Nuclear Arms Control: Optimising Verification Procedures Through Formal Modelling

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Scenario

- One role of AWE is to advise the UK Government on entering any potential nuclear treaty
- Such advice can be informed by models of potential inspection regimes in order to build trust between treaty parties, and be self-assured that all parties are treaty-compliant
- Mathematical models need to express uncertainty about weapons arsenals and nations’ intent, and ability to optimise models to find the ‘best’ inspection regime.

Inspecting items whilst using IBs

- AWE are interested in a modelling approach because information barriers (IBs) and incomplete information in nuclear arms inspections lead to uncertainty in decision making processes.

- Modelling what a nation or organisation inspecting a ‘host’ nation would believe based on their observations (and their inherent uncertainty) during an inspection is important to decision making.

Proposed solution

- We express and analyse such uncertainty in models through formal parameters, e.g. *x* as well as alerting any additional constraints on our model. For example, we could estimate another nation has '*x*' weapons where $low < x < high$.

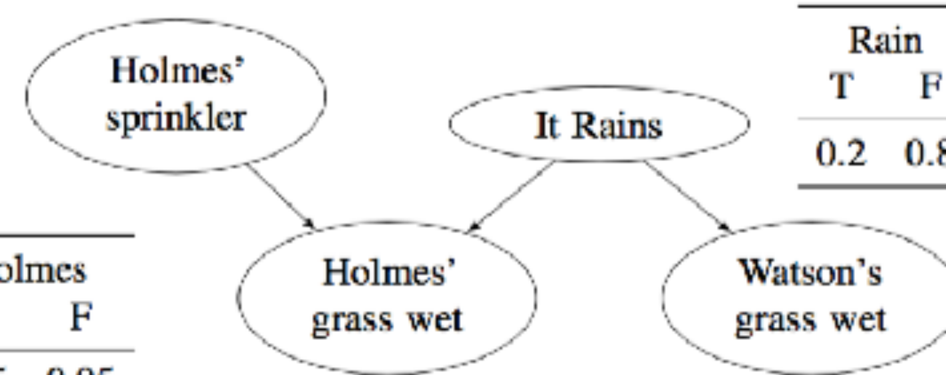
- The constraint solver finds values of *x* that satisfy all constraints given to it, or reports that this is impossible.

- We can also optimise such satisfiability, e.g. to identify the worst-case weapons arsenal within the constraints.

Mathematical background

- Bayesian Belief Networks (BBNs) are graphs that capture the relationships and dependencies between multiple events, and their associated conditional probabilities.
- We proposed a methodology for analysing these models when probabilities are uncertain. We can compute worst-case scenarios in models faced with such uncertainty.

Sprinkler On	Sprinkler Off
0.1	0.9



Rain T	Rain F
0.2	0.8

Sprinkler/Rain		Holmes T	Holmes F
Off	F	0.05	0.95
Off	T	0.7	0.3
On	F	0.95	0.05
On	T	0.99	0.01

Rain	Watson T	Watson F
F	0.05	0.95
T	0.7	0.3

Confidence analysis for nuclear arms control: SMT abstractions of Bayesian Belief Networks

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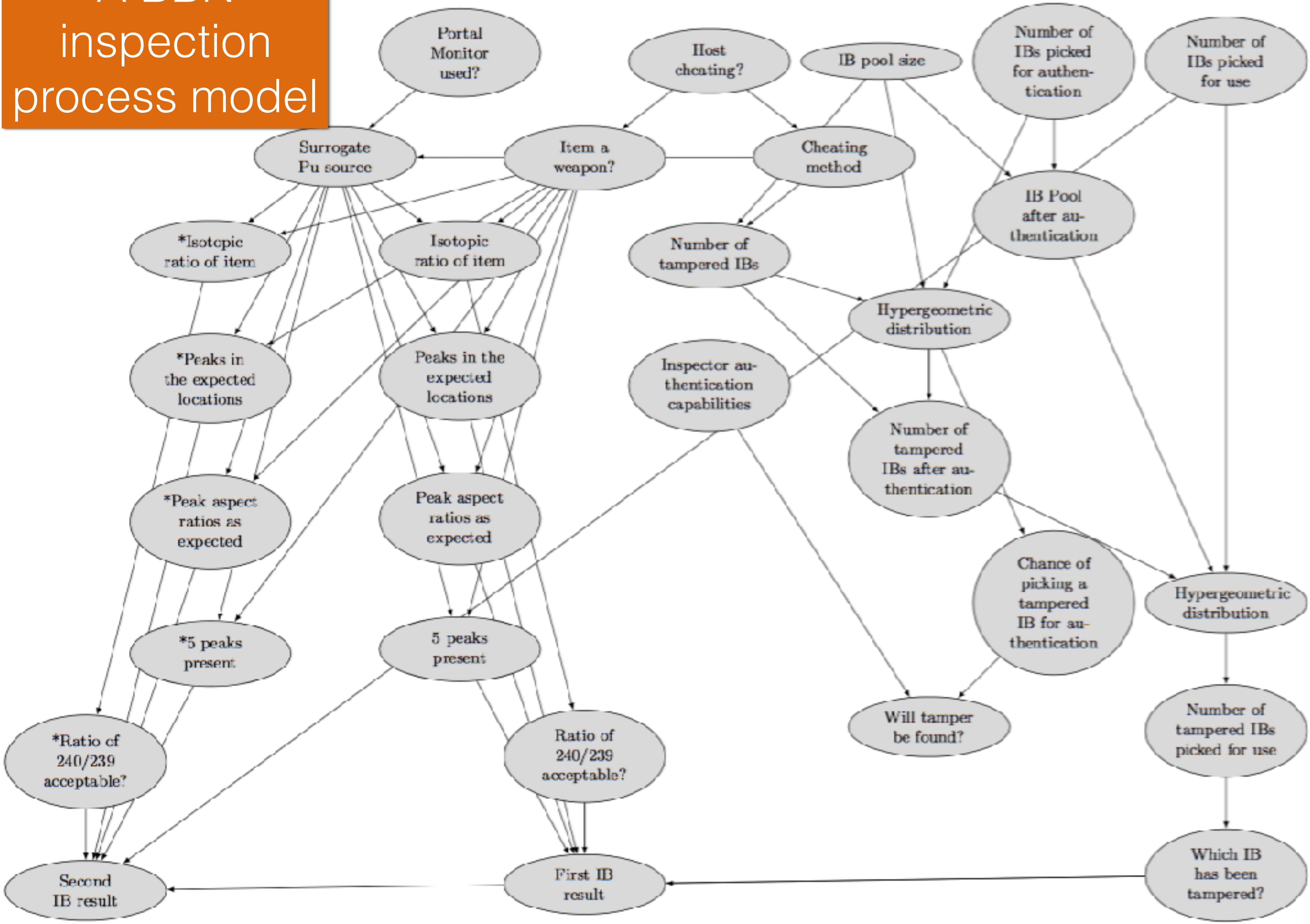
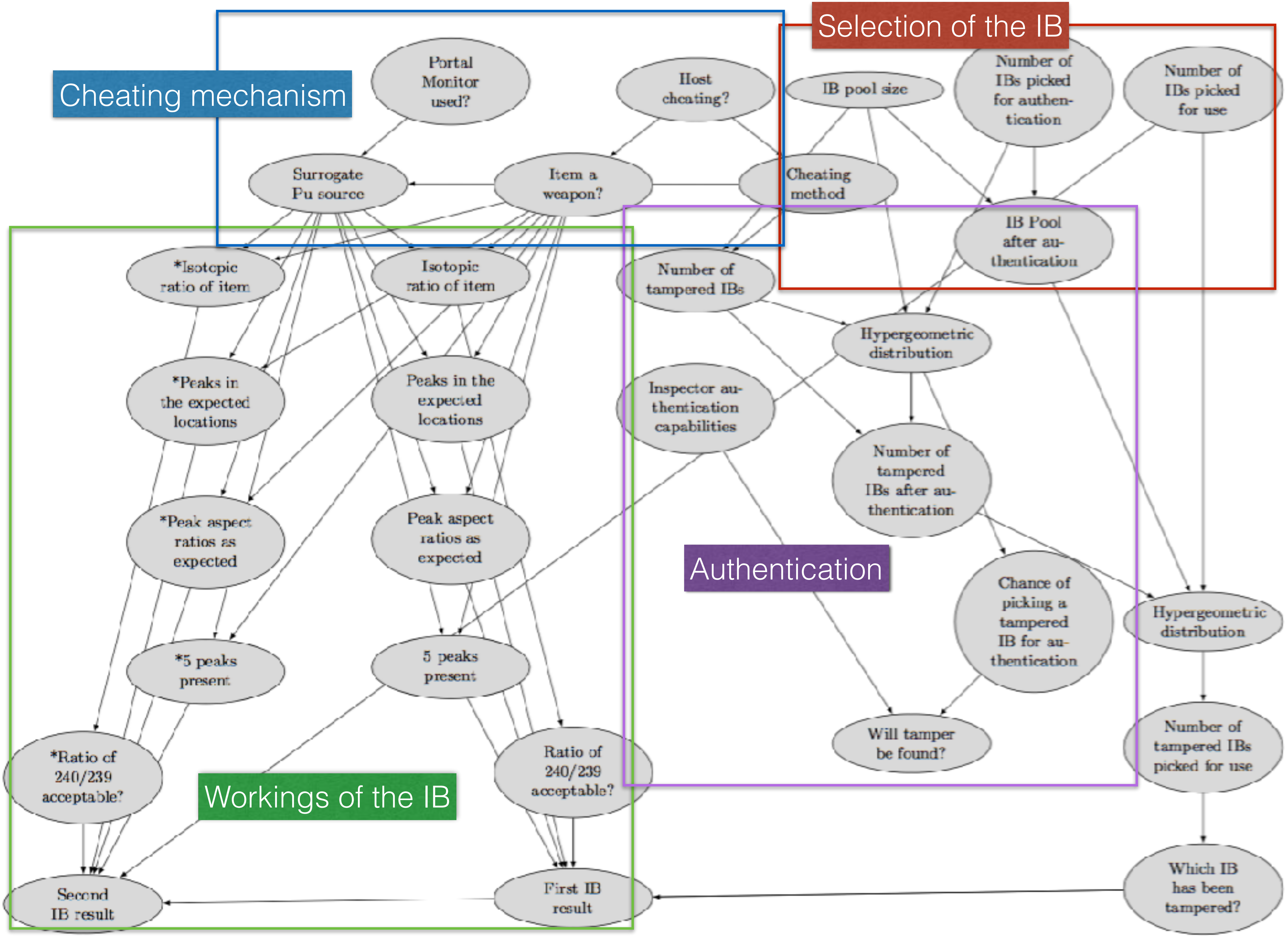
A BBN inspection process model

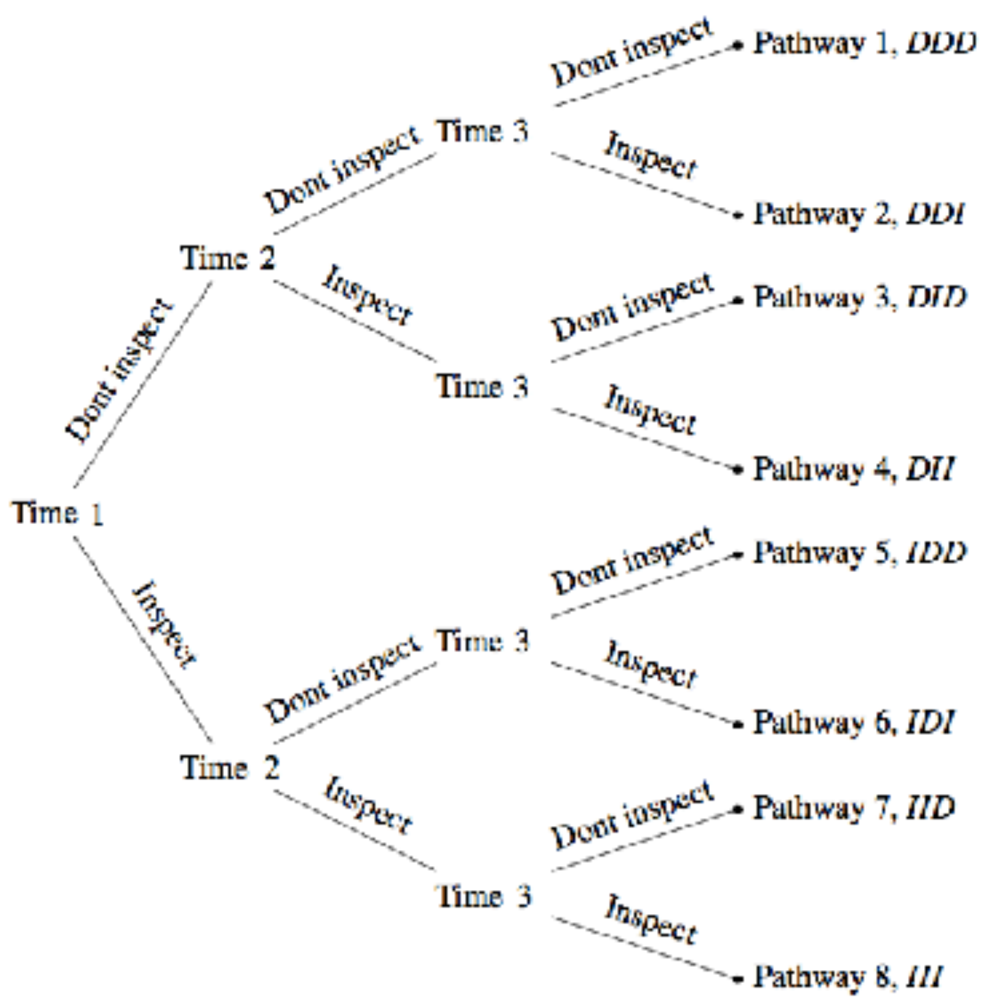



Cheating mechanism
Selection of the IB
Authentication
Workings of the IB
Portal Monitor used?
Host cheating?
IB pool size
Number of IBs picked for authentication
Number of IBs picked for use
Surrogate Pu source
Item a weapon?
Cheating method
IB Pool after authentication
*Isotopic ratio of item
Isotopic ratio of item
Number of tampered IBs
Hypergeometric distribution
*Peaks in the expected locations
Peaks in the expected locations
Inspector authentication capabilities
Number of tampered IBs after authentication
*Peak aspect ratios as expected
Peak aspect ratios as expected
Chance of picking a tampered IB for authentication
Hypergeometric distribution
*5 peaks present
5 peaks present
Will tamper be found?
Number of tampered IBs picked for use
*Ratio of 240/239 acceptable?
Ratio of 240/239 acceptable?
Which IB has been tampered?
Second IB result
First IB result

Example query

- Given we definitely observe no tamper abnormalities on the authenticated IBs, what effect does uncertainty over whether the portal monitor (body scanner) functioned correctly, have on the likelihood of the IB reporting positively that it believes nuclear material is present?
- Our approach shows the likelihood at which the IB would return positively varies in the range 0.5 to 0.7.
- We are in a position to say that we guarantee, in this model, the results cannot vary outside of this range.

Dynamical systems for inspection routines



Dynamical System Pathways

- Dynamical Systems can be used to model changes over time.
- Equations describe our beliefs about how issues interact and influence each other (the number of weapons each has, declares, sees on inspections etc).
- We use these systems to plan optimal inspection scheduling routines.

Example query

- For two nations in a treaty, they can each use at most 3 unscheduled inspections, none of which can happen at adjacent time steps. Scheduled inspections occur every 6 possible inspection time steps and start at time step 1. One nation's initial number of *W*eapons is uncertain, constrained by $low < W_0^{n1} < high$. What is the minimum number of weapons the other nation believes that the first owns by the last time step, and what inspection schedule realises this?

- Concrete values for W_0^{n1}, and inspection positions are returned, as well as values for all variables in all pathways for comparison.

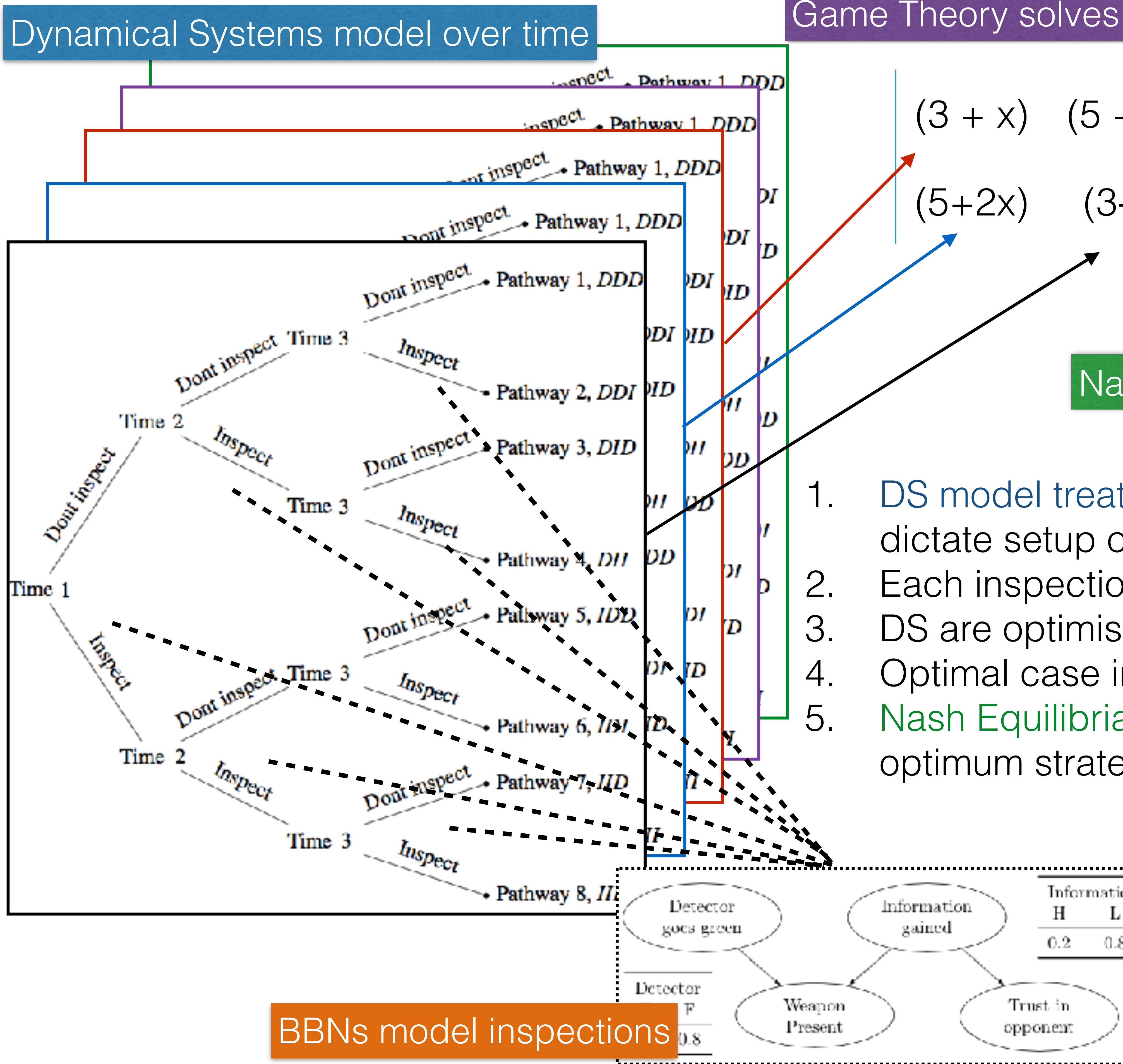
A finer-grained model

- Dynamical Systems are good at modelling treaty interactions and events over time. Bayesian Networks offer a higher fidelity model of an inspection at a particular time step.

- There are some parameters that can't be varied within the Dynamical Systems model, but multiple instances of the model can be run to overcome this.

- Games can be used to help choose between different strategies - where these strategies could be the varying parameters of the Dynamical Systems model.

- We can use these models together successfully to model finer-grained detail of any potential treaty



Game Theory solves for different parameters

(3 + x)	(5 + x)	(-1 +4x)	(5+3x)
(5+2x)	(3-x)	(4-7x)	(x)

↓

Nash Equilibria

1. DS model treaty. Parameters that dictate setup of the DS are varied
2. Each inspection leads to a BBN call
3. DS are optimised for metric of interest
4. Optimal case informs GT payoff
5. Nash Equilibria denotes overall optimum strategy

Analysis & conclusions

- Our approach allows a decision maker planning arms inspections to ask pertinent questions about mathematical models in which some of the data are uncertain, and to compute how answers may depend on variabilities in such uncertainty.

- Our models of arms control regimes can be run with different parameters, and different optimisations to find best, worst and most probable case scenarios, thus aiding decision support.

- The constraint solver provides answers to such analyses that are intelligible to the problem owner.

- Our approach scales well and could be used to evaluate treaty designs on the whole or the effects of rules within a treaty. Applications in areas with decision-support needs without data.