Probabilistic Model Checking with PRISM

Past, Present & Future

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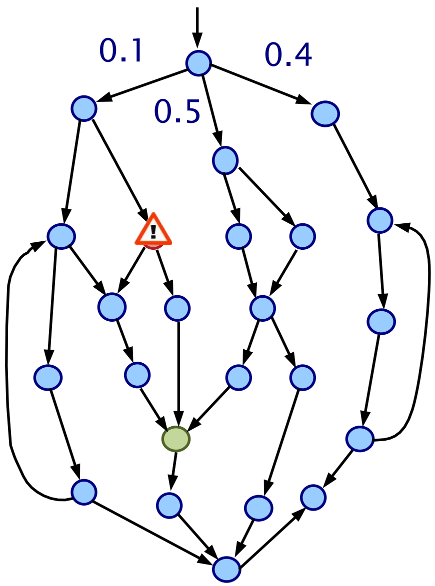
Outline

- Probabilistic model checking and PRISM
- Themes and trends
- Advances and applications
- Current research topics
- Challenges & future directions

Probabilistic model checking

- Construction and analysis of probabilistic models
  - probability: failures, uncertainty, noise, randomisation, …
  - time: delays, time-outs, failure rates, …
  - costs: energy, resources, …



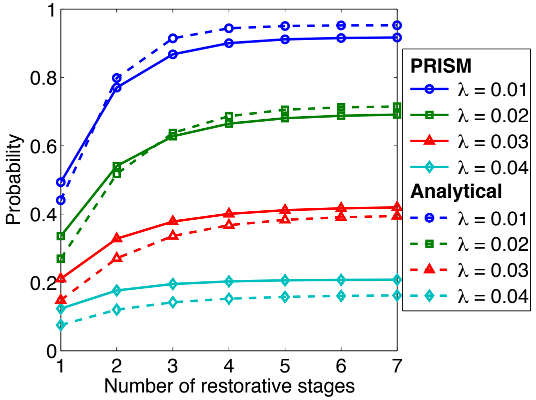
- Quantitative correctness properties expressed in temporal logic, e.g.:
  - *trigger* $\rightarrow P_{\geq 0.999} [\ F^{\leq 20}$ *deploy* $]$
  - "the probability of the airbag deploying within 20 milliseconds of being triggered is at least 0.999"
  - reliability, timeliness, performance, efficiency, …

PRISM

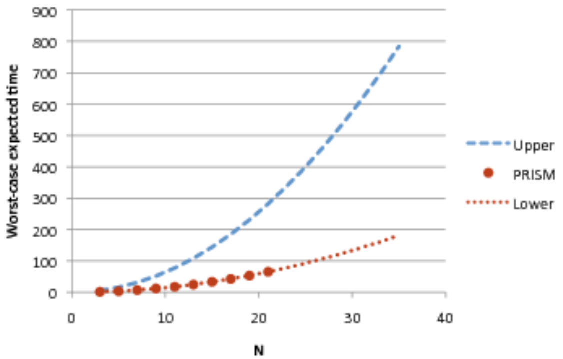
- A (brief) history
  - late 80s, early 90s: first underlying theory developed
  - 2001: first official public release of PRISM
  - 2011: version 4.0 - probabilistic real time systems
  - 2013: PRISM-games – stochastic multi-player games
- PRISM today
  - used in 100+ institutions; 50,000+ downloads
  - broadly applicable; many diverse use cases
  - many non-expert (and non-CS) users
  - 300 external papers (no involvement from PRISM team)
  - flaws found in real-systems; industrial usage

What can we do with PRISM?

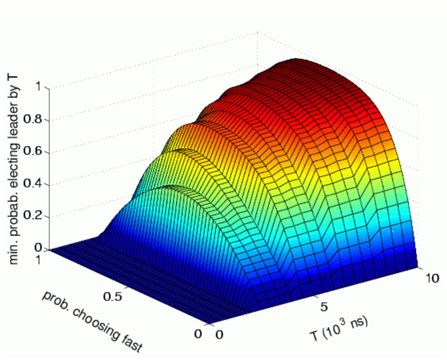
- Identify flaws in existing analyses
  - e.g. reliability of NAND multiplexing
- Investigate conjectures/models
  - e.g. Herman's self-stabilisation
  - e.g. FireWire root contention
  - e.g. cell signalling pathways (FGF)



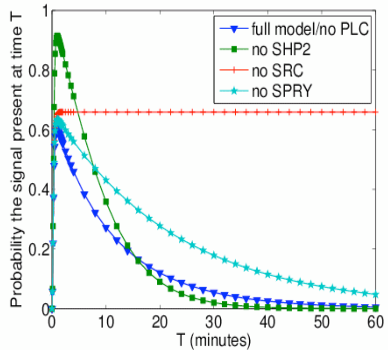
NAND



Herman



FireWire



FGF

Themes and trends

- Themes in the development of PRISM
  - theory-to-practice (and practice-to-theory)
  - wide collaboration (theory, algorithms, case studies)
  - open source software (and data)
  - overlaps/interacts with many other disciplines
- Trends
  - improvement in scalability to larger models
  - increasingly expressive/powerful classes of model
  - from verification problems to control problems
  - ever widening range of application domains

Trends

Models

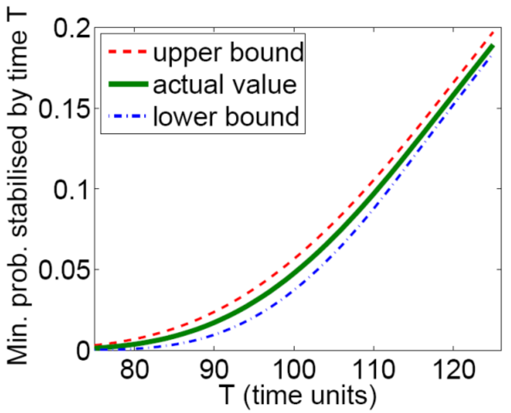
- discrete-time Markov chains
- probabilistic automata
- continuous-time Markov chains
- Markov decision processes
- probabilistic timed automata
- stochastic multi-player games
- …

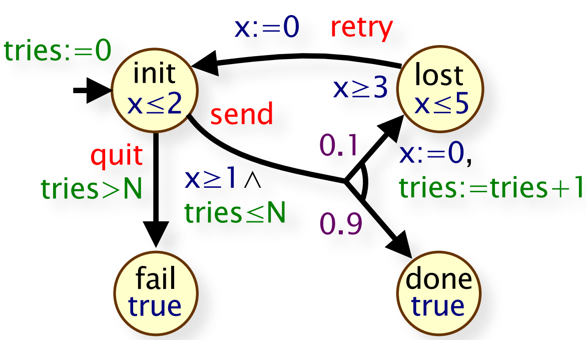
Application domains

- randomised distributed algorithms
- network/communication protocols
- computer security
- performance/reliability
- systems biology
- DNA computing
- robotics & autonomous vehicles
- wearable/implantable devices
- …

Enabling technologies

- Symbolic model checking
  - [TACAS'00] [TACAS'02] [STTT'04] [CAV'06] ...
- Real-time probabilistic verification
  - [TCS'02] [FMSD'06] [Info&Comp'07] [FORMATS'09] ...
- Quantitative abstraction refinement
  - [QEST'06] [VMCAI'09] [FMSD'10] [QEST'11] ...
- Compositional verification
  - [TACAS'10] [QEST'10] [FASE'11] [Info&Comp'13] ...
- And more...
  - statistical model checking, symmetry reduction, bisimulation minimisation, ...

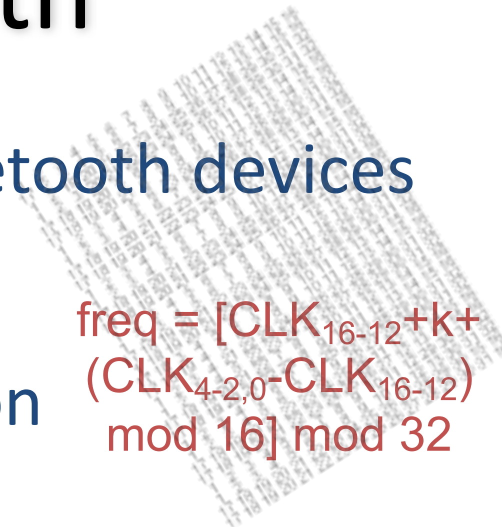




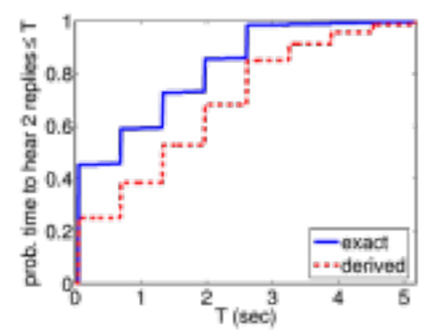
$$\frac{M_1 \models \langle A\rangle_{\geq q} \quad \langle A\rangle_{\geq q}\, M_2\, \langle G\rangle_{\geq p}}{M_1 \,||\, M_2 \models \langle G\rangle_{\geq p}}$$

Case study: Bluetooth

- Device discovery between a pair of Bluetooth devices
  - performance essential for this phase
- Detailed model from official specification
  - two asynchronous 28-bit clocks
  - pseudo-random hopping between 32 frequencies
  - random waiting scheme to avoid collisions
  - 32 Markov chains, over 3×10^{10} states each
  - 17,179,869,184 initial configurations



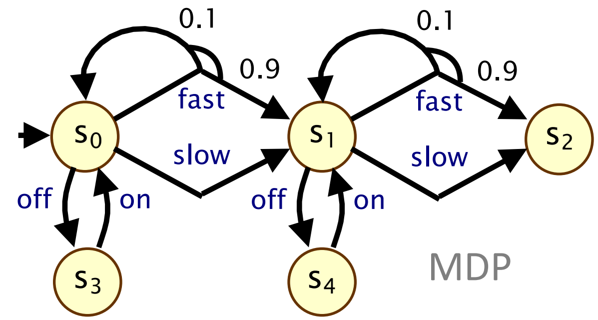
freq = $[CLK_{16-12}+k+(CLK_{4-2,0}-CLK_{16-12}) \bmod 16] \bmod 32$

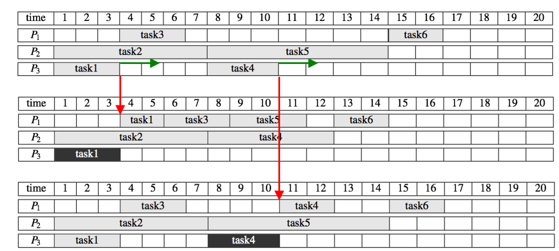


- Symbolic probabilistic model checking
  - "worst-case expected discovery time is at most 5.17s"

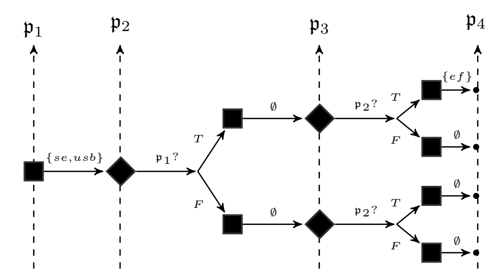
Strategy/controller synthesis

- Verification vs. control
  - verify that a system is “correct”, for any environment/adversary/… (counterexample yields flaw/attack/…)
  - synthesise a "correct-by-construction” controller from formal specification (witness yields strategy/controller)
- Applications
  - dynamic power management, robots/autonomous vehicle navigation , task/network scheduling, security, …





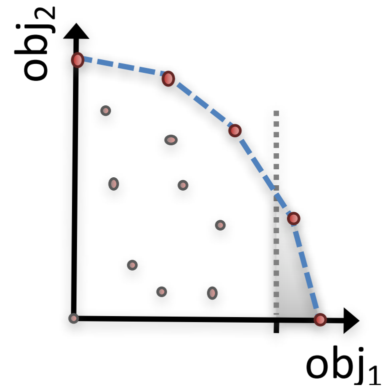
Task schedule [FMSD’13]



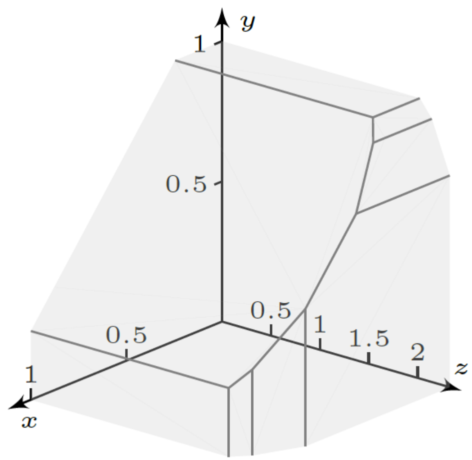
Attack-defence tree [CSF’16]

Multiple objectives

- Multi-objective controller synthesis [LMCS'08] [TACAS'11]
  - trade-offs between conflicting objectives



- Mix of optimisation and guarantees
  - e.g. "what strategy maximises probability of message transmission, whilst guaranteeing expected battery life-time is > 10 hrs?"
  - Pareto curve generation/approximation



- Extensions
  - permissive controller synthesis of multi-strategies for MDPs [LMCS'15]
  - multiple objectives for multi-player games (see later)

Robots & autonomous systems

- Navigation for mobile service robots
  - learnt probabilistic navigation maps
  - LTL task specifications + controller synthesis
  - ROS-based runtime planning implementation
  - multi-objective probabilistic guarantees on task completion/duration [IROS’14/IJCAI’15/CDC’16]

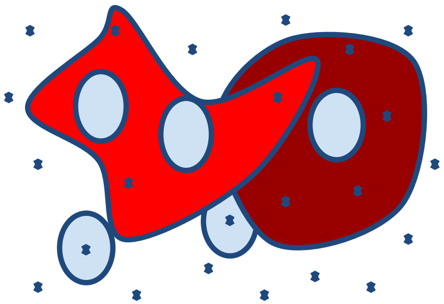
- Autonomous underwater vehicle navigation
  - incremental/parametric verification + controller synthesis
  - probabilistic programming + machine learning to generate realistic component/environment models at runtime

Parameter synthesis

- Synthesising models that are guaranteed to satisfy quantitative correctness properties is difficult
  - but we can synthesise controllers and parameters
- Parameter synthesis
  - given a parametric model and a property ϕ…
  - find the optimal parameter values, with respect to an objective function O, such that the property ϕ is satisfied, if such values exist
- Quantitative parameter synthesis
  - parameters: timing delays, rates
  - objectives: optimise probability, reward/volume

Quantitative parameter synthesis

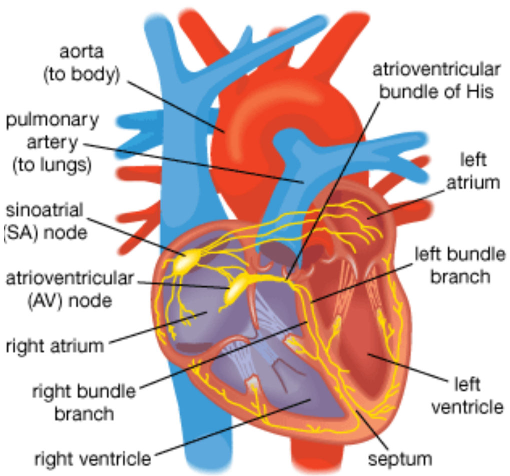
- Timed/hybrid automata
  - find optimal timing delays [EMSOFT2014] [HSB'15] [HSCC'16]
  - constraint solving, discretisation + sampling

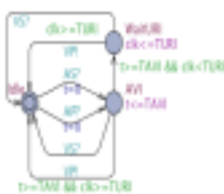


- Probabilistic timed automata
  - find delays to optimise probability [RP2014]
  - parametric symbolic abstraction-refinement
- Continuous-time Markov chains
  - find optimal rates [CMSB'14] [ActaInf'16], PRISM-PSY [TACAS'16]
  - constraint solving, uniformisation + sampling
- Focus: practical implementation, real-world usage

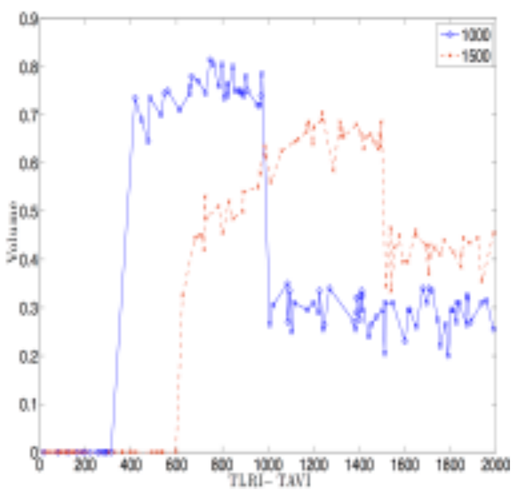
Applications

Pacemaker verification

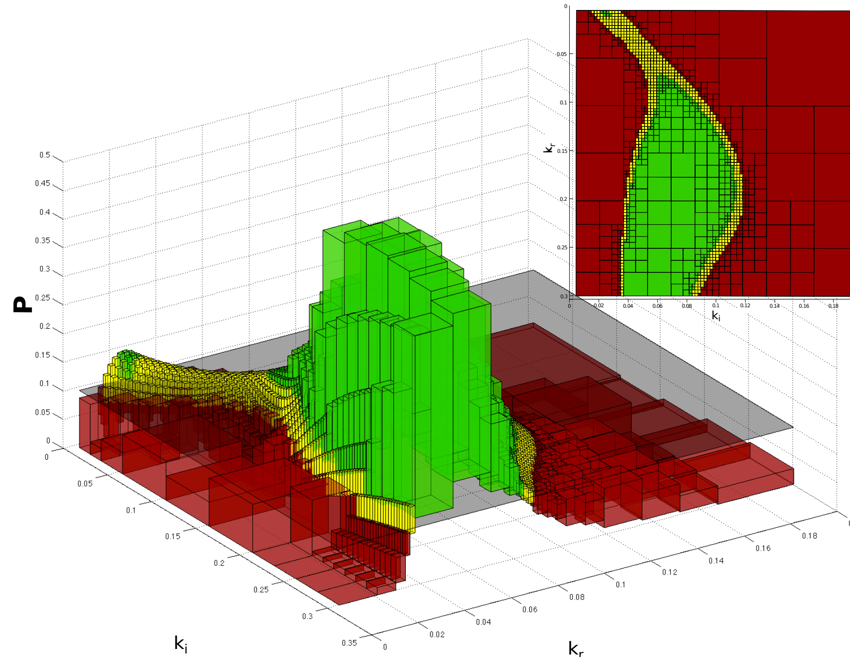




Maximal volume objective



Epidemic modelling



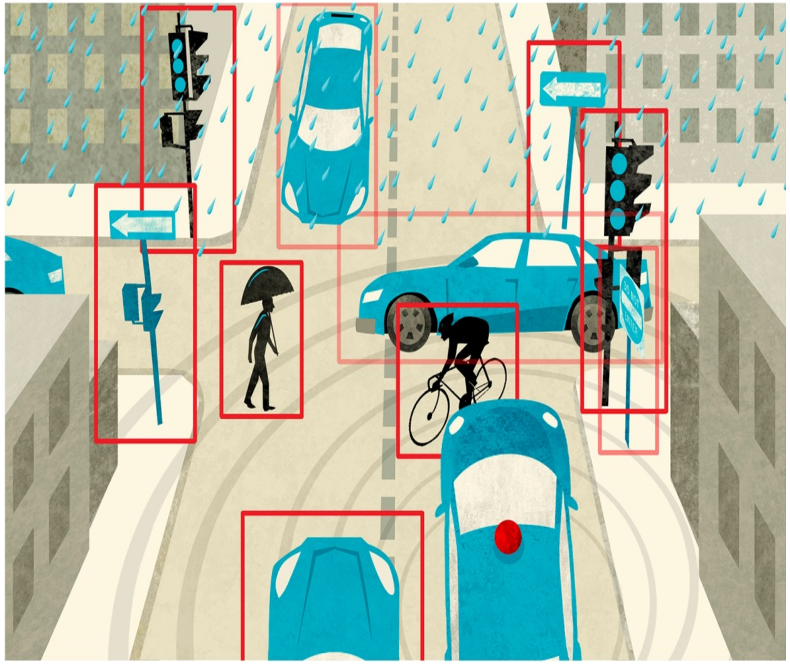
$$S + I \xrightarrow{k_i} I + I$$ Susceptible → Infected

$$I \xrightarrow{k_r} R$$ Infected → Recovered

ϕ: infection lasts at least 100 time units and ends within 120 time units

Mobile autonomy challenge

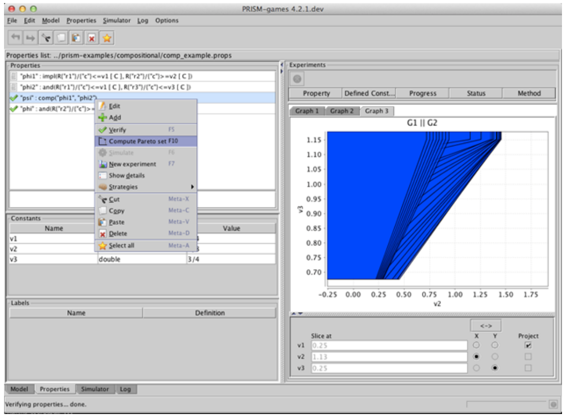
- Autonomous systems
  - interact with their environment, which is possibly adversarial
  - have goals/objectives, which may conflict
  - take decisions



- Model as stochastic games
  - well known from, e.g., decision making in economics
  - many application domains: security, energy grid, etc
- Tool PRISM-games, extension of PRISM [TACAS'16]

Stochastic multi-player games

- Probabilistic temporal logic with coalitions
  - probabilities, rewards (reachability, total, mean-payoffs/ratios, …) [FMSD’13] [ICALP’16] [ECC’16]

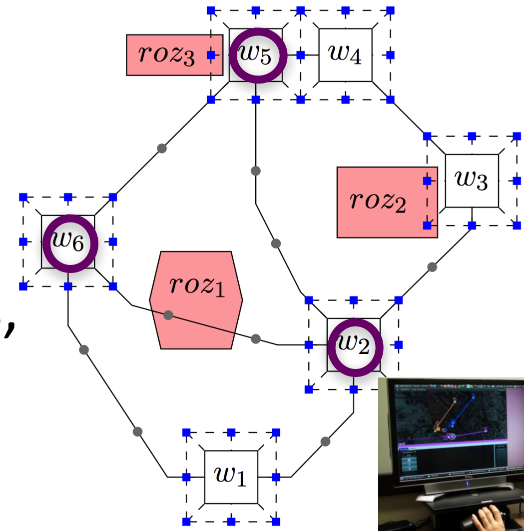


- Multi-objective strategy synthesis
  - Pareto set computation and optimal achievable trade-offs [MFCS’13] [QEST’13] [TACAS’15]

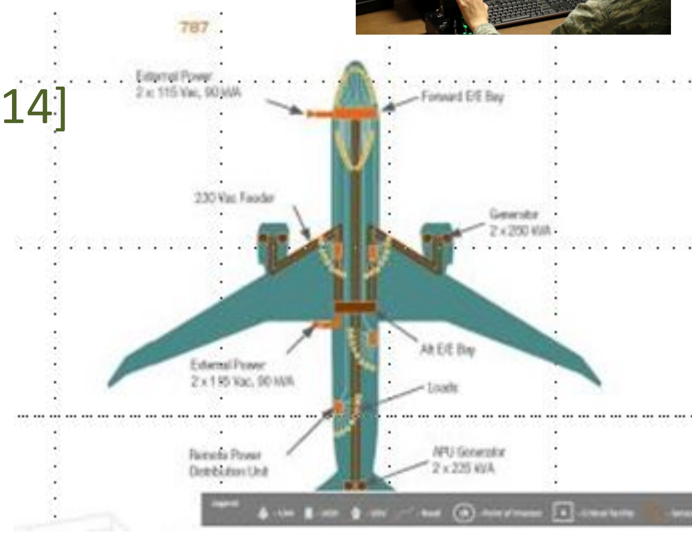
- Compositional strategy synthesis [CONCUR’14] [Inf & Comp’16]
  - assume-guarantee + multi-objective strategy synthesis
  - e.g. local strategies for $G_1 \models \phi_A$, $G_2 \models \phi_A \Rightarrow \phi_B$ compose to a global strategy for $G_1 || G_2 \models \phi_B$

Applications

- UAV path planning [ICCPS'15]
  - human operator + low-level piloting
  - quantitative mission objectives: minimise time/fuel, restricted zones, operator fatigue/workload
  - multi-objective MDPs, stoch. games

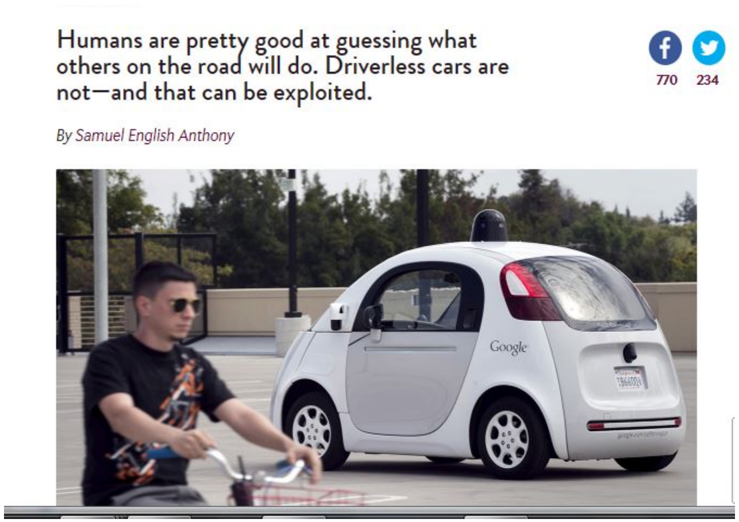


- Aircraft power distribution [CONCUR'14]
  - compositional strategy synthesis in stochastic games (PRISM-games)
  - specify control objectives in LTL using mean payoff



Are games sufficient?

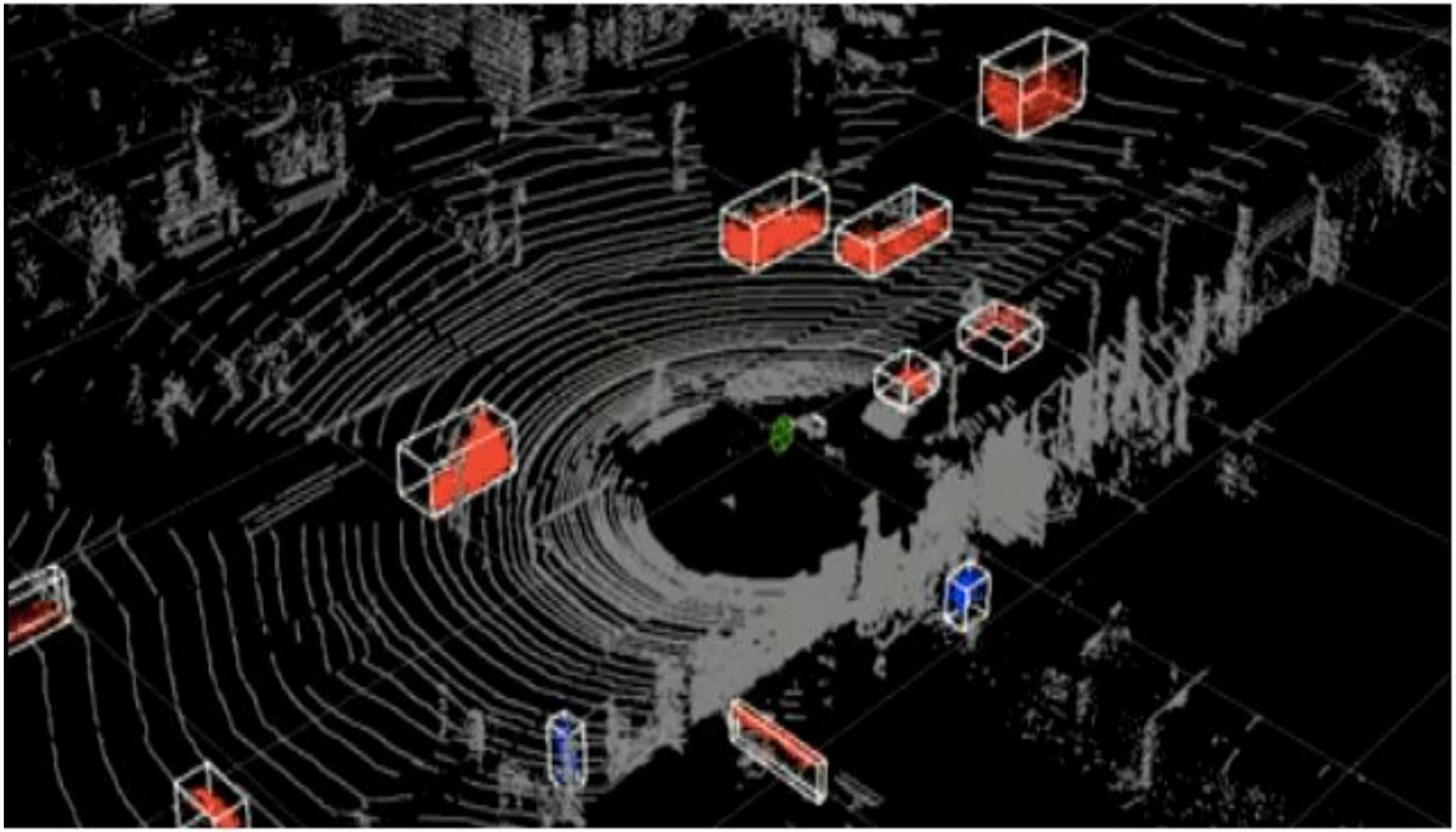
- Complex decisions!
  - goals
  - perception
  - situation awareness
  - context (social, regulatory)
- What about social subtleties?
- What to do in emergency?
  - moral decisions, handover to driver, obey traffic rules
- Need to make robots human-like…
  - need multi-modal communication, cognitive reasoning, trust, ethics, …



Quantitative verification for trust?

- Social trust: fundamental for mobile autonomy [LK16b]
  - influenced by external factors, such as social norms
  - also internal: personality, motivation, preferences
  - subjective: would you trust an autonomous taxi to take your child to school?
- Formulate a temporal logic to express X's trust in Y for G, based on probabilistic belief [HK17]
- Admits a model checking procedure, which can:
  - be used in decision-making for robots
  - explain decisions, i.e. who is accountable for the action

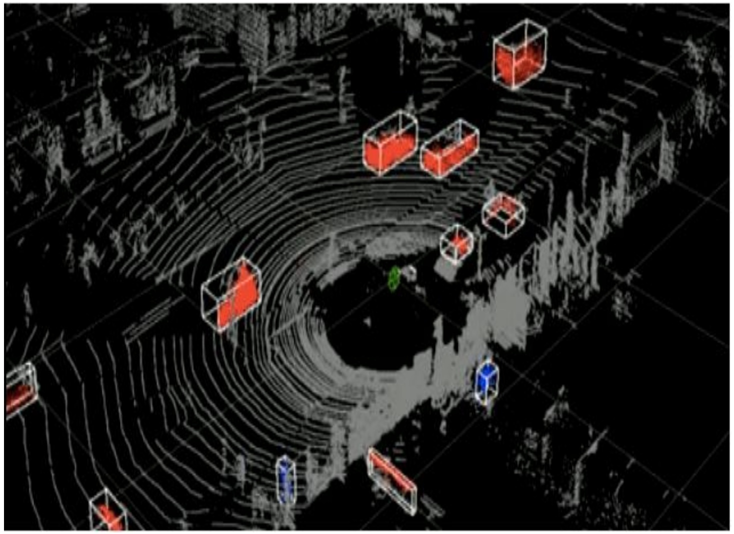
Perception software



Credits: Oxford Robotics Institute

Things that can go wrong…

- …in perception software
  - sensor failure
  - object detection failure



- Machine learning software
  - not clear how it works
  - does not offer guarantees

- Verification for machine learning?
  - some progress towards safety verification for neural networks

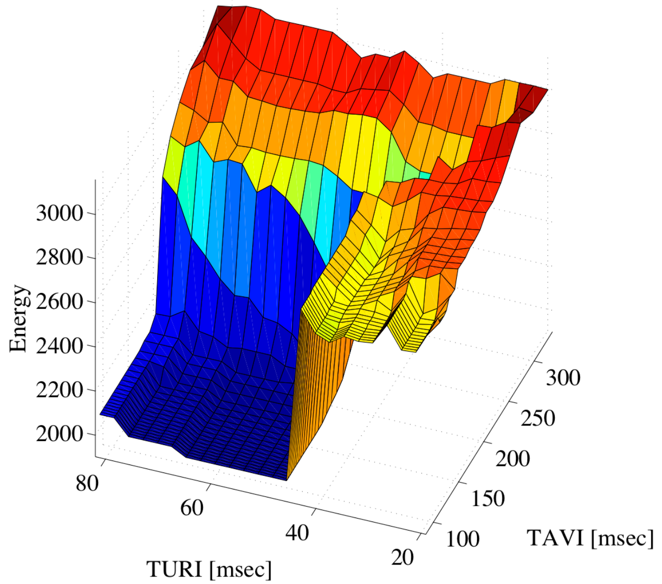
Personalisation challenge

- Device must adapt to physiology of human wearer
  - achieved through model parameterisation
  - parameter estimation, optimal parameter synthesis
- Multiple uses
  - automation of personalised medical intervention
  - device safety assurance, for testing
  - reproduce the unique characteristics for authentication
- Focus on ECG based devices
  - pacemaker models, heart models, synthetic ECGs
  - future work on anxiety monitoring and control

Pacemaker verification/optimisation

- Hybrid model-based framework
  - timed automata model for pacemaker
  - hybrid heart models in Simulink (non-linear ODEs)

- Properties
  - (basic safety) maintain 60-100 beats per minute
  - optimisation of energy usage & cardiac output [HSB'16] [HSCC'16]
  - in-silico analysis of rate-adaptive pacemakers [ICHI'14]
  - hardware in the loop [EMBC'15]

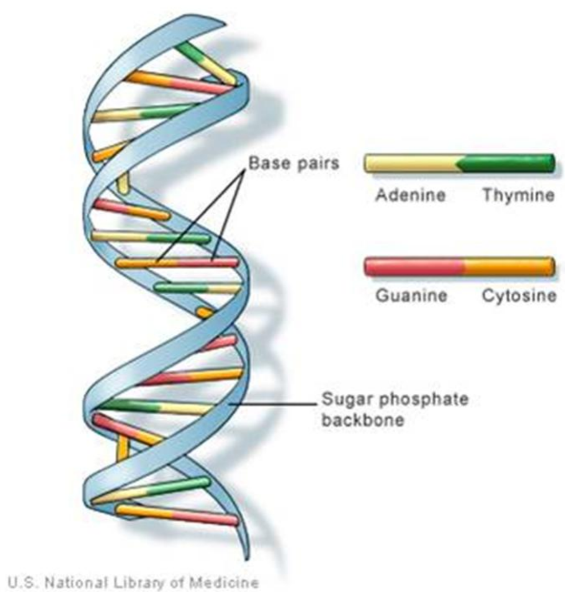


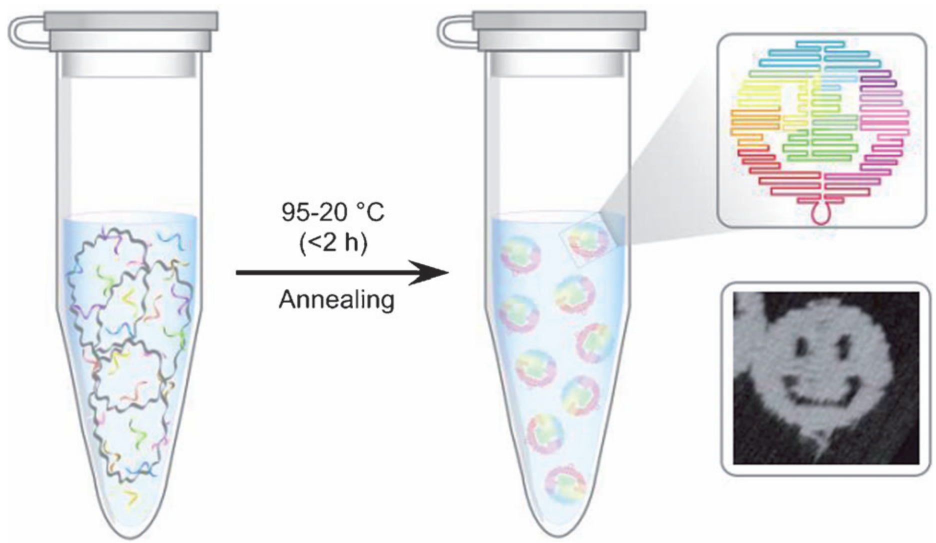
DNA computation challenge

- Moore's law, hence need to make devices smaller…
- DNA computation, directly at the molecular level
  - DNA logic circuit designs & programmable nanorobotics
  - asynchronous DNA circuit designs [DNA'16]
- Many applications envisaged
  - e.g. bio-sensing, point of care diagnostics, …
- Apply quantitative verification and synthesis to
  - find design flaws in DNA computing devices [JRSI'12]
  - analyse reliability and performance of molecular walkers
  - automatically synthesise reaction rates to guarantee a specified level of reliability

DNA nanostructures

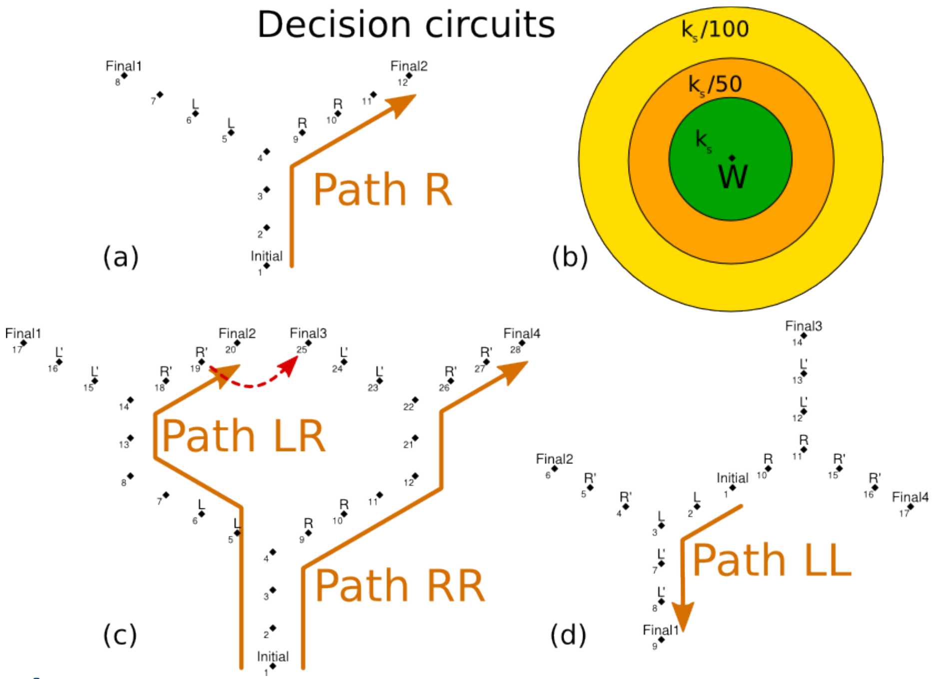
- DNA origami [Rothemund, *Nature* 2006]
  – DNA can self-assemble into structures – “molecular IKEA?”
  – programmable self-assembly (can form tiles, nanotubes, boxes that can open, etc.)



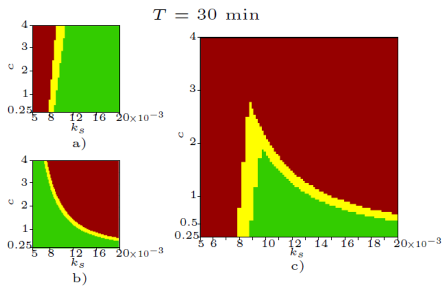


DNA walker circuits

- Computing with DNA walkers [NatComp'14]
  - branching tracks laid out on DNA origami tile
  - starts at 'initial', signals when reaches 'final'
  - can control 'left'/'right' decision
  - any Boolean function

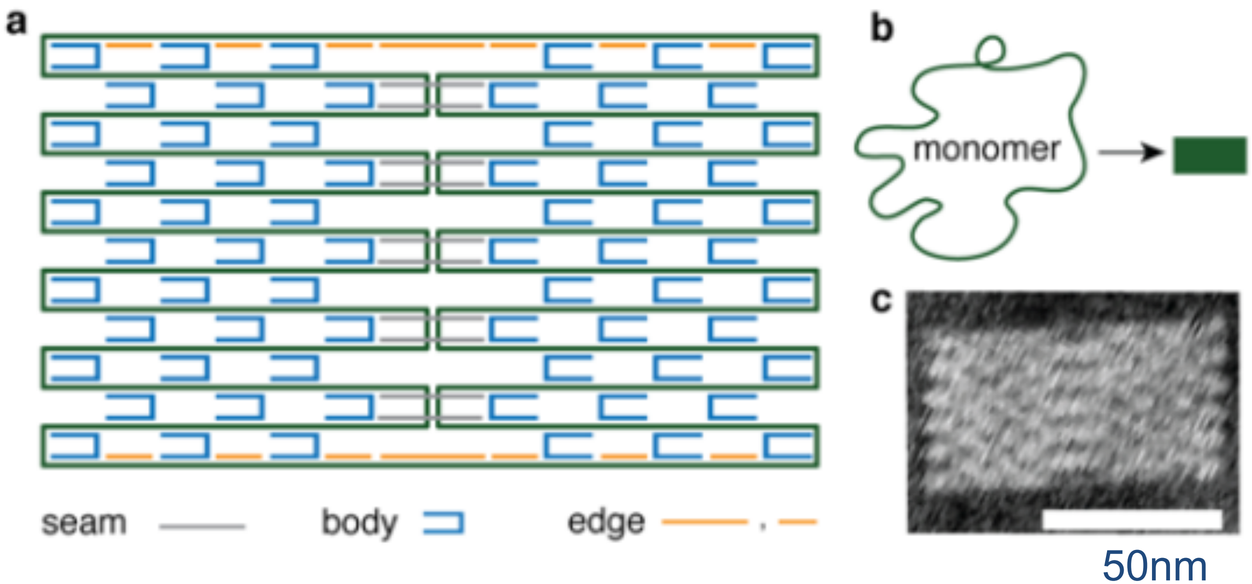


- Parameter synthesis of rates
  - for guaranteed reliability level [CMSB'14]



DNA origami tiles

- DNA origami tiles



- Aim: understand how to control the folding pathway
  - formulate an abstract Markov chain model
  - yields predictions; perform a range of experiments, consistent with predictions [Nature'15]

Conclusions

- Probabilistic model checking & PRISM
  - 15 years since first official tool release
  - significant advances in underlying theory & technologies
  - successfully deployed in many application domains

- Many research challenges and applications ahead
  - verification, synthesis, learning, trust, cognitive models, …
  - autonomous systems, DNA computing, personalised wearable/implantable devices, …

http://www.prismmodelchecker.org/

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