Probabilistic Model Checking for Safety and Performance Guarantees

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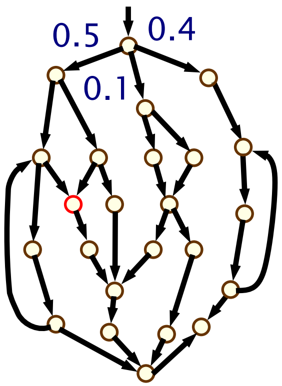
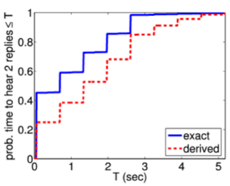
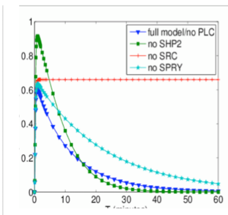
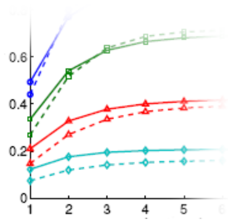
Probabilistic model checking

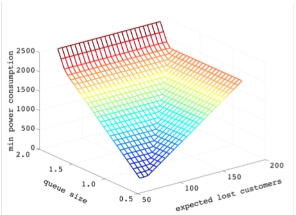
- Probabilistic model checking
  - formal construction/analysis of probabilistic models
  - "correctness" properties expressed in temporal logic
  - e.g. trigger → $P_{\geq 0.999}$ [$F^{\leq 20}$ deploy]
  - mix of exhaustive & numerical/quantitative reasoning











- Typically focus on numerical/quantitative results
  - analyse trends, look for system flaws, anomalies

- Wide range of quantitative properties expressible
  - probabilities, timing, energy, costs, rewards, …
  - reason about safety, reliability, performance, timeliness, …

PRISM (and extensions)

- PRISM model checker: www.prismmodelchecker.org
- Wide range of probabilistic models

  discrete states & probabilities: Markov chains

  + nondeterminism: Markov decision processes (MDPs)

  + real-time clocks: probabilistic timed automata (PTAs)

  + partial observability: POMDPs and POPTAs

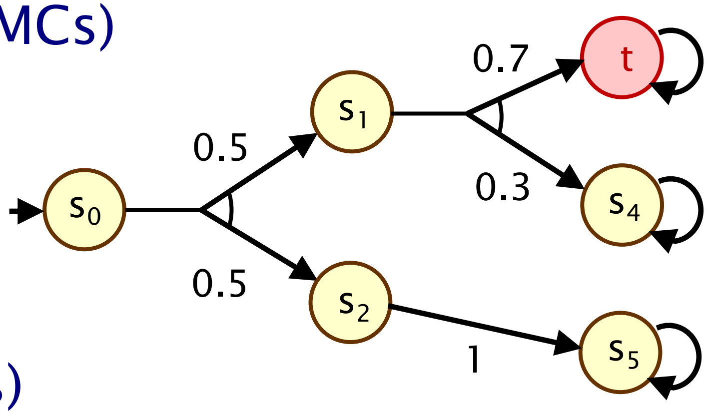
  + multiple players: (turn-based) stochastic games

  + concurrency: concurrent stochastic games

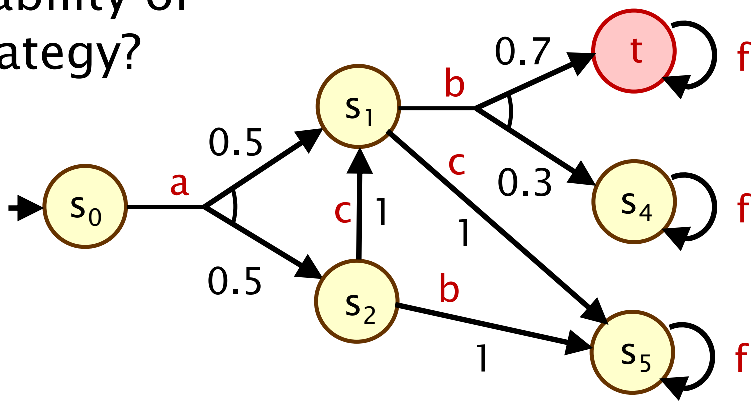
- Unified modelling language/approach
- Various verification engines: symbolic, explicit-state, exact, parametric, statistical model checking, abstraction, …
- Many application domains: network/comm. protocols, security, biology, robotics & planning, power management, scheduling, …

Probabilistic models

- Discrete-time Markov chains (DTMCs)
  - e.g. what is the probability of reaching state t?
  - e.g. $P_{<0.0001}$ [F t]

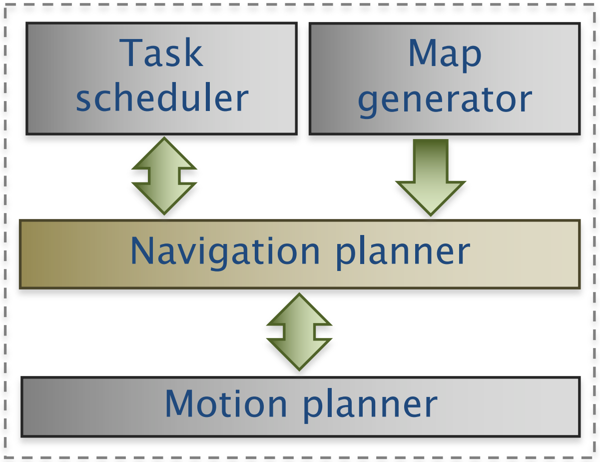


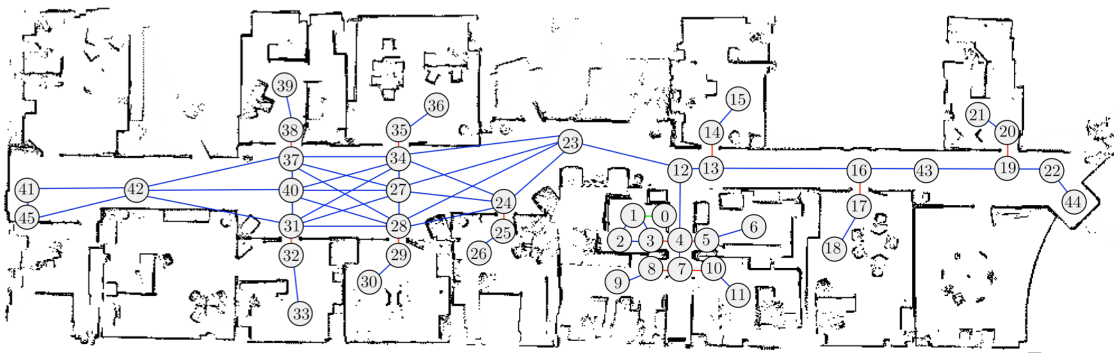
- Markov decision processes (MDPs)
  - mix nondeterministic and probabilistic choice
  - strategies (or policies) resolve actions based on history
  - e.g. what is the maximum probability of reaching t achievable by any strategy?
- Either:
  - adversarial view, i.e. verify against any possible strategy
  - or control view, i.e. synthesise a safe/optimal strategy



Application: Mobile robot navigation

- Robot navigation planning: [IROS'14,IJCAI'15,ICAPS'17,IJRR'19]
  - synthesis of plans for tasks with probabilistic guarantees
  - MDP models navigation through uncertain environment
  - stochastic time delays due to obstacles (typically human traffic)
  - MDP parameters/distributions learnt from logs of previous exploration





G4S Technology, Tewkesbury (STRANDS)

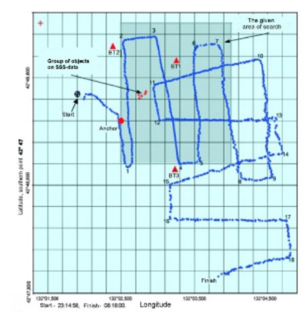
Application: Mobile robot navigation

- Formal task description using co-safe LTL
  - flexible, unambiguous specification
  - e.g. $\neg zone_3$ U ($zone_1 \wedge$ (F $zone_4$))] – “patrol zones 1 then 4, without passing through zone 3”
- Meaningful guarantees on performance
  - probability of successful task completion (within deadline)
  - optimal strategies for timely task completion
  - c.f. ad-hoc reward structures, e.g. with discounting
  - QoS guarantees fed into task planning
- Implementation and evaluation
  - finite-memory MDP strategies converted to navigation controllers
  - ROS module based on PRISM
  - 100s of hrs of autonomous deployment

Application: UUV mission plans

- PRINCESS: Developing verified adaptive software systems
  - for operation in dynamic and uncertain environments
  - focus: autonomous underwater vehicle navigation
  - DARPA-funded project, under the BRASS program

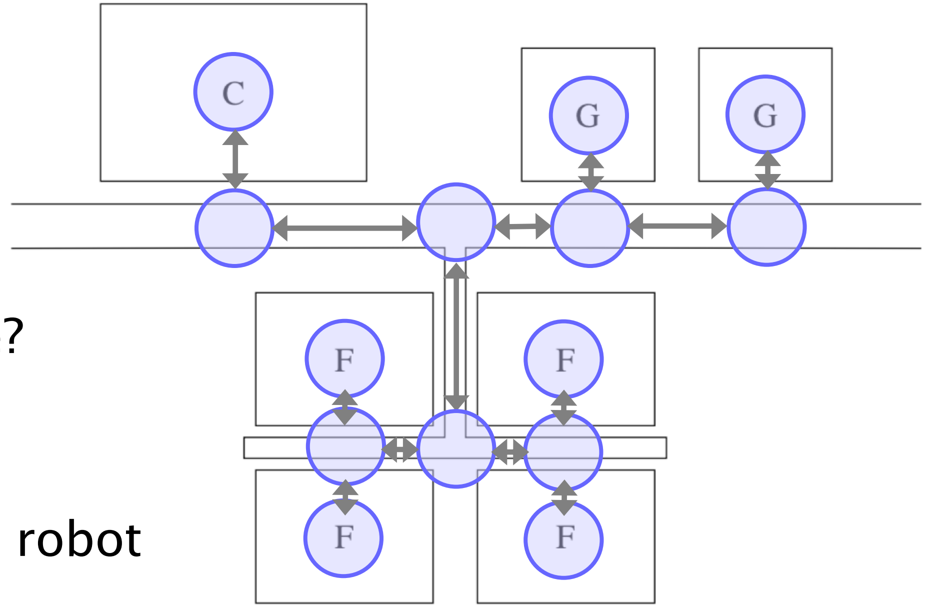
- Adaptations are verified at runtime
  - produce probabilistic guarantees of correctness/safety
  - mission (path) plans for ocean search operations



- Verification tasks
  - ensure low probability of mission failure
    - (vehicle loss due to excessive power consumption)
  - inputs: battery usage + failure models, ocean/tide models
    - Markov chain models constructed

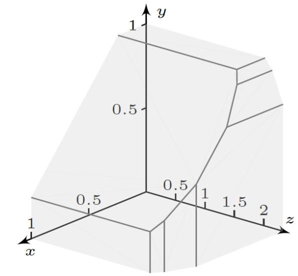
Application challenge: Smart farm

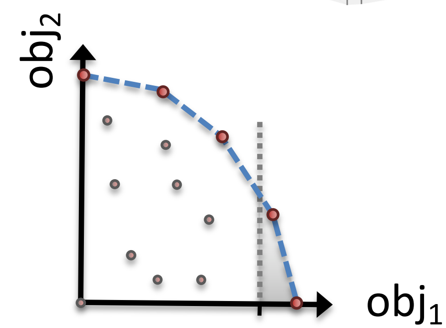
- What level of abstraction?
  - "farm-level": navigation grid (+ robot state: cargo, failures, …)
- Uncertainty/probability
  - stochastic travel delays due to humans/vehicles
  - failures of individual robots
- Verification/guarantees
  - robot task sequence completed within time T with probability p?
  - how does this vary as the underlying failures change?
  - can we synthesise a time-optimal plan?
  - how do we ensure a repair robot is always available?



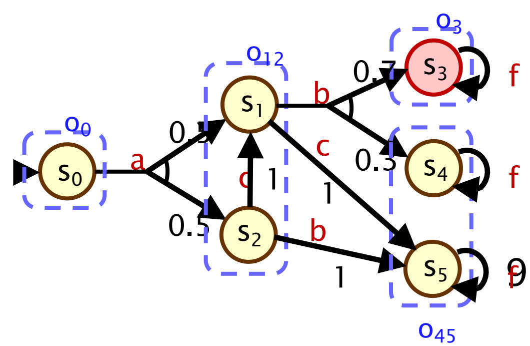
More probabilistic model checking…

- Multi-objective model checking [TACAS'11], [ICAPS'17]
  - investigate trade-offs between conflicting objectives
  - e.g., strategy to minimises expected task time, while ensuring probability of task success is > p
  - …and while ensuring location can always be reached within time T with probability q
  - multi-objective analysis via Pareto curves





- Partially observable MDPs (POMDPs) [RTS'17]
  - strategy sees only observations, not full state
  - strategy maintains belief state about the true state of the MDP
  - e.g. localisation error, sensor noise; uncertainty about state of robot 2
  - verification tool support in e.g. PRISM-pomdps



More probabilistic model checking…

- Stochastic game model checking
  - multiple agents/components with differing objectives
  - e.g., controller vs. environment; system vs. attacker
  - control + adversarial aspects combined
- PRISM-games model checker
  - probabilistic model checking of rPATL
  - "can robots 1,2 collaborate so that the probability of task completion within T is at least 0.95, whatever robots 3,4 do?"
  - turn-based and concurrent stochastic games [QEST'19]
  - Nash equilibria based properties [FM'19]

- Multi-robot systems [IROS'18]
  - combined task allocation and planning
  - performed on a sequential abstraction; probabilistic guarantees then computed on a product model fragment

Challenges

- Scalability
  - how to tackle state-space blow-up, especially for multi-robot
- Further models/properties
  - e.g. partial observability + stochastic games
- Uncertainty
  - how to represent/reason about model imprecision?
  - accuracy vs efficiency trade-offs
- Machine learning
  - how to reason about the integration of learning?