Breadth-Depth Triangulation for Validation and Verification for Modeling and Simulation of Complex Systems

William N. Reynolds
President
Least Squares Software, Inc.
bill@leastsquares.com
(505)-266-6199

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Overview

- Collaborators:
  - **Frank C. Wimberly, CMU (retired)**
  - **Marta Weber, Applied Behavioral Sciences**
- Current Practice
  - VV&A RPG – Scientific Method, compare models to reality: SMEs, Data, T&E, etc.
  - NRC Report – *Validation for Action* – how does model support intended use? Innovative approach, very relevant for intelligence analysis. Shifts problem of measuring model validity to problem of measuring action validity (how to measure quality of a decision?) *Model Docking* – comparing different simulations.
  - Social Sciences – *Triangulation* – construct and compare multiple models using multiple paradigms, viewpoints and data sources. Tests not only model↔reality, but validity of concepts. Often has apples/oranges problems.
  - Others
- All approaches hamstrung by inability to:
  - Capture all present and future relevant factors (*i.e.* identify the right model)
  - Survey enormous input/output spaces
  - Conduct experiments and collect data

Approach

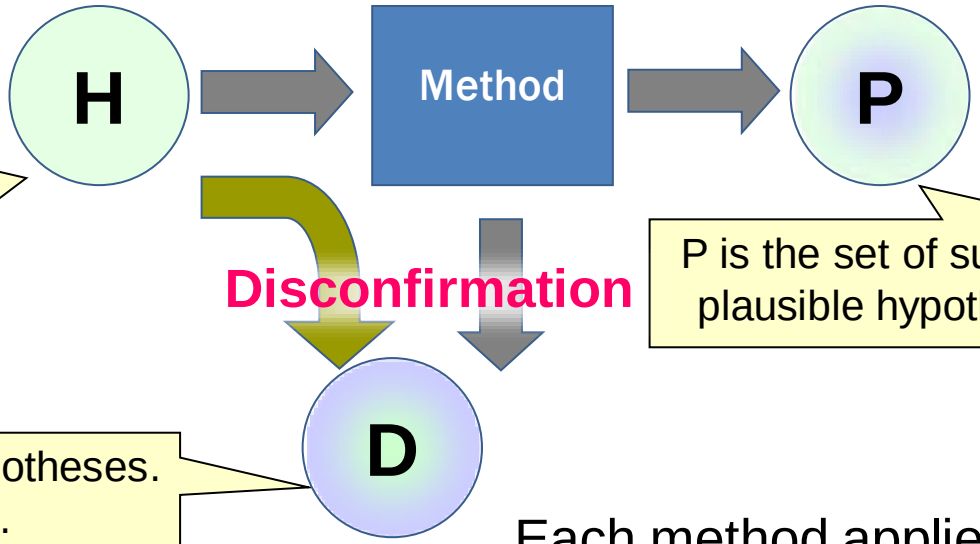
Hypothesis: Low-complexity, cognitively inexpensive, *Breadth* models, such as *Morphological Analysis (MA),* can be used as a basis for *Validation and Verification* by *Triangulation* against high-complexity, cognitively expensive, *Depth* models, such simulation.

Technical Approach:

- Structured Capture of SME Knowledge – structured techniques can be superior to unstructured judgment (*Checklist Manifesto* – Gawande)
- A tool to support MA-based V&V : MORPHINE
  - MA developed 50 years ago, idea of using it for V&V novel (patent protection applied for)
  - No available tools support MA
  - MA effective, but tricky. Methodology *ad hoc.* Need to build out methodology for developing HSCB models. Are there “Canonical” variables/states that can be used across many different models?

A Model of Structured Reasoning Techniques

H represents the set of all hypotheses considered by a method. It contains a total of **|H|** hypotheses.



P is the set of surviving plausible hypotheses.

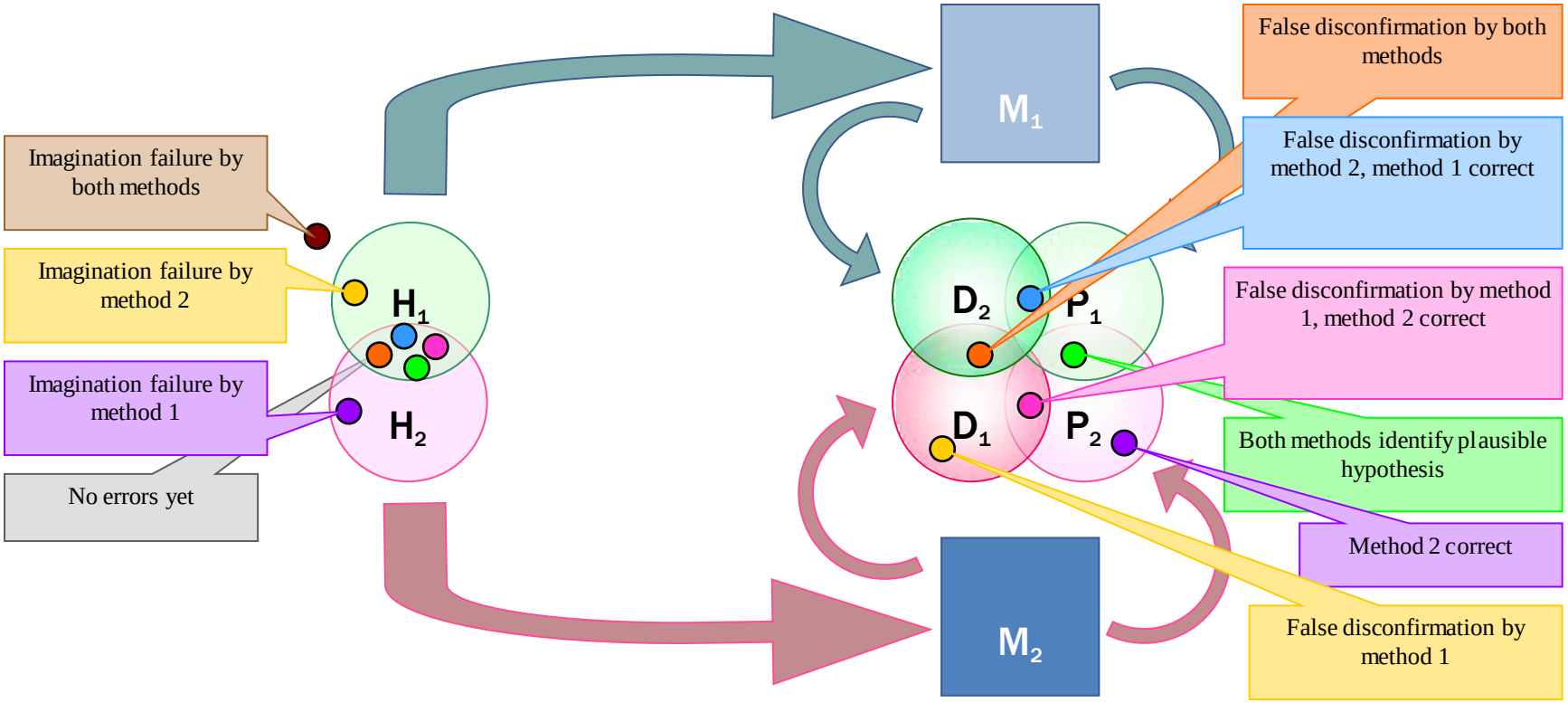
D is the set of disconfirmed hypotheses. It contains |D| elements.

Each method applied has a cost (in time, effort and/or money), which we will represent as **C**.

The fraction of initial hypotheses that are disconfirmed by method is the Discrimination of the method: $D_M = |D|/|H|$

The number of hypotheses considered per unit of cost is the Efficiency of the method: $R_M = |H|/C$

Errors in Two-Method Triangulation



☐Probability of imagination failure by both methods: $P^{MM}_{IM} = P^{1}_{IM} \bullet P^{2}_{IM}$
☐Probability of false negative by both methods: $P^{MM}_{II} = P^{1}_{II} \bullet P^{2}_{II}$
☐Probability of false positive by both methods: $P^{MM}_{I} = P^{1}_{I} \bullet P^{2}_{I}$

* Assumes errors uncorrelated!

Why Morphological Analysis?

- Morphological Analysis
  - Basic Idea – develop coarse grained survey of possibility space. Developed by Zwicky in 1950s.
  - *Breadth Analysis*. Used to understand basic mechanisms, disseminate results, and to guide and validate *Depth* analysis (simulation).
  - Provides a systematic encoding of *Expert Knowledge*
  - First prototype focused on leadership support for pathways (the interaction between leadership decisions and level-of-effort on pathways).

Example Problem: Denied Activity with Cover Program (*e.g.* Tunneling & Gardening)

1. Break problem into descriptive variables.
2. Eliminate configurations by eliminating incompatible state configurations. (X in the matrix).

		Hidden Program		Leadership Mix			Hidden Pathway Financing			Overt Pathway Financing	
		None	Exists	Overt Only	Both	Hidden (Overt as Cover)	High	Low	None	High	Low
Hidden Program	None										
	Exists										
Leadership Mix	Overt Only		X								
	Both	X									
	Overt as Cover	X									
Hidden Pathway Financing	High	X		X							
	Low	X		X							
	None		X		X	X					
Overt Pathway Financing	High										
	Low										

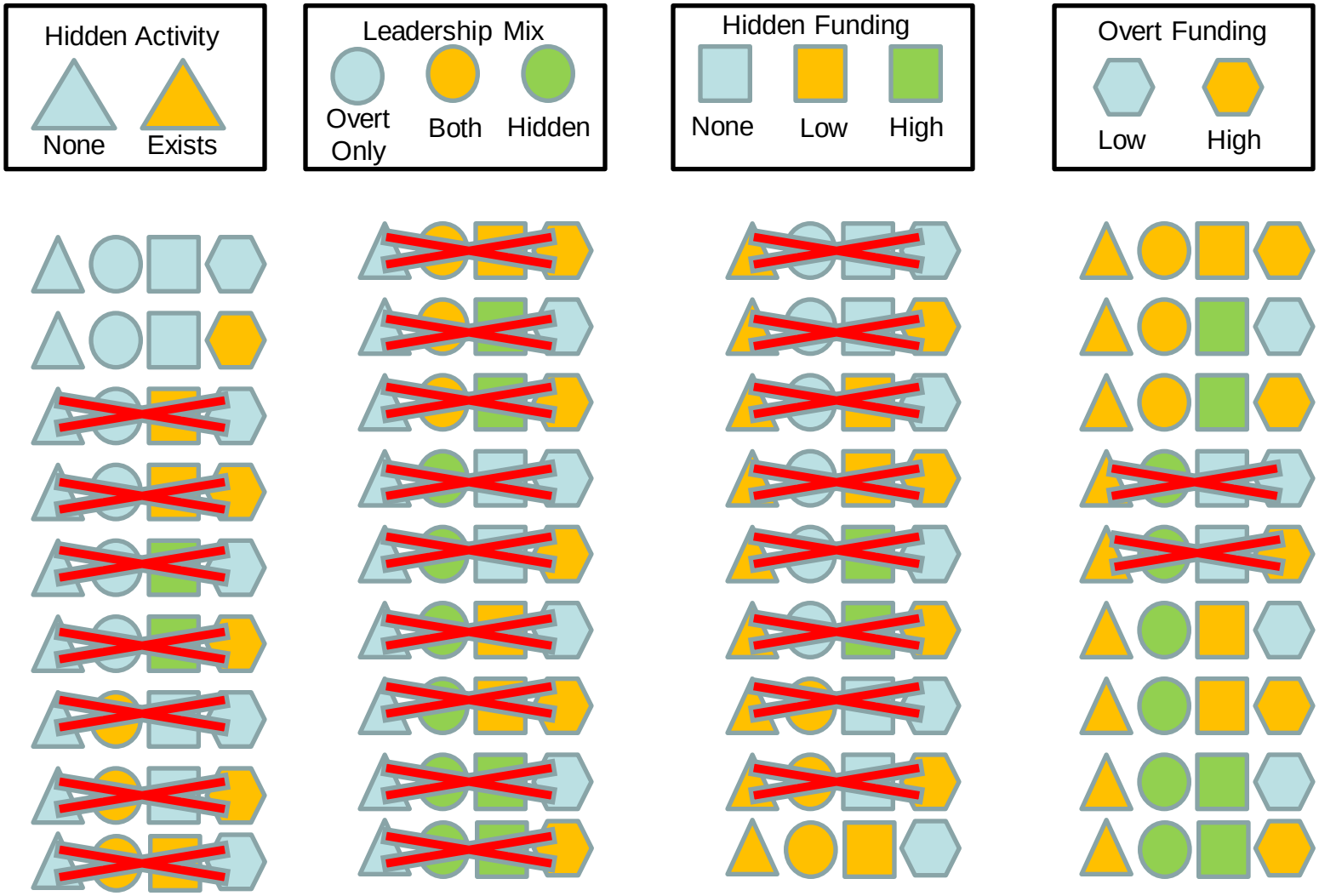
3. Enumerate possible configurations
   a. 9 *Allowed* out of
   b. 36 *Possible* states

Validation Criteria!

	Hidden Program	Leadership Mix	Hidden Funding	Overt Funding
1	none	overt	none	low
2	none	overt	none	high
3	exists	both	low	low
4	exists	both	low	high
5	exists	both	high	low
6	exists	both	high	high
7	exists	hidden	low	low
8	exists	hidden	low	high
9	exists	hidden	high	low
10	exists	hidden	high	high

Disallow configuration 8: three-element constraint (hidden lower than overt not consistent with hidden preference)

Illustration of MA Reduction of the State Space



Master Equation MA

- Which state-to-state transitions are likely?
- Understanding allowable and possible transitions provides insights which make probe (system stimulus) design easier and more reliable
  - Leadership Probe: Leadership is shifted towards *Hidden* or *Overt* program, (*e.g.* by denying vegetables). Expect funding to shift in consonance with the leadership shift.
  - Funding Probe: Overall levels of funding will increase or decrease. High/Low => Low/Low (Overt/Hidden funding)

Example Probe: Leadership Favors Overt Program

Leadership Shift	Funding Shift
4O-Fav	F-0

Leadership Mix	3	Both
Hidden Funding		Low
Overt Funding		Low

Leadership Mix	2	Overt
Hidden Funding		None
Overt Funding		High

Leadership Mix	7	Hidden
Hidden Funding		Low
Overt Funding		Low

Leadership Mix	2	Overt
Hidden Funding		None
Overt Funding		High

Leadership Mix	3	Both
Hidden Funding		Low
Overt Funding		Low

Leadership Mix	9	Hidden
Hidden Funding		High
Overt Funding		Low

Leadership Mix	4	Both
Hidden Funding		Low
Overt Funding		High

Leadership Mix	10	Hidden
Hidden Funding		High
Overt Funding		High

Leadership Mix	6	Both
Hidden Funding		High
Overt Funding		High

Leadership Mix	1	Overt
Hidden Funding		None
Overt Funding		Low

Leadership Mix	1	Overt
Hidden Funding		None
Overt Funding		Low

Leadership Mix	2	Overt
Hidden Funding		None
Overt Funding		High

Leadership Mix	2	Overt
Hidden Funding		None
Overt Funding		High

Leadership Mix	4	Both
Hidden Funding		Low
Overt Funding		High

Leadership Mix	5	Both
Hidden Funding		High
Overt Funding		Low

Leadership Mix	6	Both
Hidden Funding		High
Overt Funding		High

Non-Modeled behavior:
- Hidden program dismantled
- Funding/resources available

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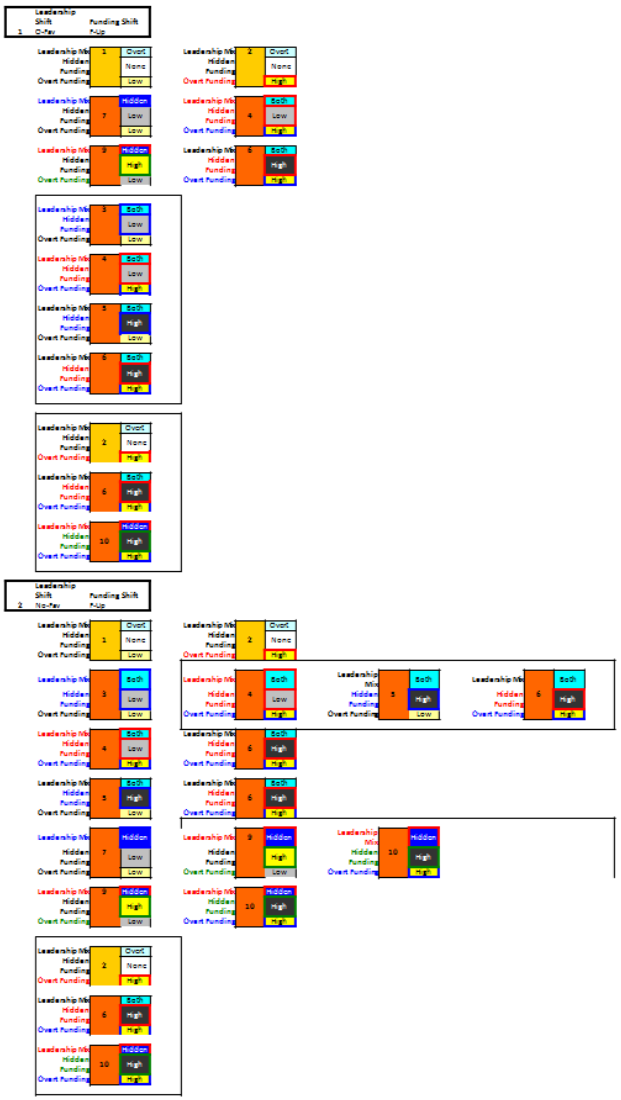
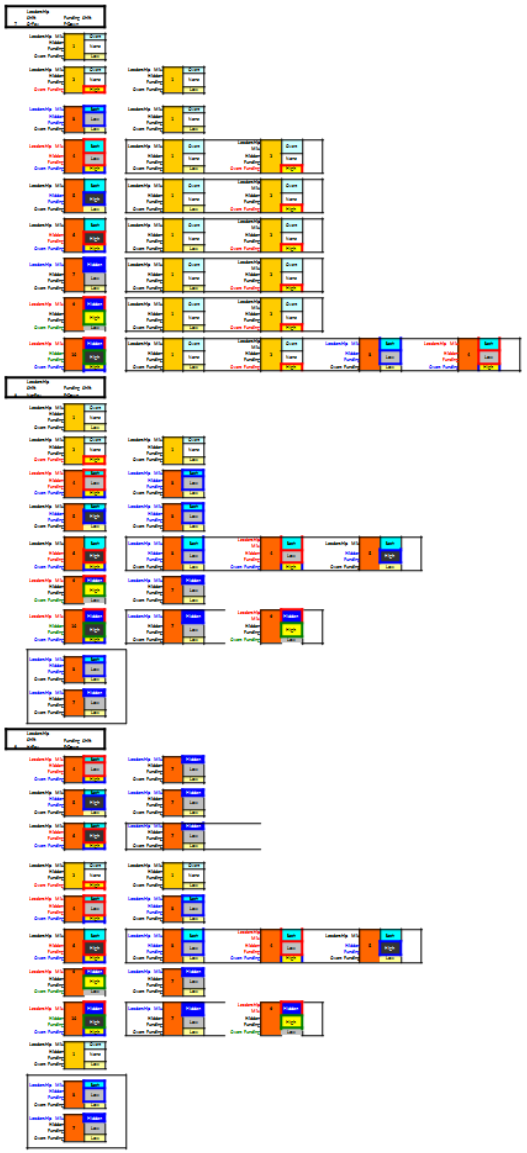
Full Transition Analysis

Revolutionary Research . . . Relevant Result





Using MA Transitions to Assess Probe

- Observable Element: *Overt Funding*
- Two possible states: *Hi* and *Low*

Overt Low States

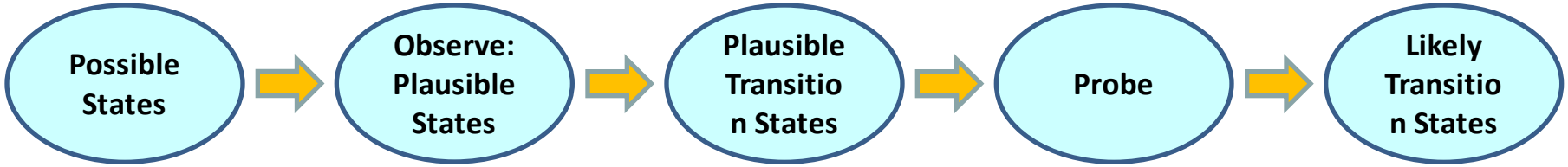
1	none	overt	none	low
3	exists	both	low	low
5	exists	both	high	low
7	exists	hidden	low	low
9	exists	hidden	high	low

Overt Hi States

2	none	overt	none	high
4	exists	both	low	hi
6	exists	both	hi	hi
10	exists	hidden	hi	hi

- For a given observable state, which probes are most likely to reveal hidden state?

General Procedure:



Overt Low States

1	none	overt	none	low
3	exists	both	low	low
5	exists	both	hi	low
7	exists	hidden	low	low
9	exists	hidden	hi	low

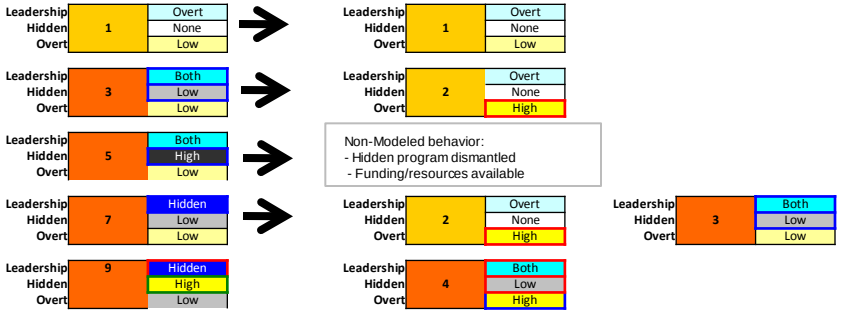
Overt Hi States

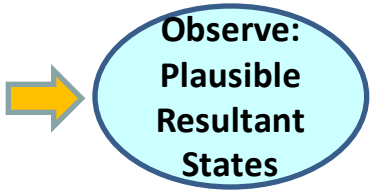
2	none	overt	none	hi
4	exists	both	low	hi
6	exists	both	hi	hi
10	exists	hidden	hi	hi

Observe Overt Funding Low

Overt Low States

1	none	overt	none	low
3	exists	both	low	low
5	exists	both	hi	low
7	exists	hidden	low	low
9	exists	hidden	hi	low





Non-Modeled

Leadership	5	Both
Hidden		High
Overt		Low

Overt Funding Hi

Leadership	2	Overt
Hidden		None
Overt		High
Leadership	4	Both
Hidden		Low
Overt		High

Overt Funding Low

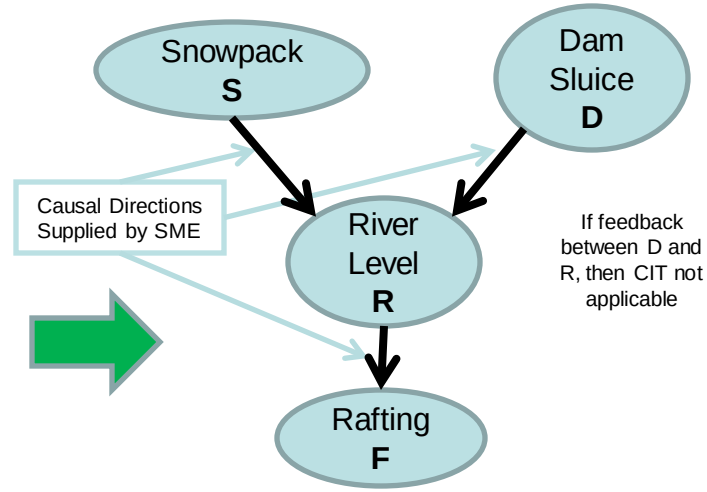
Leadership	1	Overt
Hidden		None
Overt		Low
Leadership	3	Both
Hidden		Low
Overt		Low

Causal Validation Using MA and Causal Inference Theory

- Causality – what leads to what? Deep problem from philosophy.
- Experts often have very good knowledge of Causal Relationships in a system
- Causal Inference Theory: recent (last 20 years) development in learning causal structures from data (CMU: Scheines, Glymour & Spirtes, UCLA: Pearl).
  - Approach hinges on fact statistical tests of independence reveal causal relationships, in particular, comparison of statistical tests:
    - $X \perp\!\!\!\perp Y$ ("X independent of Y")
    - $X \perp\!\!\!\perp Y \mid Z$ ("X independent of Y given Z")
- **Validation Approach:**
  1. **Solicit Causal Linkages from SMEs using MA.**
  2. **Generate samples from simulation.**
  3. **Use statistical tests from CIT on sample data to confirm/disconfirm solicited causal relations.**

		Snowpack		Sluice Gate		River Level			Rafting Activity	
		low	high	shut	open	low	medium	high	no	yes
Snowpack	low									
	high									
Sluice Gate	shut									
	open									
River Level	low		X		X					
	medium									
	high									
Rafting Activity	no									
	yes					X	X			

Constraint in block implies causal link



The elicited causal model predicts the following dependencies:

- $S \perp\!\!\!\perp D$
- NOT $(S \perp\!\!\!\perp D \mid R)$
- $D \perp\!\!\!\perp F \mid R$
- $S \perp\!\!\!\perp F \mid R$

These follow from principle of ***d-separation***

Generate a *Contingency Table* by conducting an ensemble of simulation runs. **Test** statistical hypotheses using ***G Test*** (or **Chi-Square**)***.*** For example:

- $S \perp\!\!\!\perp D$ tests hypothesis $P(S,D) = P(S)P(D)$
- $S \perp\!\!\!\perp D|R$ tests $P(S,D,R) = P(S|R)P(D|R)P(R)$.

Contingency Table of Simulation Runs for S,D,R

	Dam Sluice		
Snowpack	**Shut**	**Open**	
Low	1983	0	1983
High	0	0	0
	1983	0	
	River	**Low**	
	Total	1983	
Total Samples	10000		

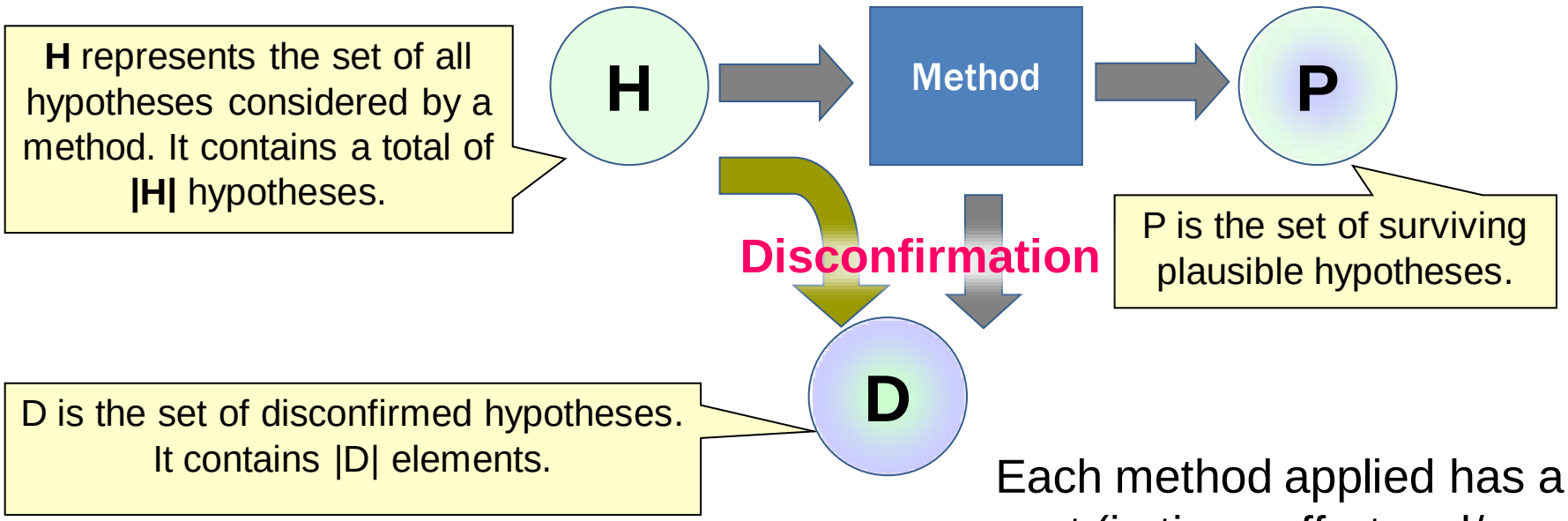
Expect frequency 0 from MA table!

	Dam Sluice		
Snowpack	**Shut**	**Open**	
Low	11	1367	1378
High	694	696	1390
	705	2063	
	River	**Medium**	
	Total	2768	

	Dam Sluice		
Snowpack	**Shut**	**Open**	
Low	1804	79	1883
High	2133	1233	3366
	3937	1312	
	River	**High**	
	Total	5249	

BACKUP

A Model of AM/SATs



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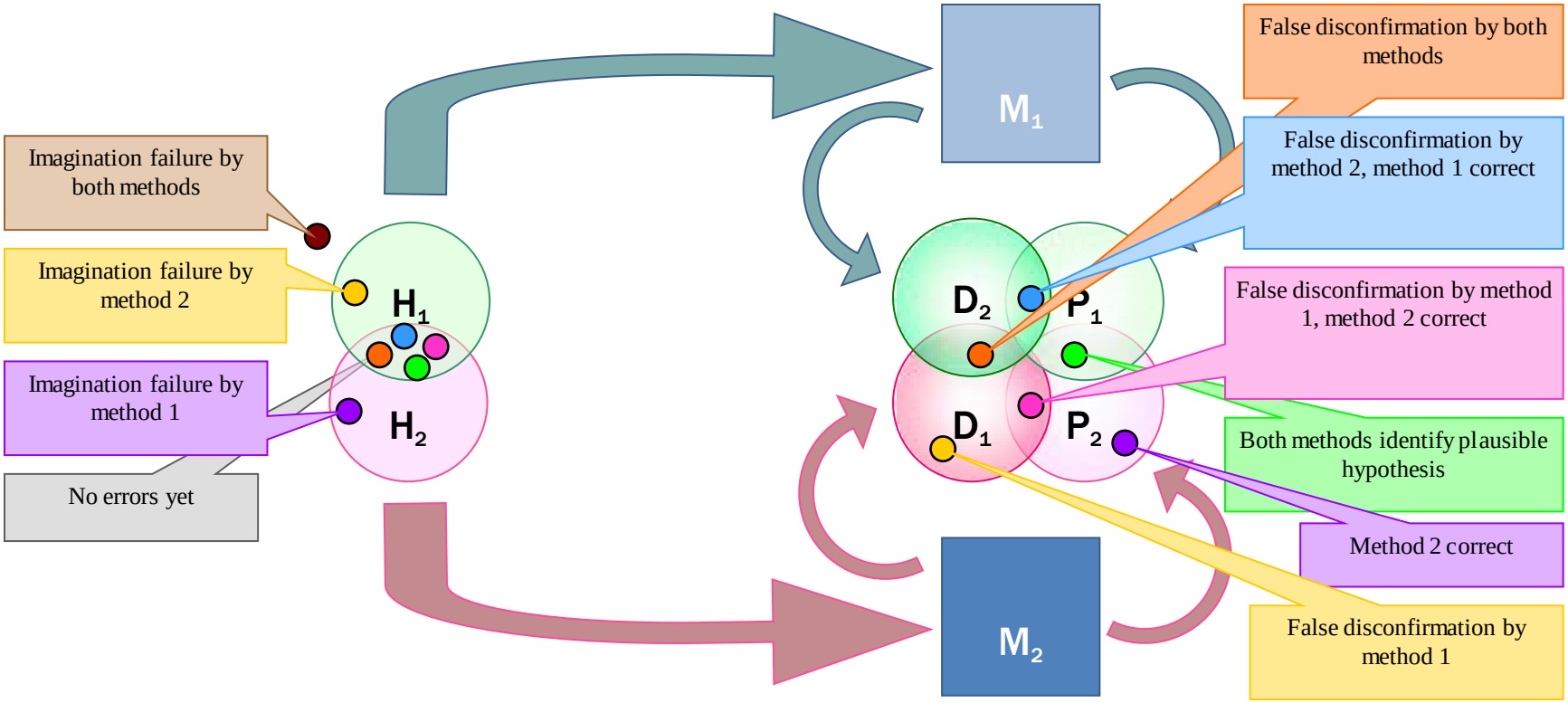
The number of hypotheses considered per unit of cost is the Efficiency of the method: $R_M = |H|/C$

The fraction of initial hypotheses that are disconfirmed by method is the Discrimination of the method: $D_M = |H|/|D|$

Correlations in Error Rate



$P(E_1 = Y, E_2 = Y) = P(E_1 = Y| E_2 = Y)\ P(E_2 = Y)$

If we use the same method twice, then $P(E_1 = Y| E_2 = Y) = 1$ (error in method 2 always produces error in method 1), so no reduction in error rate. Any decorrelation in component method error rates leads to reduction in overall error rate. Question is: At what cost?