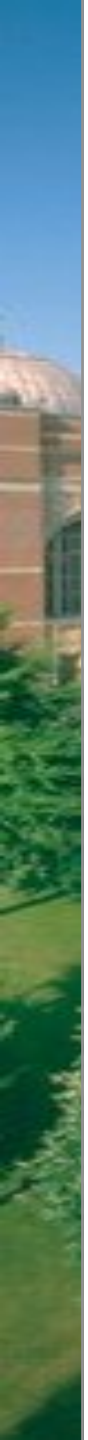

Probabilistic Model Checking and Strategy Synthesis

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UC Berkeley, October 2014

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Joint work with: Marta Kwiatkowska, Vojtěch Forejt, Gethin Norman, Hongyang Qu, Aistis Simaitis, Taolue Chen, Klaus Draeger, Mateusz Ujma, Bruno Lacerda, Nick Hawes

Overview

- Probabilistic model checking
  - verification vs. strategy synthesis
  - Markov decision processes (MDPs)
  - example: robot navigation
- Multi-objective probabilistic model checking
  - examples: power management/team-formation
- Stochastic (multi-player) games
  - example: energy management
- Permissive controller synthesis

Motivation

- Verifying probabilistic systems…
  - unreliable or unpredictable behaviour
    - failures of physical components
    - message loss in wireless communication
    - unreliable sensors/actuators
  - randomisation in algorithms/protocols
    - random back-off in communication protocols
    - random routing to reduce flooding or provide anonymity

- We need to verify quantitative system properties
  - "the probability of the airbag failing to deploy within 0.02 seconds of being triggered is at most 0.001"
  - not just correctness: reliability, timeliness, performance, …
  - not just verification: correctness by construction

Probabilistic model checking

System

Model description

```
module A
  a : [0..N] init N;
  ab : [0..N] init 0;
  [r1] a>0 → k1*a : (a'=a-1)&(ab'=ab+1);
  [r2] ab>0 → k2*ab : (a'=a+1)&(ab'=ab-1);
  [r3] a>0 → k3*a : (a'=a-1);
endmodule
```

System requirements

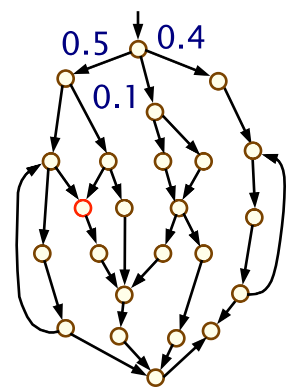
$P_{\leq 0.1}$ [F *fail*]

Probabilistic temporal logic specification

e.g. PCTL, CSL, LTL

Probabilistic model checker

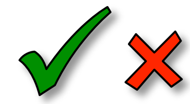
e.g. PRISM



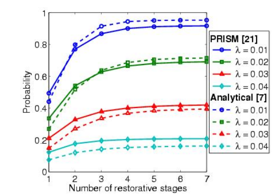
Probabilistic model

e.g. Markov decision process

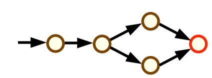
Result



Quantitative results



Counter-example, strategy



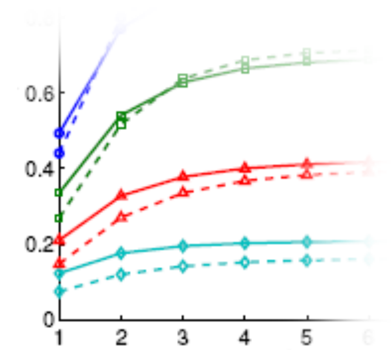
Probabilistic model checking

- Many types of probabilistic models supported
- Wide range of quantitative properties, expressible in temporal logic (probabilities, timing, costs, rewards, …)
- Often focus on numerical results (probabilities etc.)
  - analyse trends, look for system flaws, anomalies

- $P_{\leq 0.1}$ [F *fail*] – "the probability of a failure occurring is at most 0.1"

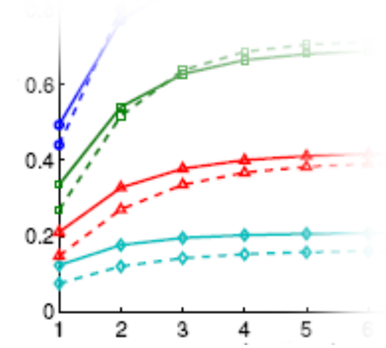
↓

- $P_{=?}$ [F *fail*] – "what is the probability of a failure occurring?"



Probabilistic model checking

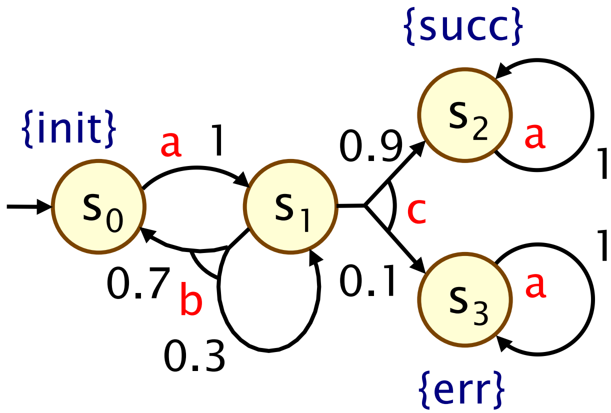
- Many types of probabilistic models supported
- Wide range of quantitative properties, expressible in temporal logic (probabilities, timing, costs, rewards, …)
- Often focus on numerical results (probabilities etc.)
  - analyse trends, look for system flaws, anomalies
- Provides "exact" numerical results/guarantees
  - compared to, for example, simulation
- Combines numerical & exhaustive analysis
  - especially useful for nondeterministic models



- Fully automated, tools available, widely applicable
  - network/communication protocols, security, biology, robotics & planning, power management, …

Markov decision processes (MDPs)

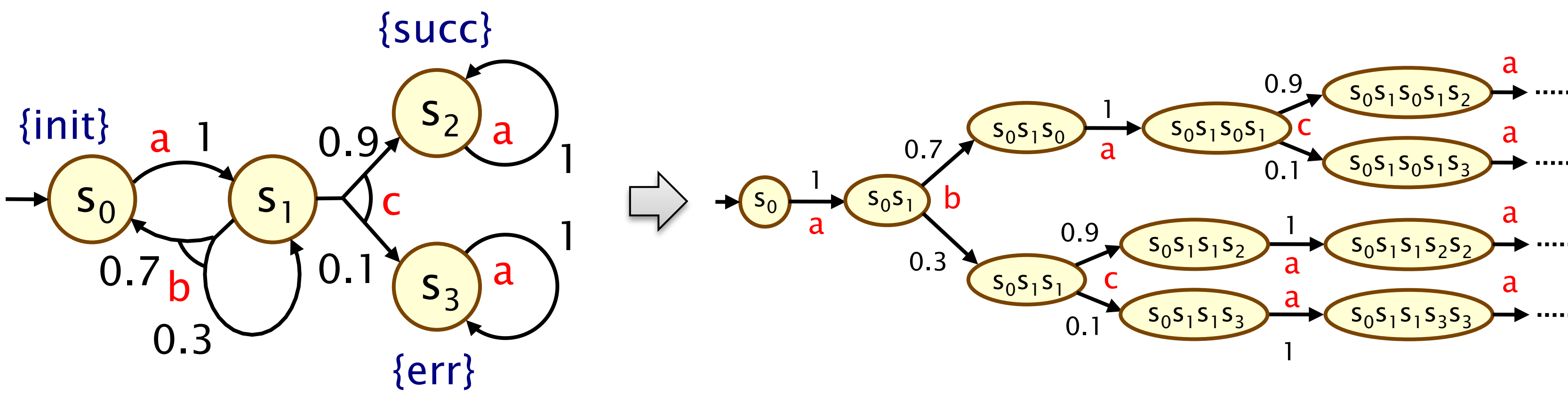
- Markov decision processes (MDPs)
  - widely used also in: AI, planning, optimal control, …
  - model nondeterministic as well as probabilistic behaviour



- Nondeterminism for:
  - control: decisions made by a controller or scheduler
  - adversarial behaviour of the environment
  - concurrency/scheduling: interleavings of parallel components
  - abstraction, or under-specification, of unknown behaviour

Strategies

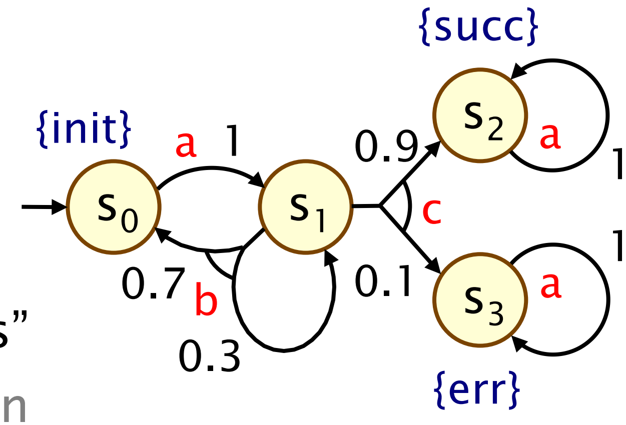
- A strategy (or "policy" or "adversary")
  - is a resolution of nondeterminism, based on history
  - i.e. a mapping from finite paths to (distributions over) actions
  - induces an (infinite-state) discrete-time Markov chain



- Classes of strategies:
  - memory: memoryless, finite-memory, or infinite-memory
  - randomisation: deterministic or randomised

Verification vs. Strategy synthesis

- 1. Verification
  - quantify over all possible strategies (i.e. best/worst-case)
  - $P_{\leq 0.1}$ [F *err*] : “the probability of an error occurring is ≤ 0.1 for all strategies”
  - applications: randomised communication protocols, randomised distributed algorithms, security, …

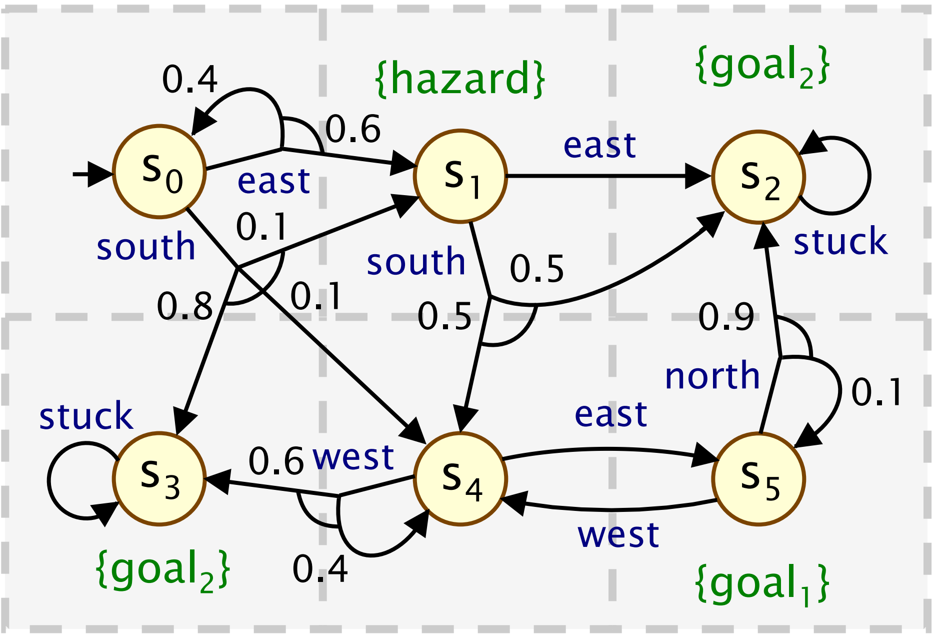


- 2. Strategy synthesis
  - generation of "correct-by-construction" controllers
  - $P_{\leq 0.1}$ [F *err*] : "does there exist a strategy for which the probability of an error occurring is ≤ 0.1?”
  - applications: robotics, power management, security, …

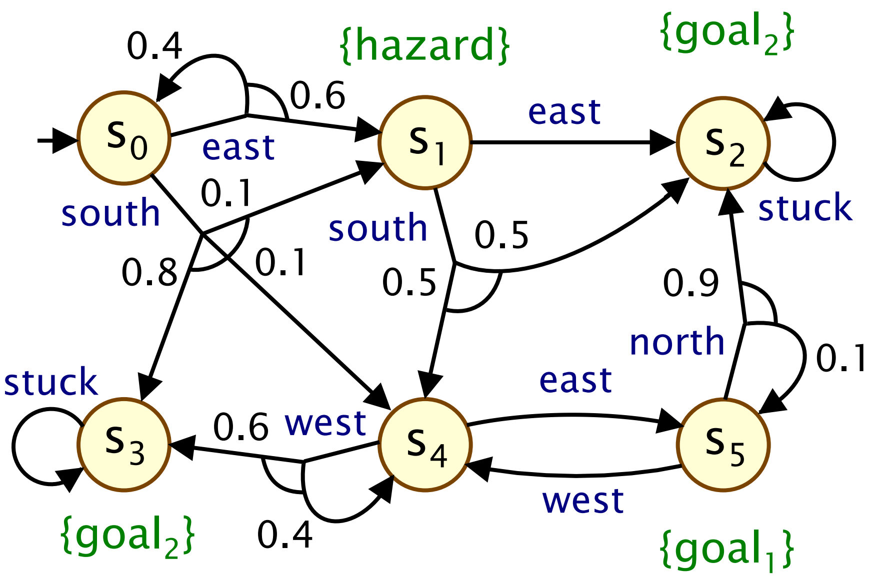
- Two dual problems; same underlying computation:
  - compute optimal (minimum or maximum) values

Running example

- Example MDP
  - robot moving through terrain divided in to 3 x 2 grid



Example – Reachability



Verify: $P_{\leq 0.6}$ [F goal$_1$]

or

Synthesise for: $P_{\geq 0.4}$ [F goal$_1$]

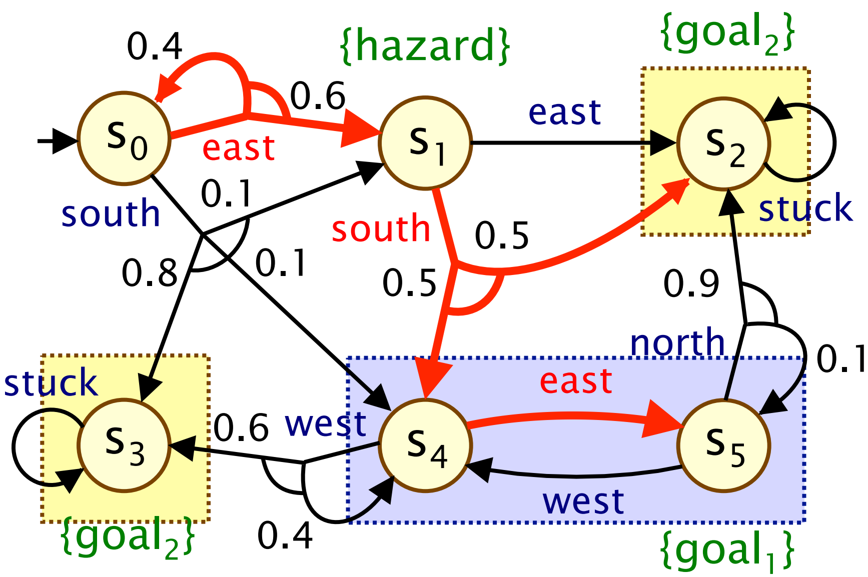
$\Downarrow$

Compute: $P_{max=?}$ [F goal$_1$]

Optimal strategies:
memoryless and deterministic

Computation:
graph analysis + numerical soln. (linear programming, value iteration, policy iteration)

Example – Reachability



Optimal strategy:
s$_0$: east
s$_1$: south
s$_2$: –
s$_3$: –
s$_4$: east
s$_5$: –

Verify: $P_{\leq 0.6}$ [F goal$_1$]

or

Synthesise for: $P_{\geq 0.4}$ [F goal$_1$]

⇓

Compute: $P_{max=?}$ [F goal$_1$] = 0.5

Optimal strategies:
memoryless and deterministic

Computation:
graph analysis + numerical soln.
(linear programming, value iteration, policy iteration)

MDPs – Other properties

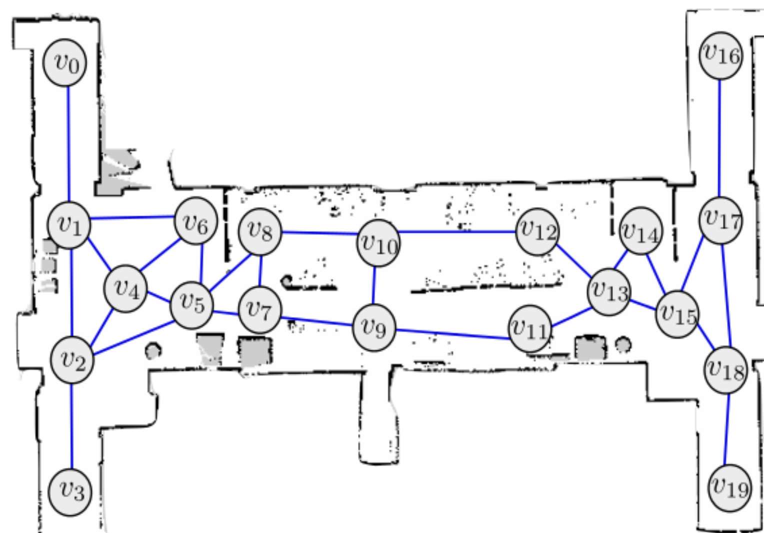
- Costs and rewards (expected, accumulated values)
  - e.g. $R_{min=?}$ [F $goal_2$] – "what is the minimum expected number of moves needed to reach $goal_2$?"
  - optimal strategies: memoryless and deterministic
  - similar computation to probabilistic reachability

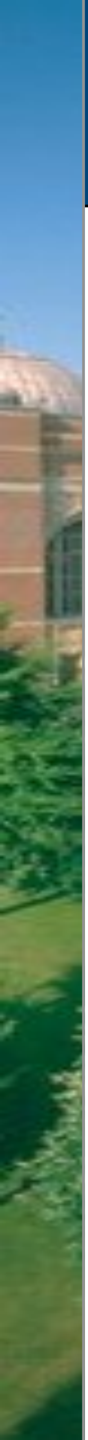
- Probabilistic LTL (multiple temporal operators)
  - e.g. $P_{max=?}$ [(G¬hazard) ∧ (GF $goal_1$)] – "maximum probability of avoiding hazard and visiting $goal_1$ infinitely often?"
  - optimal strategies: finite-memory and deterministic
  - build product MDP, graph analysis, probabilistic reachability

- Expected cost/reward to satisfy (co-safe) LTL formula
  - e.g. $R_{min=?}$ [¬$zone_3$ U ($zone_1$ ∧ (F $zone_4$)] – "minimise exp. time to patrol zones 1 then 4, without passing through 3".

Application: Robot navigation

- Navigation planning for a service robot [IROS'14]
  - MetraLabs Scitos A5 robot + PRISM-based ROS module
- MDP-based strategy synthesis
  - MDP navigation map learnt with transition probabilities/times
  - high-level planning using MDPs + multiple co-safe LTL tasks
  - finite-memory strategies used to construct controllers
  - low-level navigation with separate continuous-space planner





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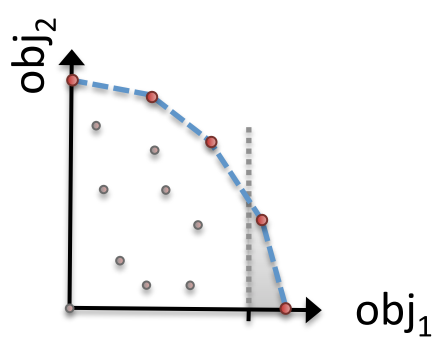
Multi-objective model checking

- Multi-objective probabilistic model checking
  - investigate trade-offs between conflicting objectives
  - in PRISM, objectives are probabilistic LTL or expected rewards
- Achievability queries: multi($P_{>0.95}$ [F *send*], $R^{time}_{>10}$ [C])
  - e.g. "is there a strategy such that the probability of message transmission is > 0.95 and expected battery life > 10 hrs?"
- Numerical queries: multi($P_{max=?}$ [F *send*], $R^{time}_{>10}$ [C])
  - e.g. "maximum probability of message transmission, assuming expected battery life-time is > 10 hrs?"
- Pareto queries:
  - multi($P_{max=?}$ [F *send*], $R^{time}_{max=?}$ [C])
  - e.g. "Pareto curve for maximising probability of transmission and expected battery life-time"



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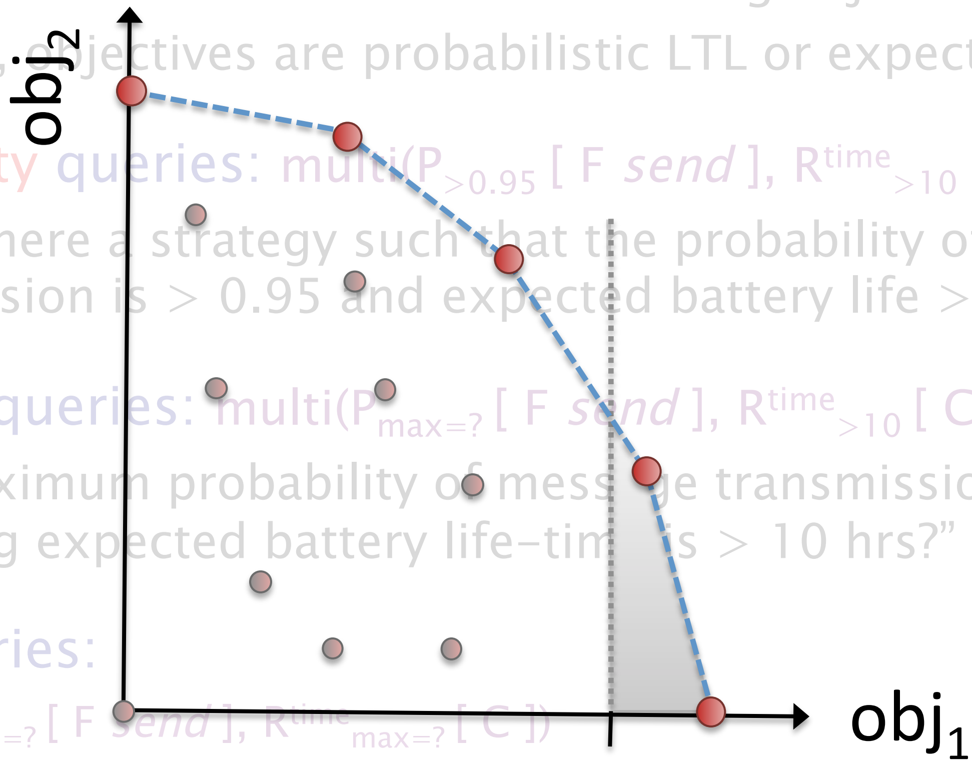


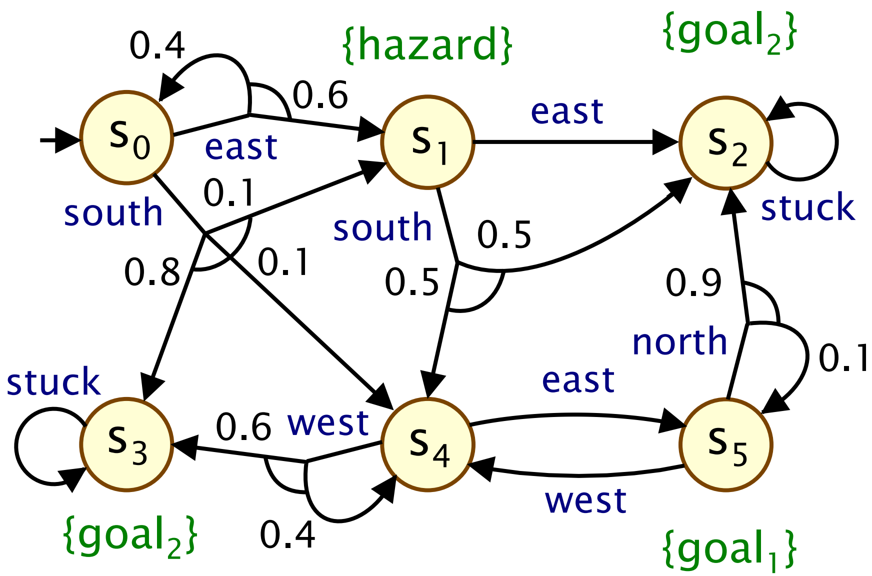
Multi-objective model checking

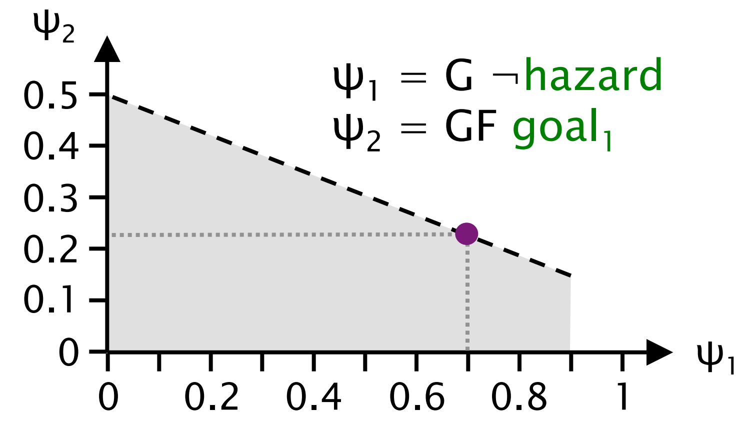
- Optimal strategies:
  - usually finite-memory (e.g. when using LTL formulae)
  - may also need to be randomised

- Computation:
  - construct a product MDP (with several automata), then reduces to linear programming [TACAS'07,TACAS'11]
  - can be approximated using iterative numerical methods, via approximation of the Pareto curve [ATVA'12]

- Extensions [ATVA'12]
  - arbitrary Boolean combinations of objectives
    - e.g. $\psi_1 \Rightarrow \psi_2$ (all strategies satisfying ψ_1 also satisfy ψ_2)
    - (e.g. for assume-guarantee reasoning)
  - time-bounded (finite-horizon) properties

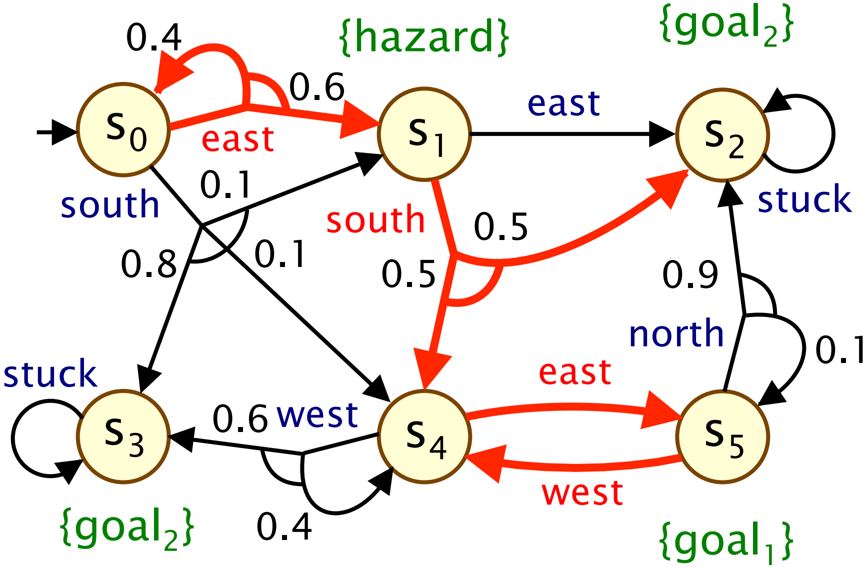
Example – Multi-objective

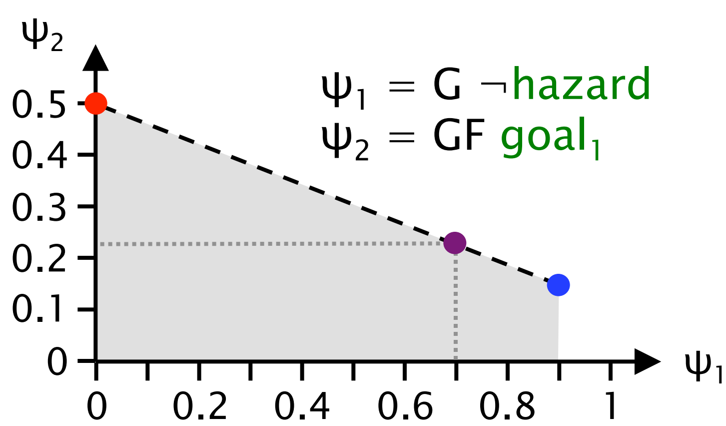




- Achievability query
  - $P_{\geq 0.7}$ [G ¬hazard] ∧ $P_{\geq 0.2}$ [GF goal$_1$] ? True (achievable)
- Numerical query
  - $P_{max=?}$ [GF goal$_1$] such that $P_{\geq 0.7}$ [G ¬hazard] ? ~0.2278
- Pareto query
  - for $P_{max=?}$ [G ¬hazard] ∧ $P_{max=?}$ [GF goal$_1$] ?

Example - Multi-objective





Strategy 1 (deterministic)

s_0 : east

s_1 : south

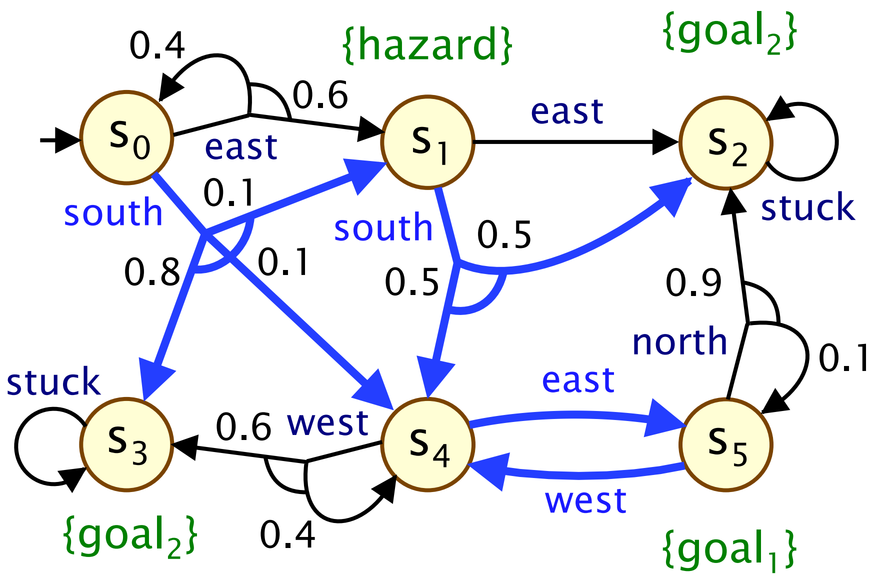
s_2 : –

s_3 : –

s_4 : east

s_5 : west

Example - Multi-objective



Strategy 2
(deterministic)

s_0 : south

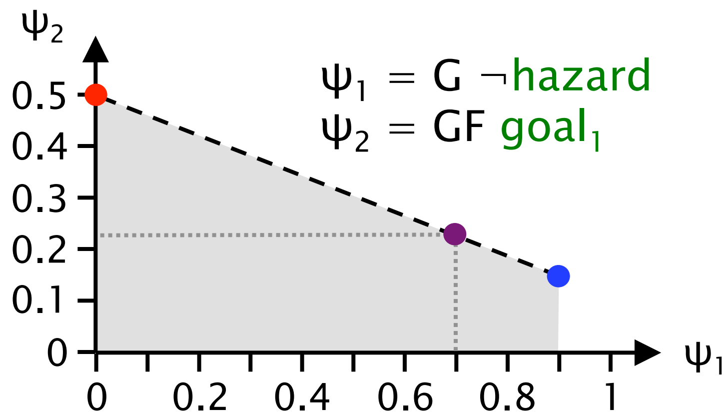
s_1 : south

s_2 : –

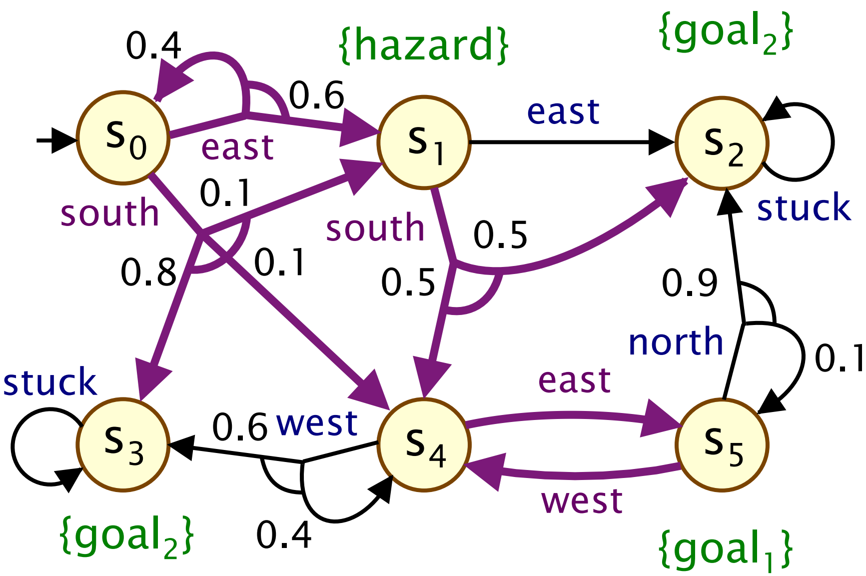
s_3 : –

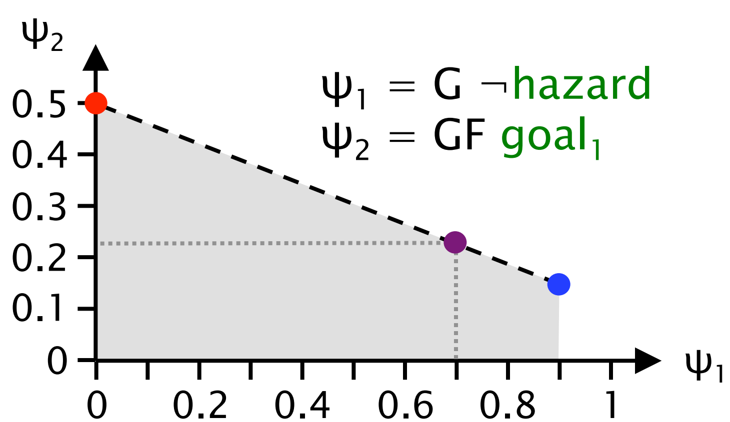
s_4 : east

s_5 : west



Example - Multi-objective





Optimal strategy:
(randomised)

s_0 : 0.3226 : east

0.6774 : south

s_1 : 1.0 : south

s_2 : –

s_3 : –

s_4 : 1.0 : east

s_5 : 1.0 : west

Multi-objective: Applications

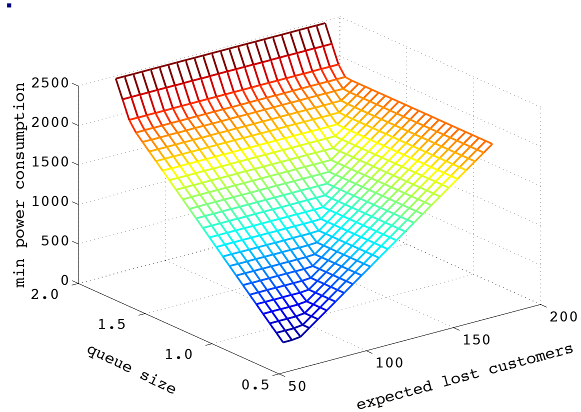
Synthesis of controllers for dynamic power management [TACAS'11]

IBM TravelStar VP disk drive

- switches between power modes:
- active/idle/idlelp/stby/sleep

MDP model in PRISM:

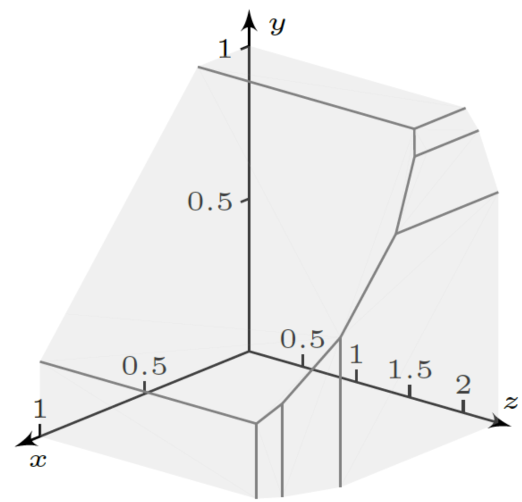
- power manager
- disk requests
- request queue
- power usage



Multi-objective:

"minimise energy consumption,
subject to constraints on:
(i) expected job queue size;
(ii) expected number of lost jobs

Synthesis of team formation strategies [CLIMA'11, ATVA'12]



Pareto curve:

x="probability of completing task 1";
y="probability of completing task 2";
z="expected size of successful team"

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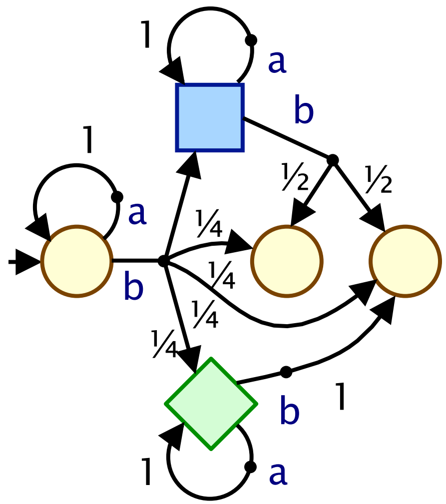
Stochastic multi-player games (SMGs)

- Stochastic multi-player games
  - players control states; choose actions
  - models competitive/collaborative behaviour
  - applications: security (system vs. attacker), controller synthesis (controller vs. environment), distributed algorithms/protocols, …

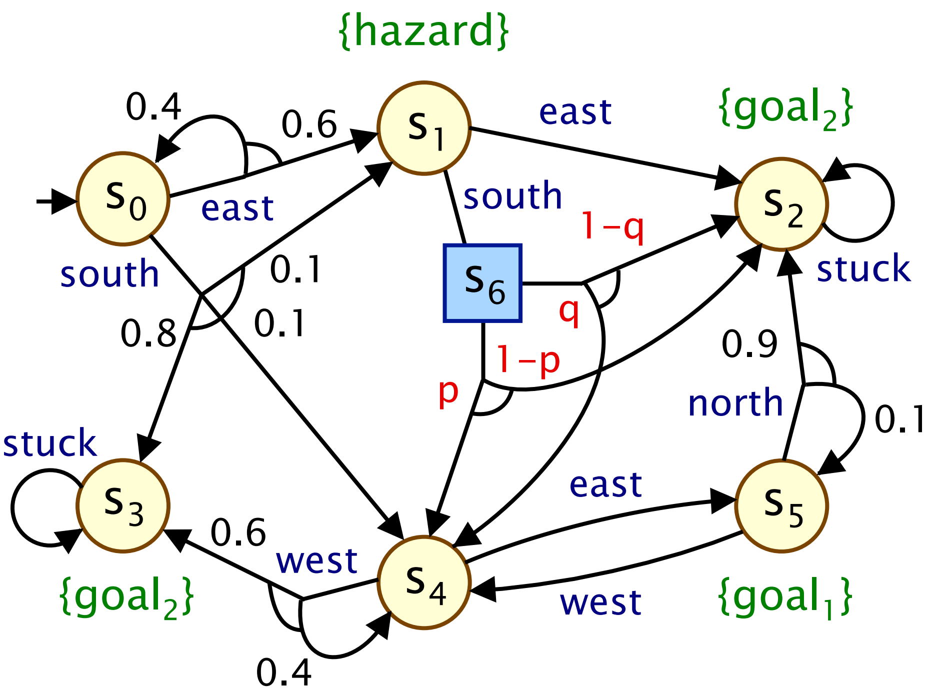


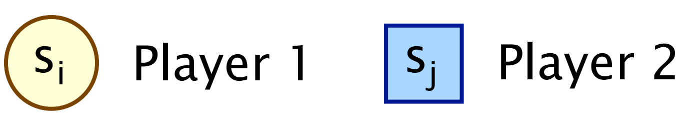
- Property specifications: rPATL
  - $\langle\langle\{1,2\}\rangle\rangle\ P_{\geq 0.95}\ [\ F^{\leq 45}\ \mathit{done}\ ]$: "can nodes 1,2 collaborate so that the probability of the protocol terminating within 45 seconds is at least 0.95, whatever nodes 3,4 do?"
  - formally: $\langle\langle C\rangle\rangle\psi$: do there exist strategies for players in C such that, for all strategies of other players, property ψ holds?

- Model checking [TACAS'12,FMSD'13]
  - zero sum properties: analysis reduces to 2-player games
  - PRISM-games: www.prismmodelchecker.org/games

Example - Stochastic games

- Two players: 1 (robot controller), 2 (environment)
  - probability of s_1–south→s_4 is in [p,q] = [0.5–Δ, 0.5+Δ]





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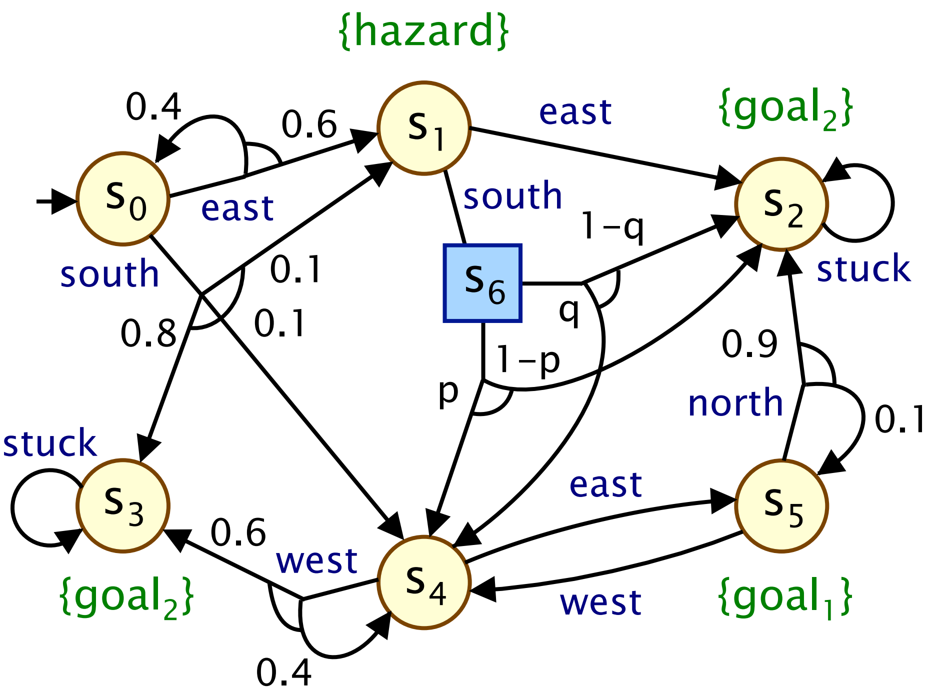
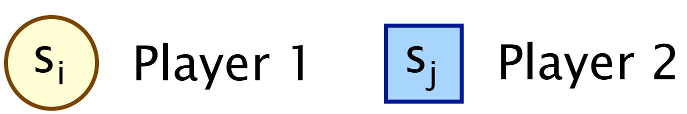


rPATL: $\langle\langle\{1\}\rangle\rangle\ P_{max=?}[\ F\ goal_1\ ]$

Optimal strategies:
memoryless and deterministic

Computation: graph analysis
& numerical approximation



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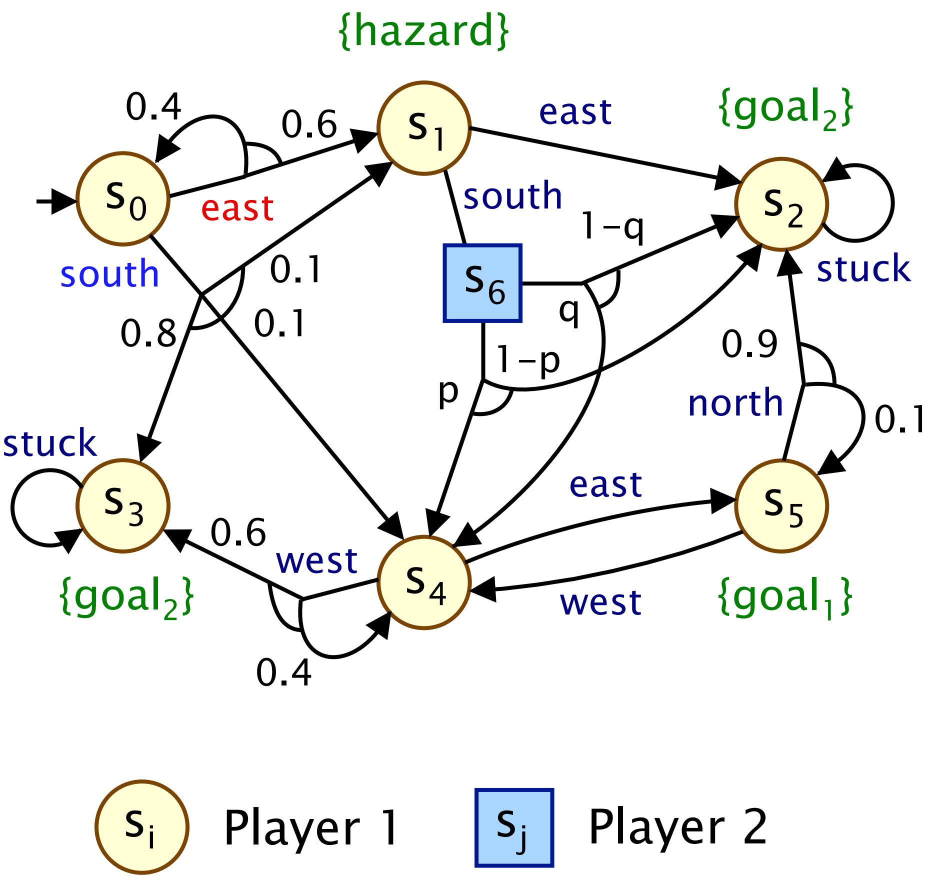

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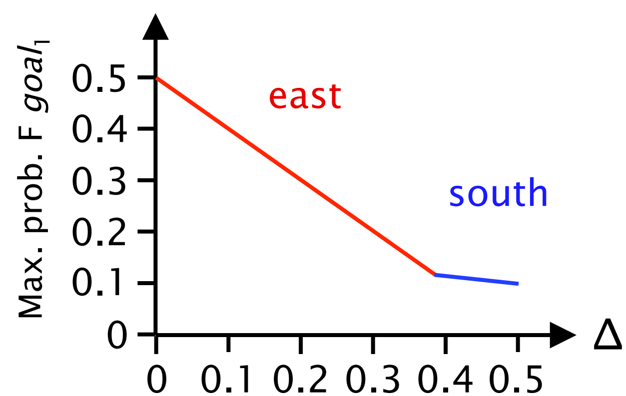
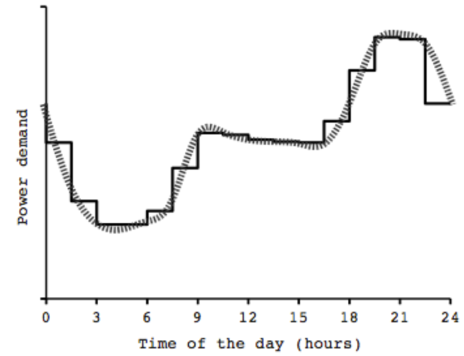
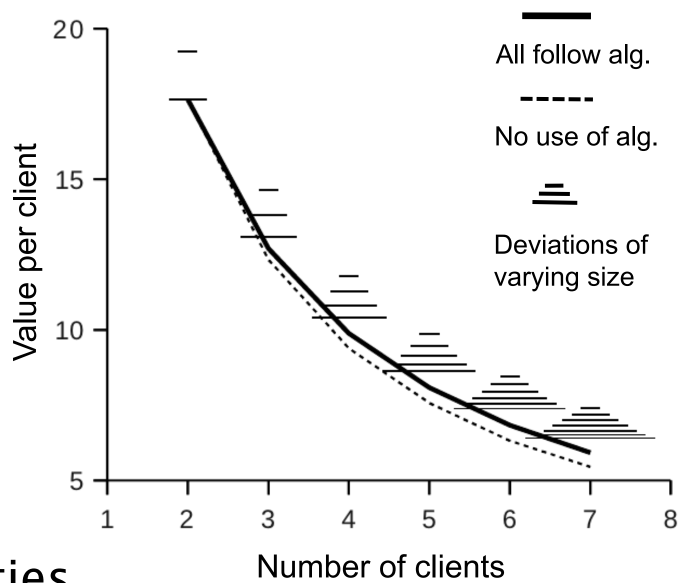


Application: Energy management

- Energy management protocol for Microgrid
  - randomised demand management protocol
  - random back-off when demand is high
- Original analysis [Hildmann/Saffre'11]
  - protocol increases "value" for clients
  - simulation-based, clients are honest
- Our analysis
  - stochastic multi-player game model
  - clients can cheat (and cooperate)
  - model checking: PRISM-games
  - exposes protocol weakness (incentive for clients to act selfishly
  - propose/verify simple fix using penalties





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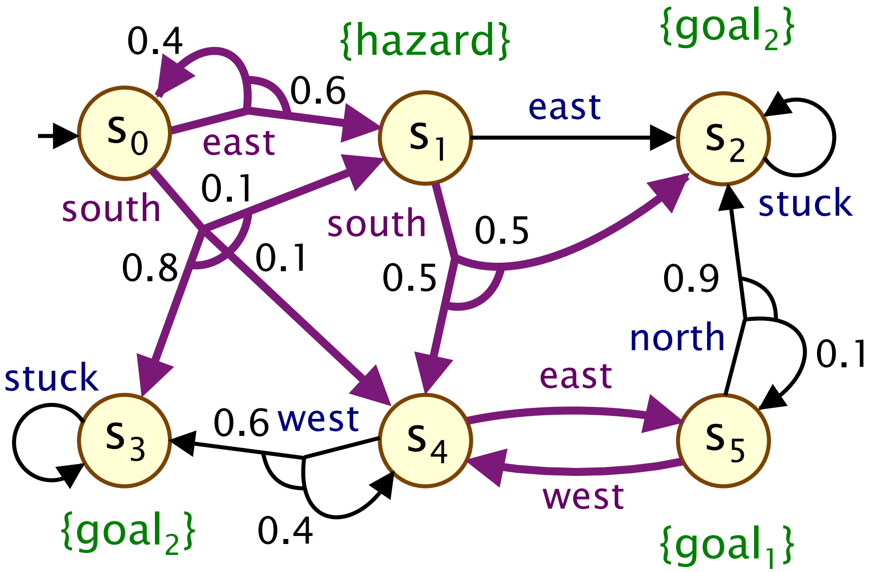
Permissive controller synthesis

- Multi-strategy synthesis [TACAS'14]
  - for Markov decision processes and stochastic games
  - choose sets of actions to take in each state
  - controller is free to choose any action at runtime
  - flexible/robust (e.g. actions become unavailable or goals change)

- Example



Multi-strategy:

s_0 : east or south

s_1 : south

s_2 : –

s_3 : –

s_4 : east

s_5 : west

Permissive controller synthesis

- Multi-strategies and temporal logic
  - multi-strategy Θ satisfies a property $P_{>p}$ [F goal] iff any strategy σ that adheres to Θ satisfies $P_{>p}$ [F goal]
- We quantify the permissivity of multi-strategies
  - by assigning penalties to each action in each state
  - a multi-strategy is penalised for every action it blocks
  - static and dynamic (expected) penalty schemes
- Permissive controller synthesis
  - ∃ a multi-strategy satisfying $P_{\leq 0.6}$ [F $goal_1$] with penalty < c?
  - what is the multi-strategy with optimum permissivity?
  - reduction to mixed-integer LP problems
  - applications: energy management, cloud scheduling, …

Conclusion

- Probabilistic model checking
  - verification vs. controller synthesis
  - Markov decision processes, temporal logic, PRISM
- Recent directions and extensions
  - multi-objective probabilistic model checking
  - model checking for stochastic games
  - permissive controller synthesis
- Challenges
  - stochastic games: multi-objective, equilibria, richer logics
  - partial information/observability
  - probabilistic models with continuous time (or space)
  - scalability, e.g. symbolic methods, abstraction

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