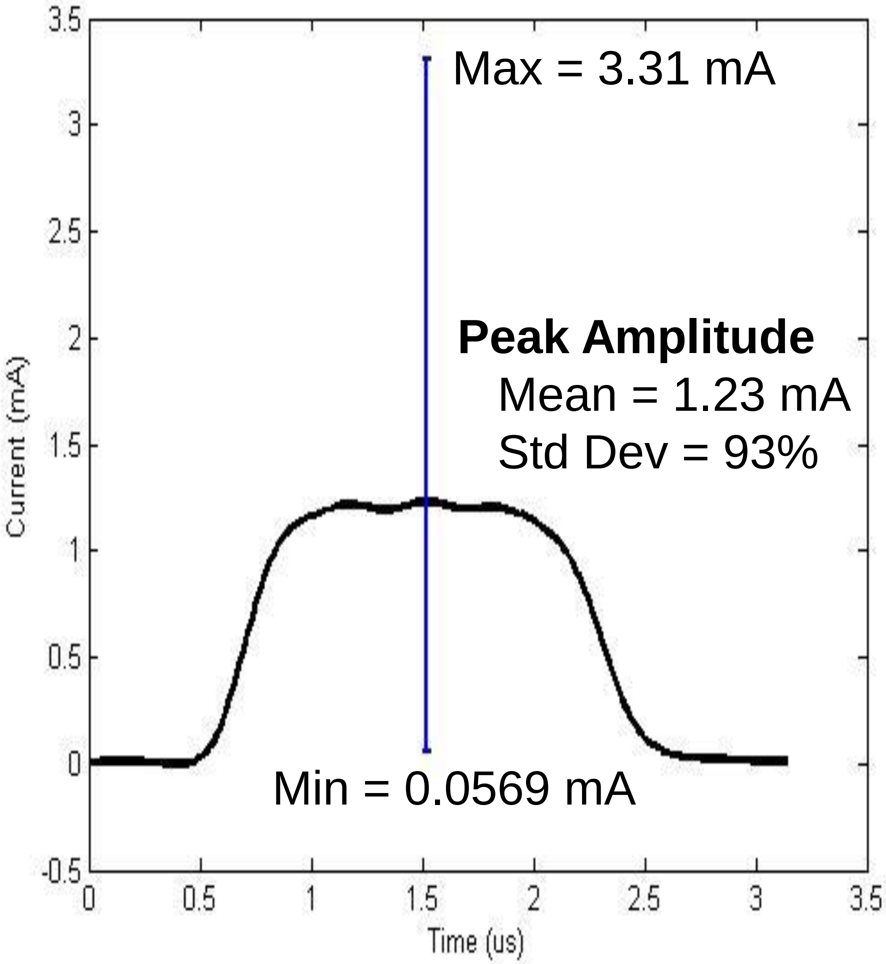


Main Effects Analysis Experimental Data



Model Uncertainty Quantification Simulated Data

- How does +/-x% range on model parameters affect simulation output?
- Simulate same range of radiation pulses as experimental data set
  - Account for effect of parameter variation
    - Measurement uncertainty in parameter extraction
    - "Approximation" in parameters (e.g. derived from doping profile)
- Analyze ~80 simulation runs



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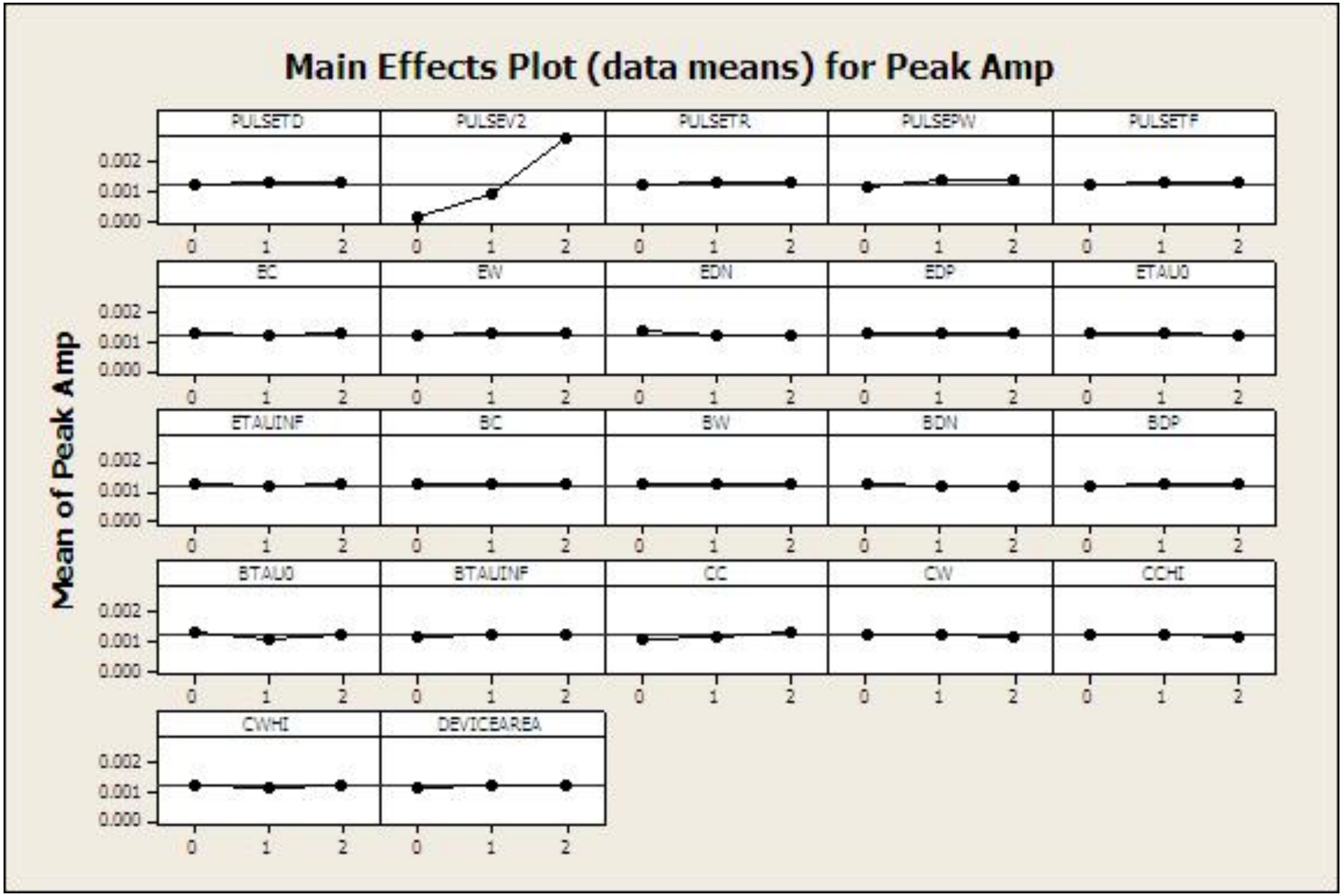
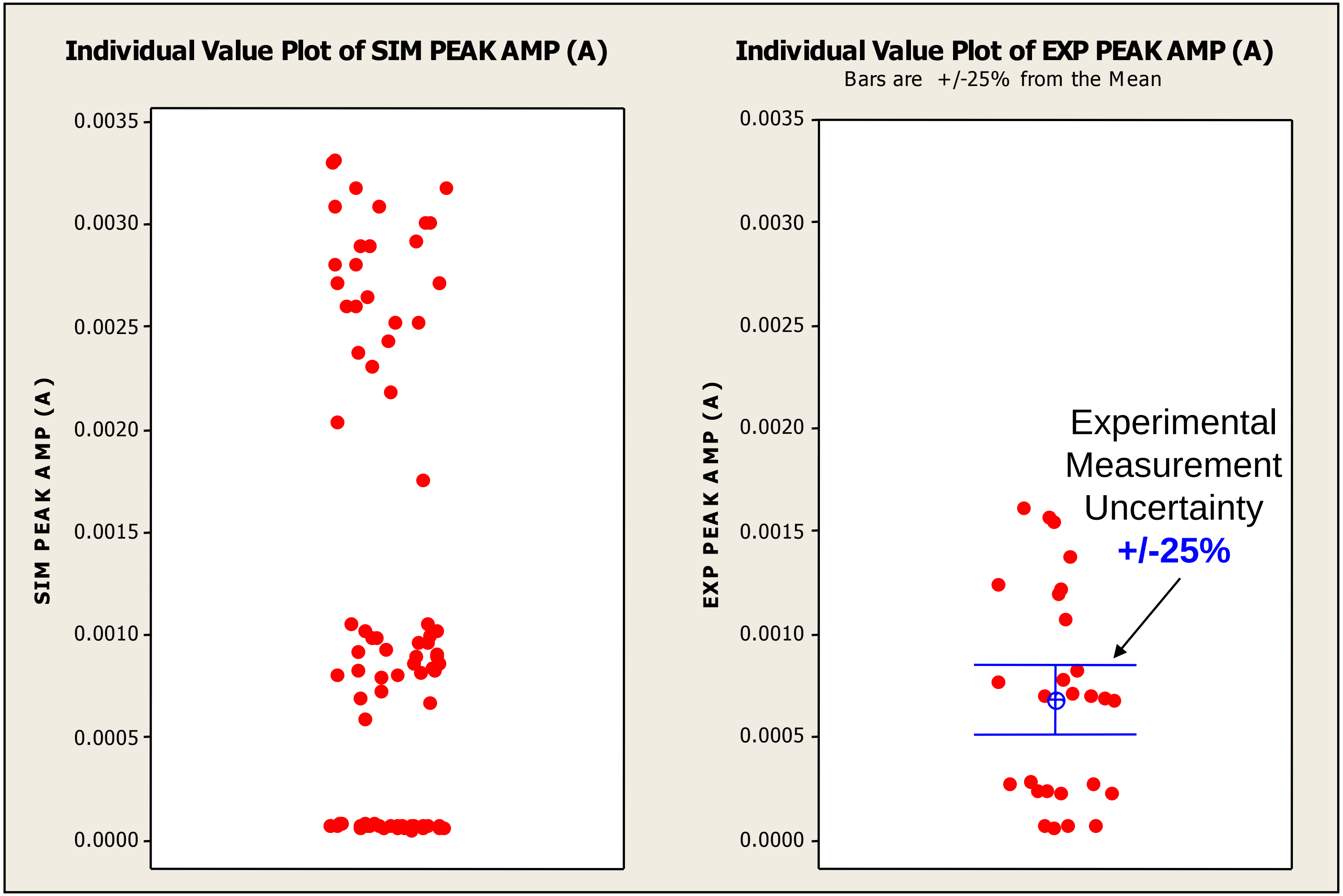
Main Effects Analysis Simulation Data



Validation Comparison Population (Pooled) Statistics



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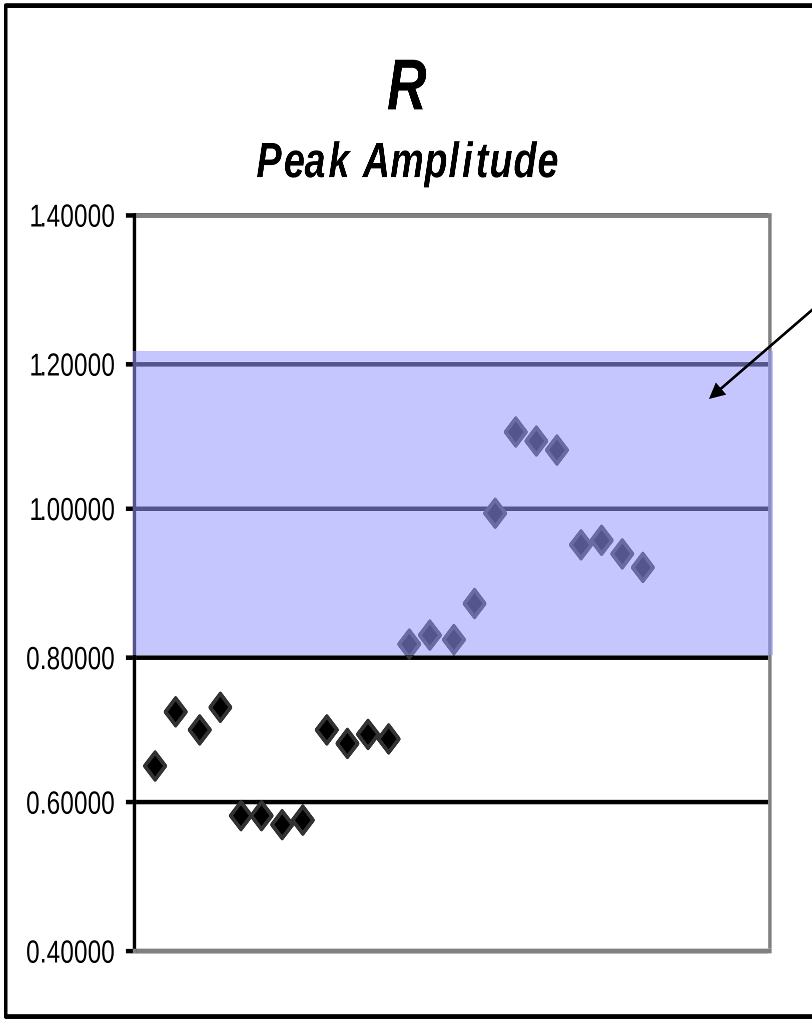
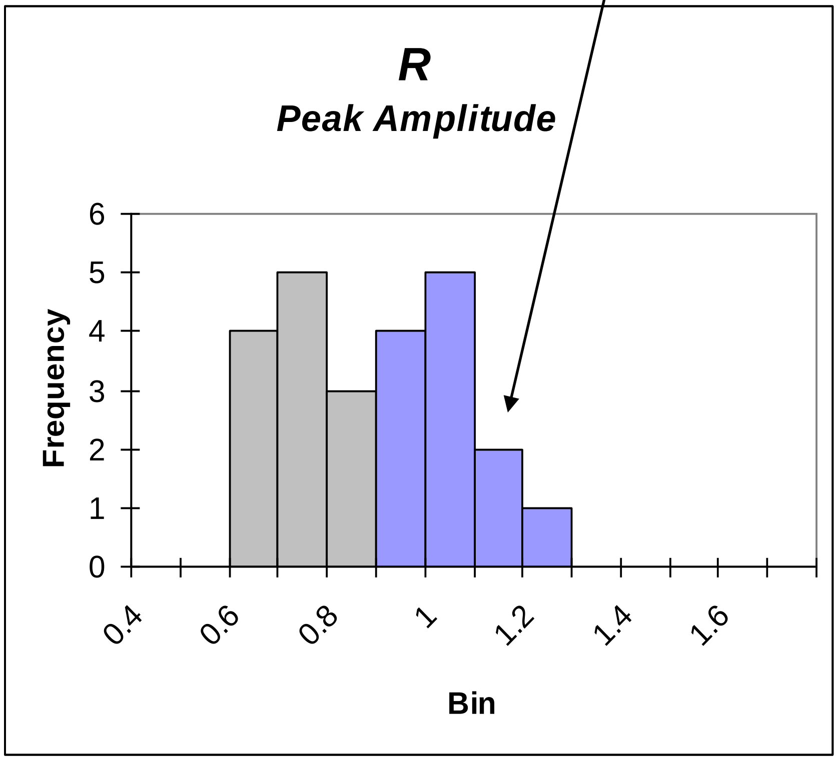
Validation Metrics Should Provide More information than *"Pass/Fail"*



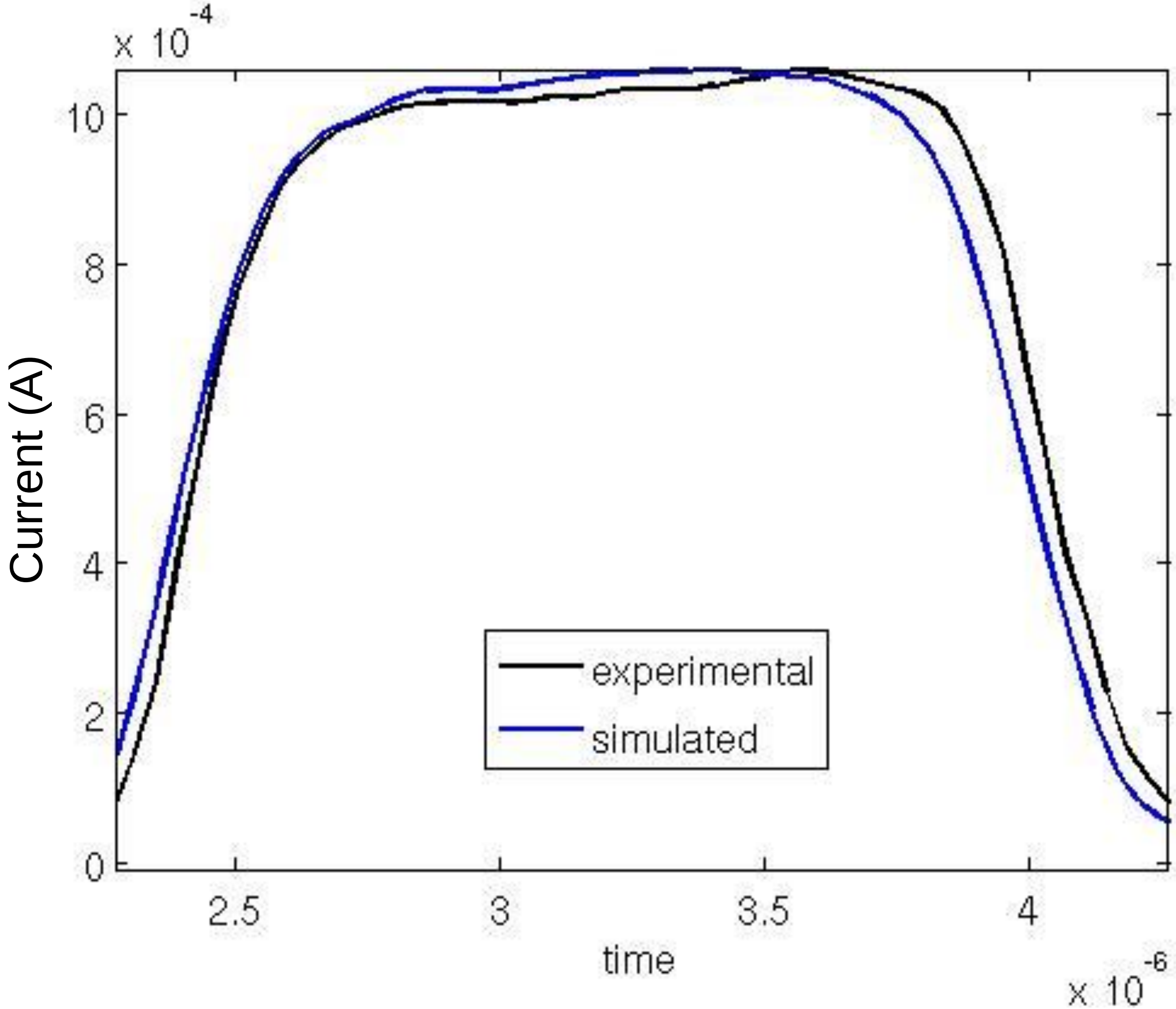
"Pass" Region

0.8 < R < 1.2

50% Pass Rate

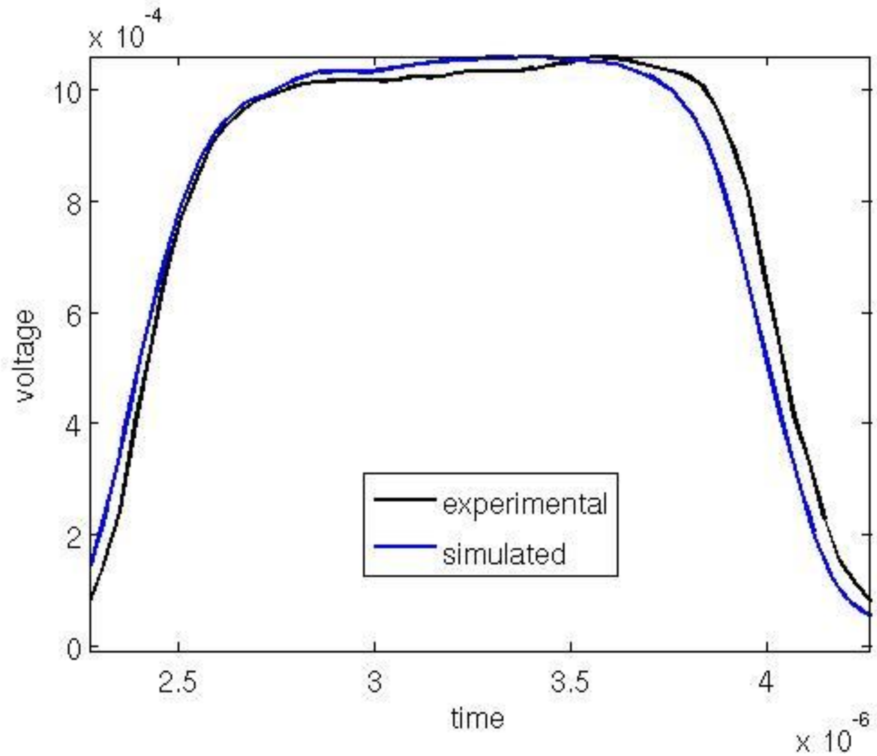


Validation Comparison
Individual (Shot-by-Shot) Comparison



Peak Amplitude	
1.06 mA	1.05 mA
Pulse Width	
1.60 us	1.54 us
Rise Time	
0.235 ns	0.247 ns
Fall Time	
0.235 ns	0.229 ns
Experiment	**Simulation**

Validation Metrics



% Error

$$\%Error = \frac{Exp - Sim}{Exp} \times 100\%$$

Peak Amplitude (mA)

$$\frac{1.05 - 1.06}{1.05} \times 100\% = -0.95\%$$

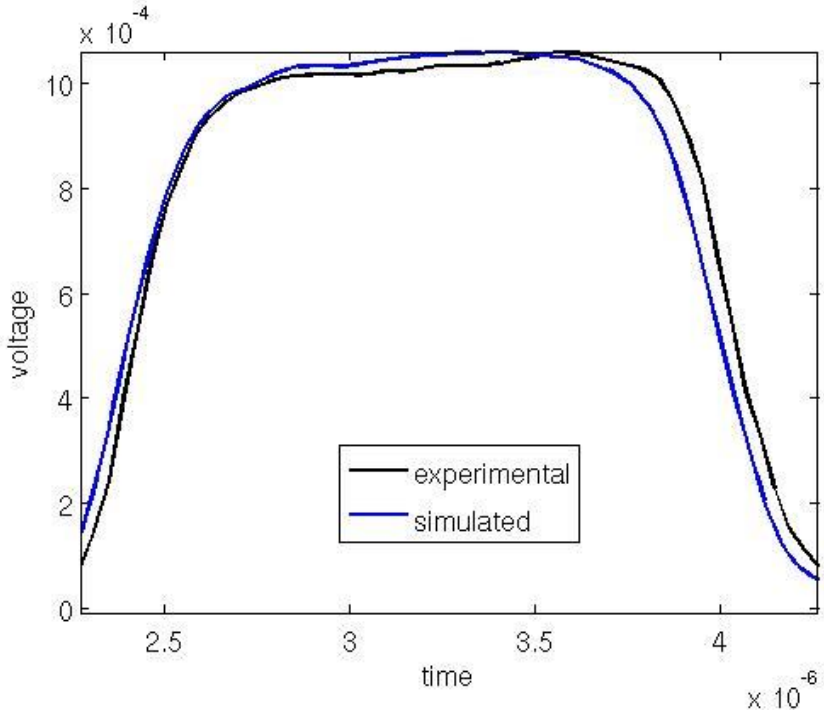
Ratio

$$R = \frac{Sim}{Exp}$$

Peak Amplitude (mA)

$$\frac{1.06}{1.05} = 1.009524$$

Validation Metrics



Individual Measures of Response

	R
Peak Amplitude (PA)	**1.0095**
Pulse Width (PW)	**0.9625**
Rise Time (RT)	**1.0511**
Fall Time (FT)	**0.9574**

Combination Metric (Weighted Sum)

$$X = a \cdot PA + b \cdot PW + c \cdot RT + d \cdot FT$$

For

a	**3**
b	**3**
c	**1**
d	**2**

$$\mathbf{R_{combo} = 0.98487} \leftarrow R_{combo} = \frac{X_{Sim}}{X_{exp}}$$

Model Validation

- Comprehensive & rigorous analysis at all levels in validation hierarchy (circuit/system complexity)

- Validation Test Suite provides satisfactory coverage of PIRT

- ***Confident extrapolation to "un-testable" environments***

Summary of Where We Are

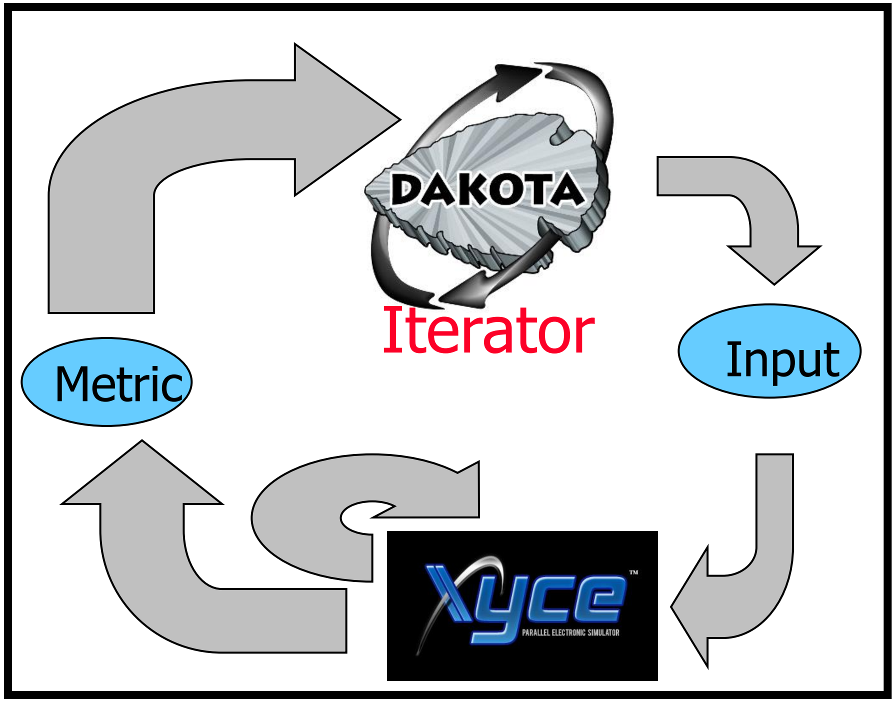
- M&S can be used to support Design Qualification Process
  - Close interaction with customer essential to ensure relevance to application
  - Model credibility established (& quantified) through V&V
  - Requires investment to develop adequate predictive capability
    - Still need experiments

- Iterative & Collaborative Process
  - Involve application customer, code & model developers, analysts & experimentalists

But We Have A lot More Work to Complete …. by March '07

Once predictive capability is attained, use a sound iterative process (Optimization, Design of Experiments, Monte-Carlo) to find:

- Margin distribution
- Worst case offset (find offending device/circuit input configurations)
- Margin sensitivity to scenarios



So We are Improving Optimization Algorithms for Simulation-Based Applications

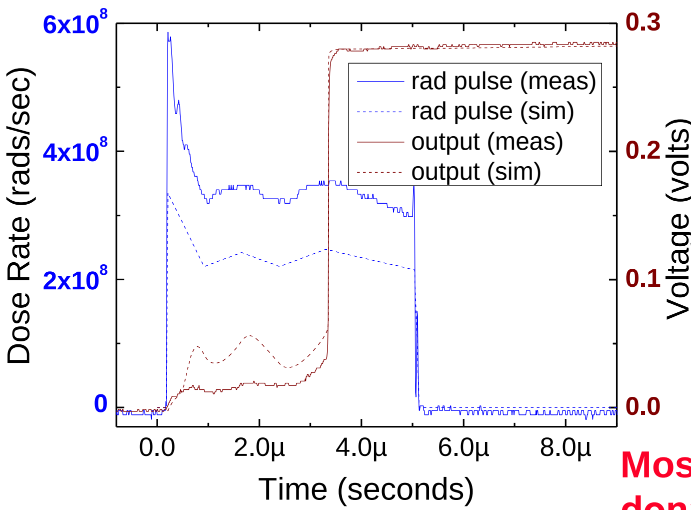
Conventional Approach = Sequential

Step 1: Parameter Studies

Step 2: Optimization

Step 3: Sensitivity Analysis

→ A lot of simulations are needed (!!)

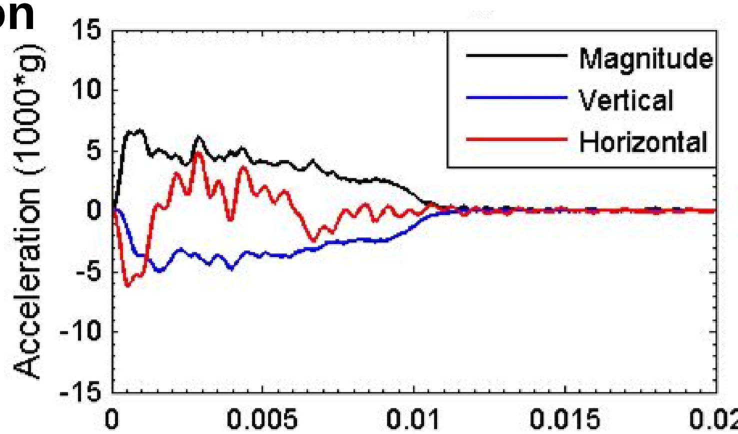


Xyce

Most simulators don't compute derivatives!

Where we are going: One-Stop Shopping

- **If you have derivatives, use them.**
  - **Otherwise: Derivative-free optimization**
- **Sensitivity/Robustness of optimum**
- **Response Characterization**
- **Global/Multiple optimum**
- **If you have a computing budget:**
  - **Efficient space exploration**
- **Adaptive scaling**



Mech. Deform. Code

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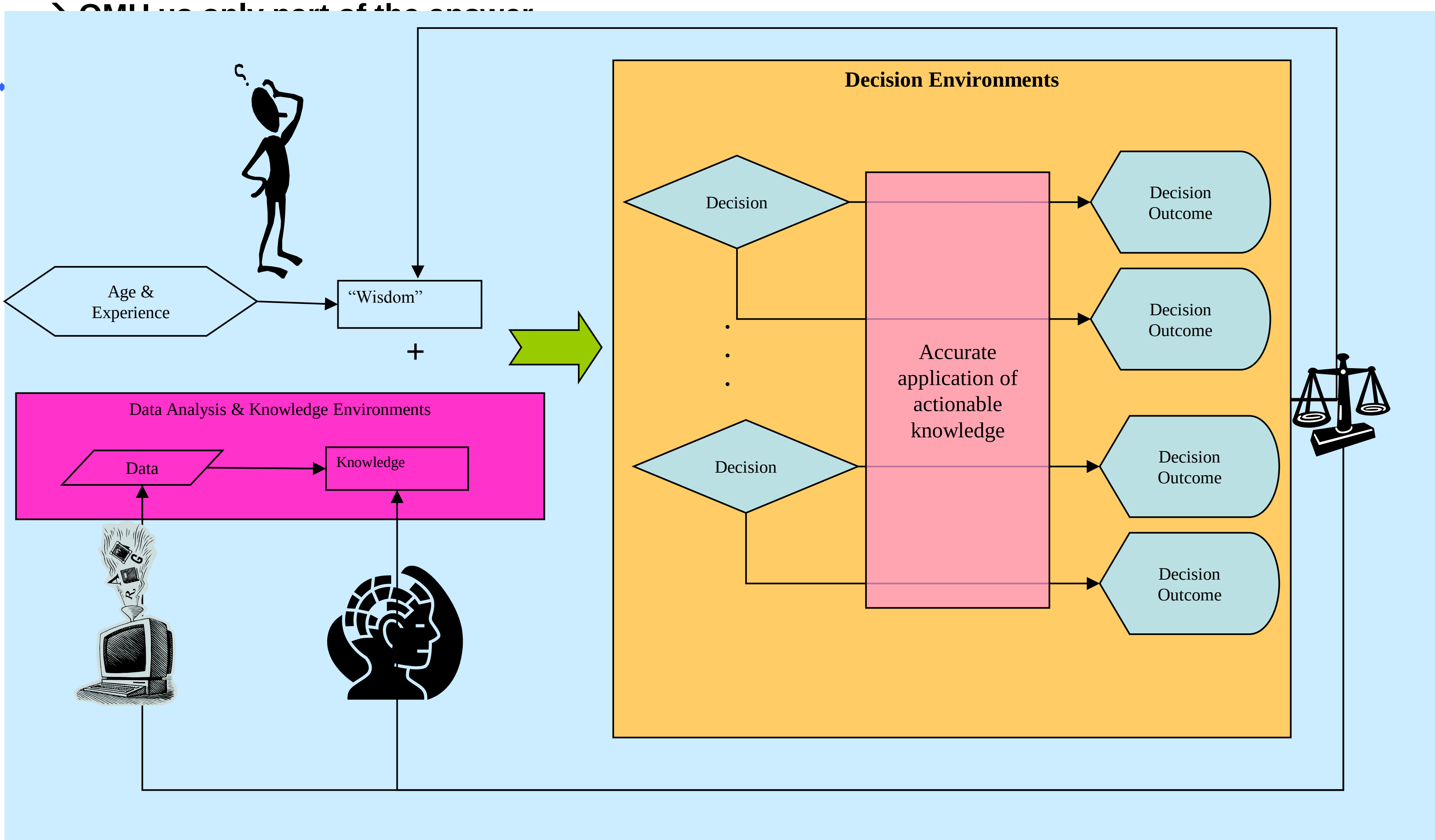
But how is your methodology and fancy algorithms going to help me make decisions?

- High-Consequence Scenarios need Risk-Informed Decision-Making
  - QMU as only part of the answer



Follow-up Questions?

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- **Cheryl Lam (the PI):** clam@sandia.gov

Back-Up Slides

Challenges and Constraints

- **Limited Simulation Budget** (say, 10 runs max!!!!) **and Time**
  - How do we allocate simulation budget across system and subsystems?
  - How do we do adequate UQ across system levels?
  - What do we do if we’re not in the asymptotic region of convergence?

- **Limited Experimental Testing Budget** (say, 1 system level test!!!!)
  - How do we determine data adequacy?
  - How do we know a priori we have tested “correctly”?
  - How do we leverage historical data of “old” systems for “new” or “modified” systems?

- **Ongoing software development**
  - How does validation at different stages of code development affect the general V&V process, and, in particular, the credibility at each subsystem ?

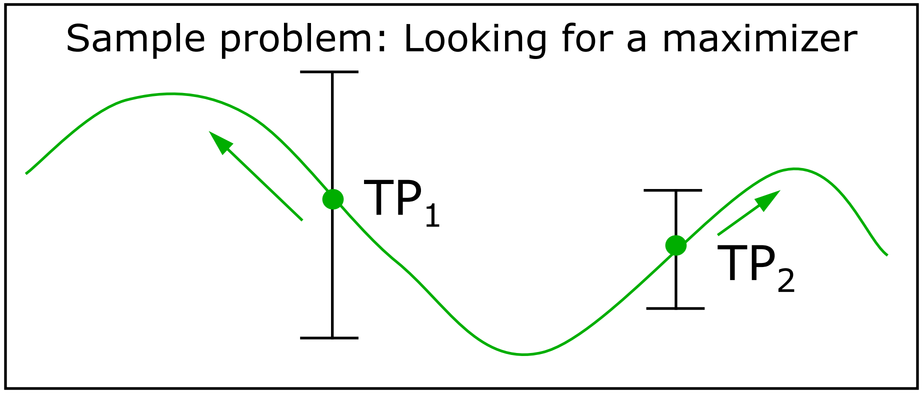
- **Electrical Problem**
  - Little (virtually no) previous validation performed for electrical models
    - Develop methodology for validation of electrical models
  - Limited knowledge of test setup

Optimization Algorithm Decision-Maker

Current algorithms

- Accept next guess based on some notion of (sufficient) increase (or decrease)

“ $f(TP_1) > f(TP_2)$ ”



Which trial point (and search direction) is better?

Next-generation algorithms

- Create a general decision-maker that considers rankings and probability metrics:

$\sigma(f(TP_2)) < \sigma(f(TP_1))$

$f(TP_2) < F_{critical}$

$Prob(f(TP_2) < \Phi_{critical}) > \alpha$

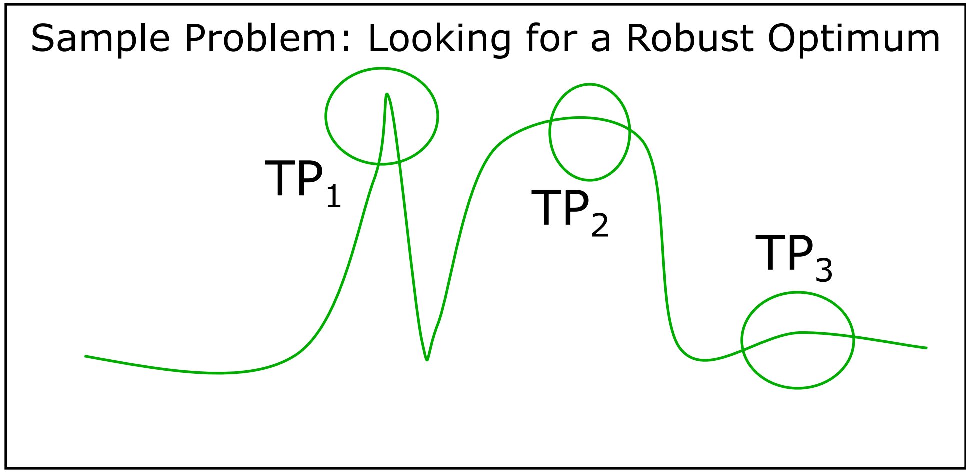
Potential Benefits:

- **Dismisses parameter-space regions (around trial points)**
  - **With large variances**
  - **where critical thresholds are exceeded**
- **Makes “meaner” decisions if on a tight computing budget**

→ assess computational savings

"Robust"/Multiple Optima

- **Accept guess as optimum based on inability to find better guess within decreasing search region.**
  - **Say, TP_1 is found optimum.**
  - **But, a design at TP_1 looks like it is** not robust **to small design perturbations** (BADNESS!)

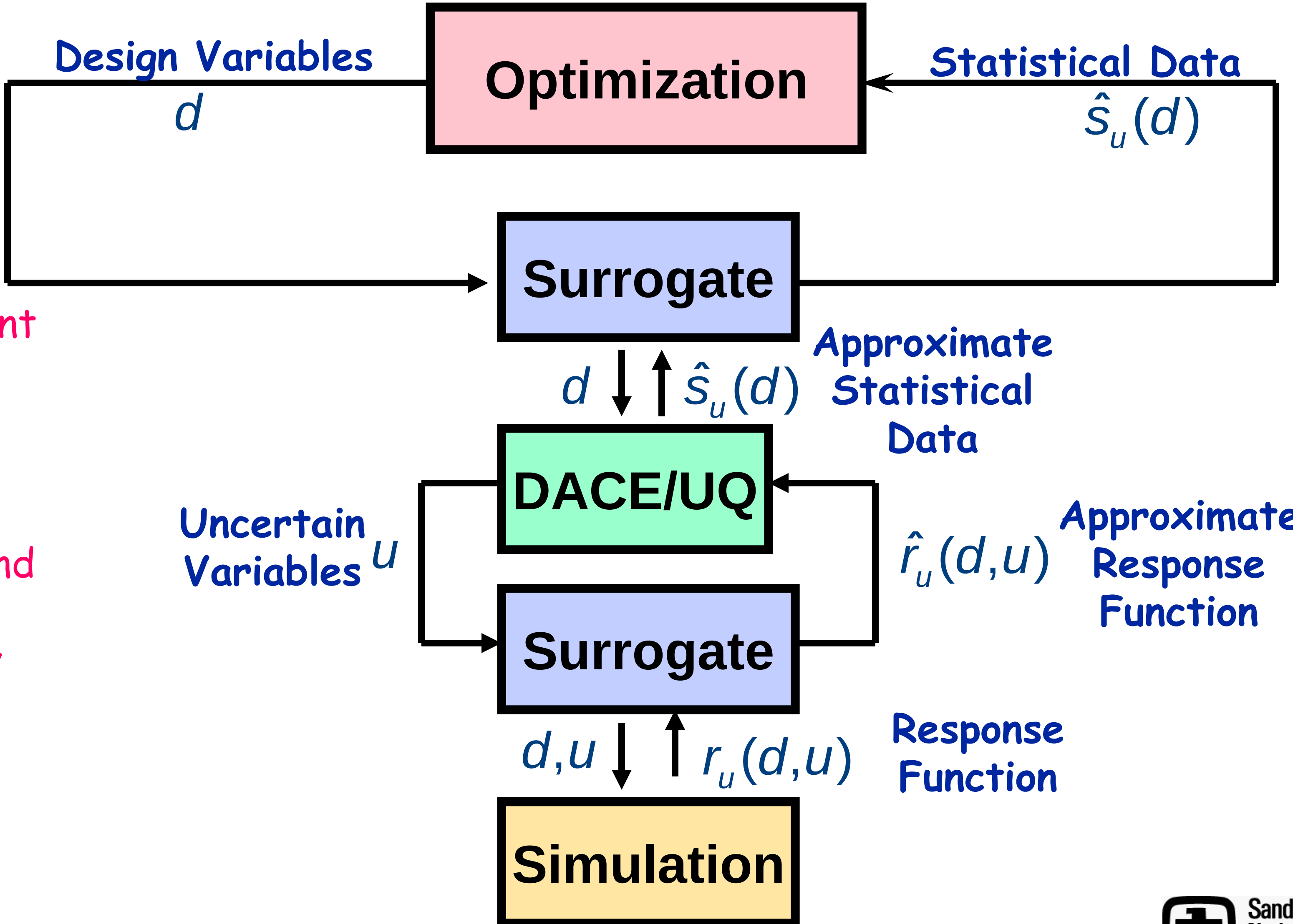


- **Next-generation algorithms: decision-maker chooses "best" point (iterating toward optimum) based on sensitivity (?)**

Next-generation algorithms: Track regional "optimum" to generate set of multiple solutions

Framework for Multi-Fidelity Optimization Under Uncertainty

Expected Improvement Function balances evaluation cost across fidelities and degrees of uncertainty



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Pattern Search Methods

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V&V and QMU Processes Working Together with Optimization