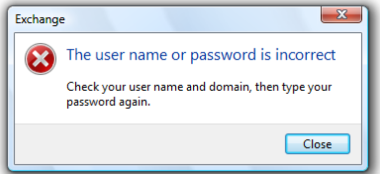
Controlling information in probabilistic systems
The case of fault diagnosis

PhD defence of Engel Lefaucheux

Supervisors: Nathalie Bertrand and Serge Haddad

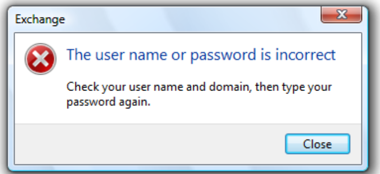
Septembre 24th 2018 – IRISA/LSV/Inria Rennes

Systems give information



Information disclosure

Systems give information



- Disclose useful information to the user

Information disclosure

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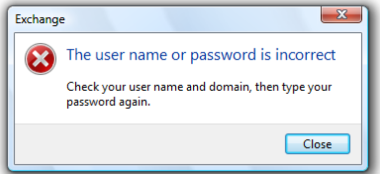

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- Disclose secret information to an attacker

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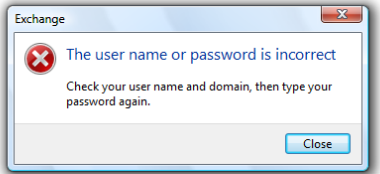

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Analysing and controlling the revealed information is crucial

Fault diagnosis

Detecting faulty behaviours

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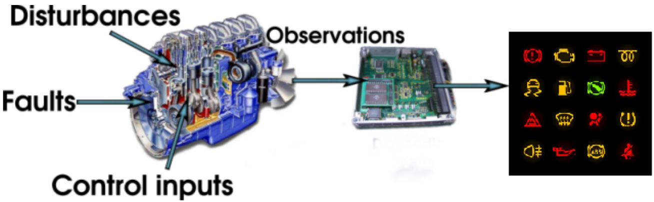

Fault diagnosis

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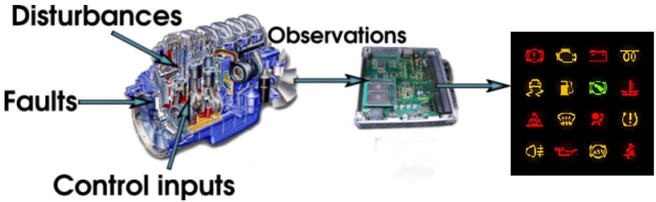

Diagnoser: must emit a verdict when faults occur, based on observations

Features of a diagnoser

Verdict: information provided

Correctness: accuracy of the verdict

Reactivity: delay before a verdict is given

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Diagnosability: does there exist a diagnoser?

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Diagnosability: does there exist a diagnoser?
Synthesis: how to build a diagnoser?

Why diagnosis?

Faults and/or failures are unavoidable for some systems

- Components have a finite lifetime
- Reactive systems suffer from unpredictable behaviours of the environment

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Faults and/or failures are unavoidable for some systems

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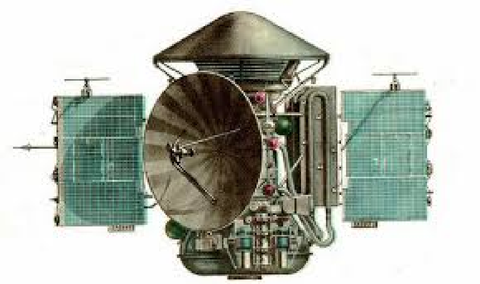
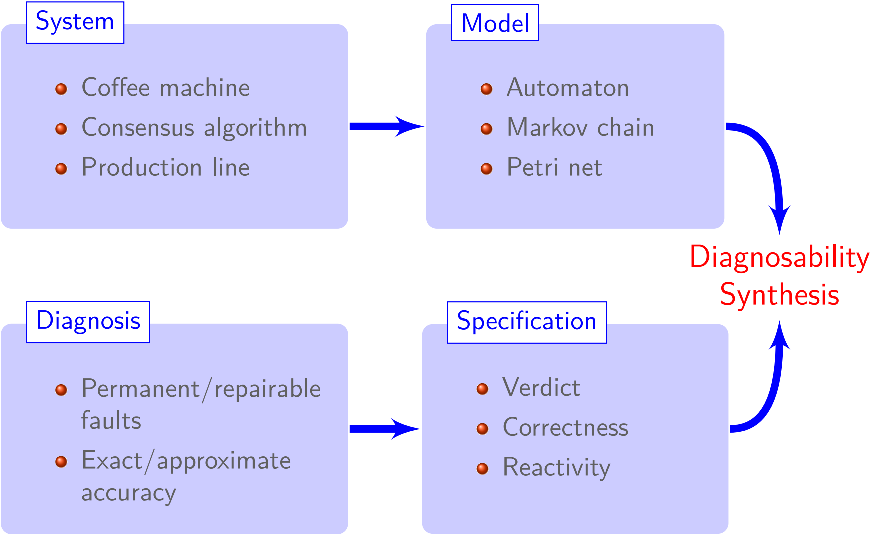
Consequences of unhandled faults may be critical

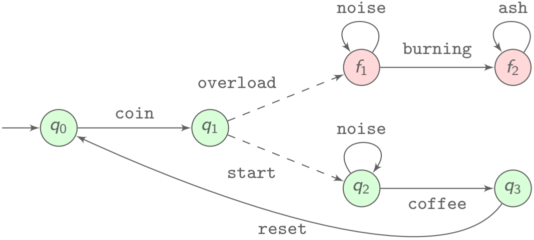
- Financial losses
- Human casualties



The model-based approach



A model for the coffee machine



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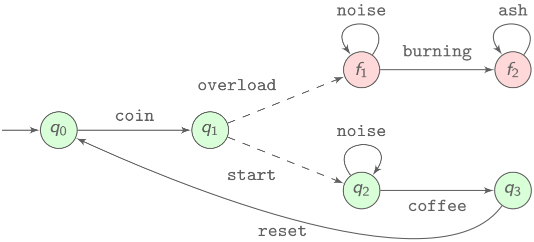
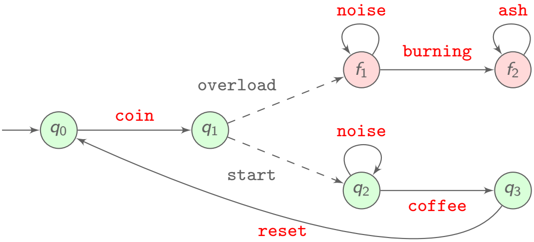


Partial observation

A model for the coffee machine

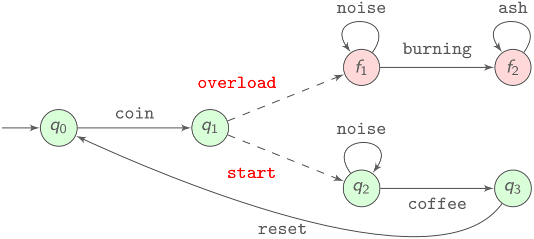


Partial observation

Observable events

$\rightarrow$

A model for the coffee machine

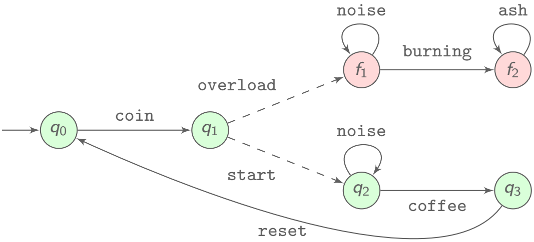


Partial observation

Observable events/unobservable events

$\longrightarrow$ / $\dashrightarrow$

A model for the coffee machine



Partial observation

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Run: $q_0 \xrightarrow{\texttt{coin}} q_1 \overset{\texttt{start}}{\dashrightarrow} q_2 \xrightarrow{\texttt{noise}} q_2$ | *Observation:* `coin noise`

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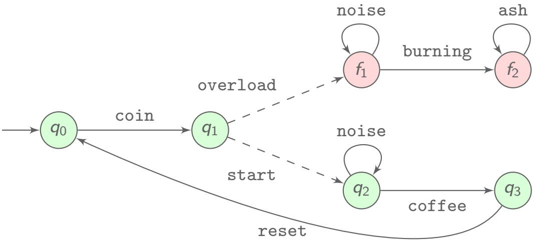

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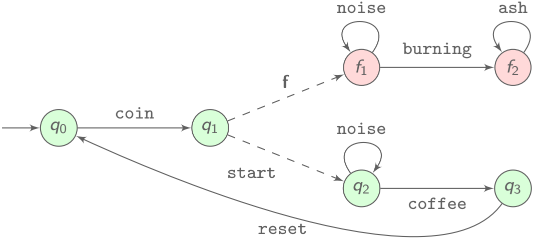

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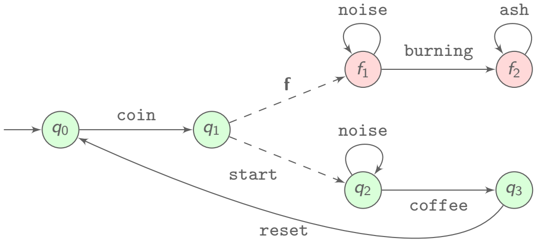
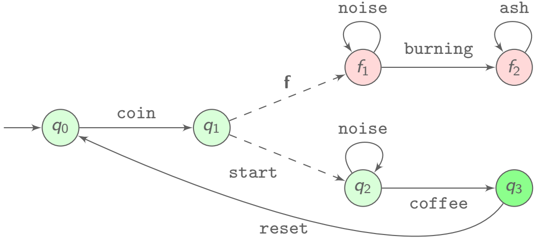
Classifying observations



Observation $\longrightarrow$ Set of potential states of the system

Classifying observations



Observation $\longrightarrow$ Set of potential states of the system

✓ `coin coffee` *surely correct*

$$\mathtt{Obs}^{-1}(\mathtt{coin\ coffee}) = \{q_0 \xrightarrow{\mathtt{coin}} q_1 \xrightarrow{\mathtt{start}} q_2 \xrightarrow{\mathtt{coffee}} q_3\}$$

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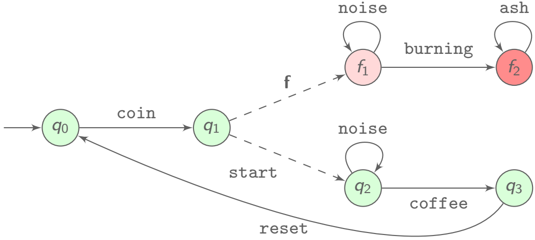
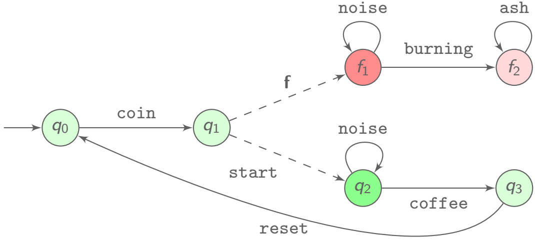


Observation $\longrightarrow$ Set of potential states of the system

✓	`coin coffee`	*surely correct*
✗	`coin burning`	*surely faulty*

$$\mathtt{Obs}^{-1}(\mathtt{coin\ burning}) = \{q_0 \xrightarrow{\mathtt{coin}} q_1 \xrightarrow{\mathbf{f}} f_1 \xrightarrow{\mathtt{burning}} f_2\}$$

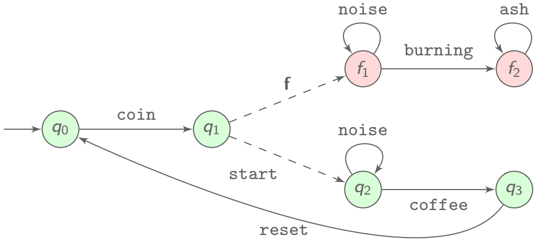


Observation $\longrightarrow$ Set of potential states of the system

✓	`coin coffee`	*surely correct*
✗	`coin burning`	*surely faulty*
?	`coin noise`	*ambiguous*

$$\mathtt{Obs}^{-1}(\mathtt{coin\ noise}) = \{q_0 \xrightarrow{\mathtt{coin}} q_1 \xrightarrow{\mathtt{start}} q_2 \xrightarrow{\mathtt{noise}} q_2, q_0 \xrightarrow{\mathtt{coin}} q_1 \xrightarrow{\mathbf{f}} f_1 \xrightarrow{\mathtt{noise}} f_1\}$$

Diagnosers for logical systems [SSLST95]



- Verdict: detection of faults
- Correctness: if a fault is claimed, a fault occurred
- Reactivity: every fault will be detected after a bounded delay

[SSLST96] Sampath, Sengupta, Lafortune, Sinnamohideen and Teneketzis, *Failure diagnosis using discrete-event models*, IEEE TCST, 1996.

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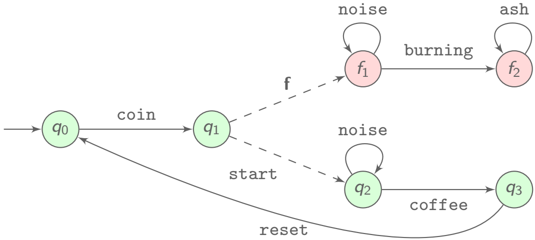

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Correct but not reactive diagnoser: claiming a fault when `burning` occurs

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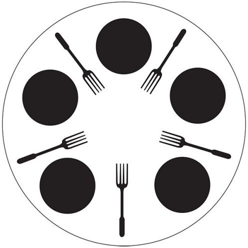
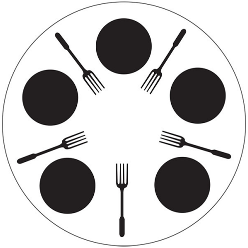
Useful to model some systems



Internal random behaviour

The call for probabilistic models

Useful to model some systems



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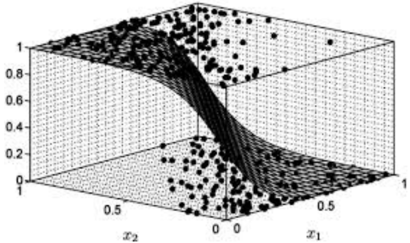

Models through statistical analysis

The call for probabilistic models

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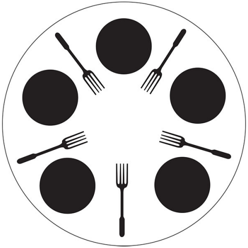

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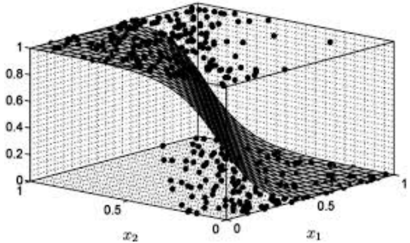

Models through statistical analysis

Enable quantitative requirements

The call for probabilistic models

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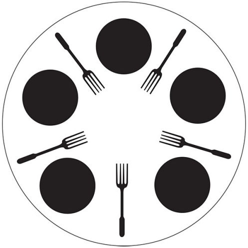

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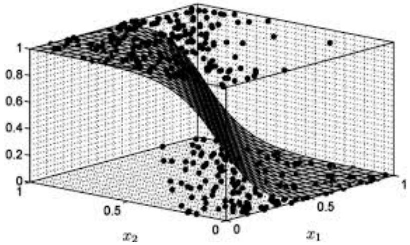
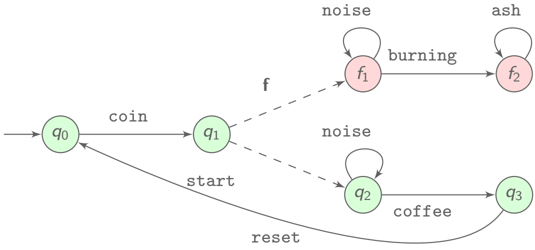


Models through statistical analysis

Enable quantitative requirements

- Is the system diagnosable, ignoring negligible behaviours?
- What is the measure of undetected faults?
- What is the average delay of fault detection?

A probabilistic model for the coffee machine



Probability of a run

Run $\rho = q_0 \xrightarrow{\texttt{coin}} q_1 \overset{\texttt{start}}{\dashrightarrow} q_2 \xrightarrow{\texttt{noise}} q_2$

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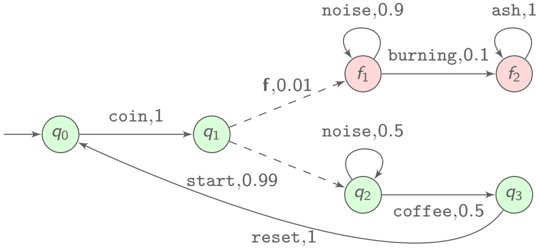

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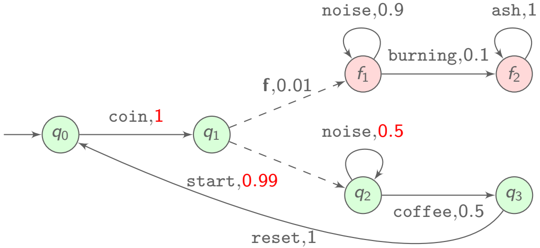

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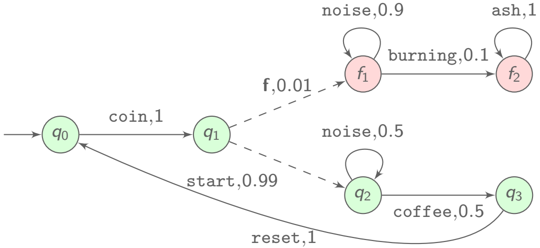

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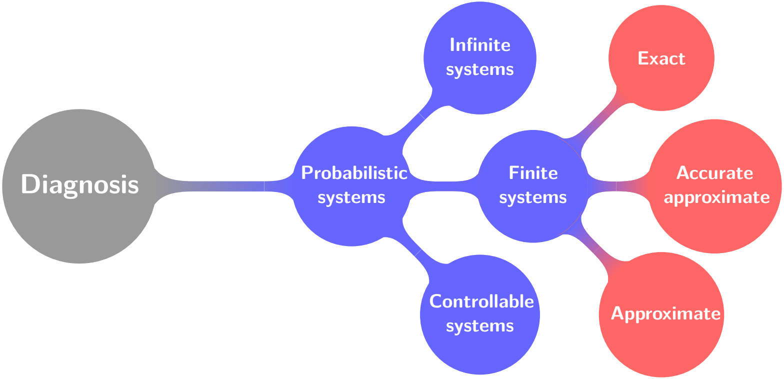
$\rightarrow$ Defines a probability measure on the set of infinite runs

Contributions on the diagnosis of probabilistic systems



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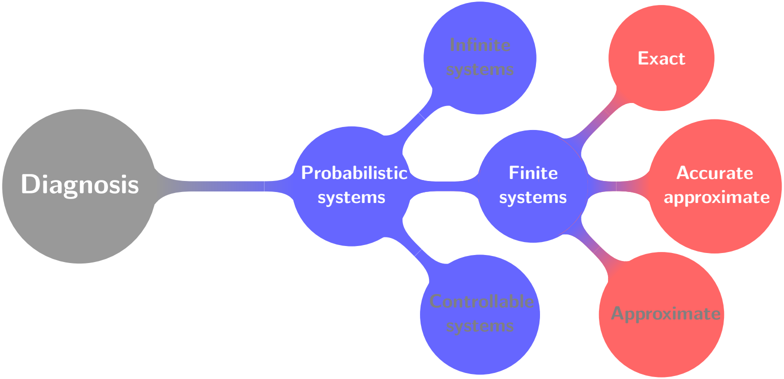


Challenges

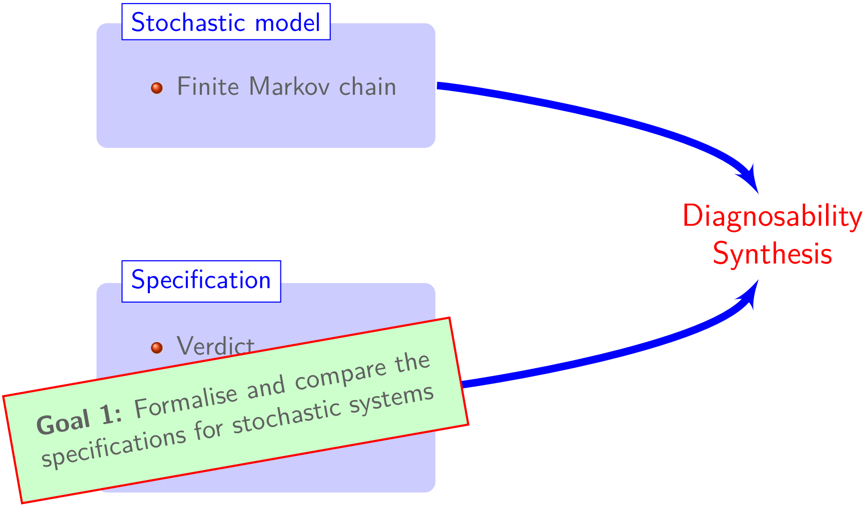
Stochastic model

- Finite Markov chain

Specification

- Verdict
- Correctness
- Reactivity

Diagnosability
Synthesis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Goal 1: Formalise and compare the specifications for stochastic systems

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Goal 2: Decidability and complexity of diagnosability and synthesis

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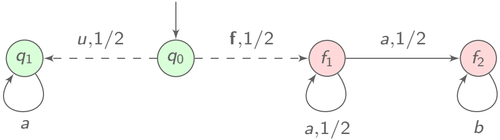
Goal 1: Formalise and compare the specifications for stochastic systems

Goal 2: Decidability and complexity of diagnosability and synthesis

Many possible specifications

Verdict: information provided



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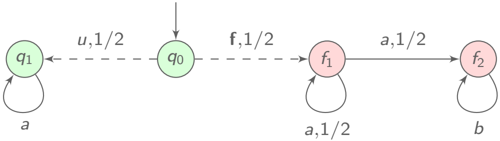

a^n is ambiguous

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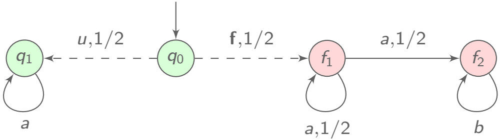

a^n is ambiguous

Faults are detected almost surely:

$$\lim_{n\to\infty} \mathbb{P}(\{q_0 \xrightarrow{\mathbf{f}} f_1(\xrightarrow{a} f_1)^n, q_0 \xrightarrow{\mathbf{f}} (f_1 \xrightarrow{a})^n f_2\}) = 0$$

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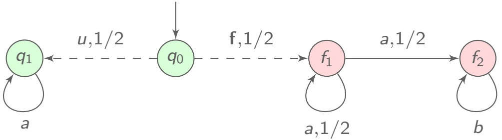

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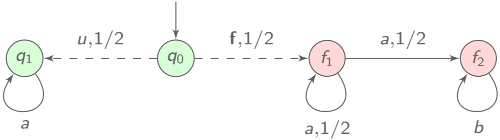

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Faulty runs or all ambiguous runs?

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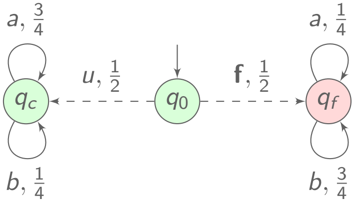

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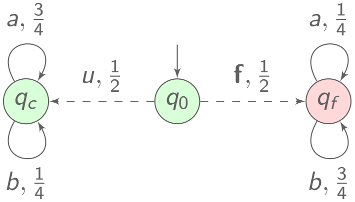

Not exactly diagnosable

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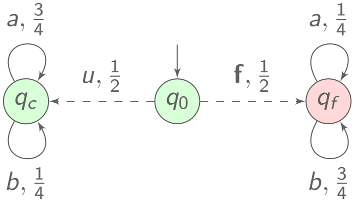

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However a high proportion of b implies a highly probable faulty run

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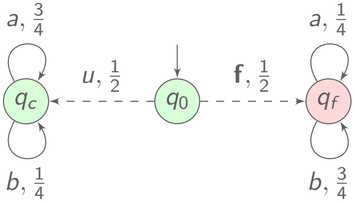

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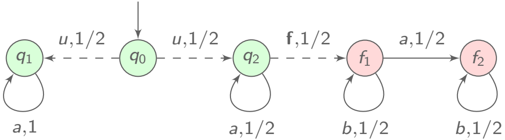

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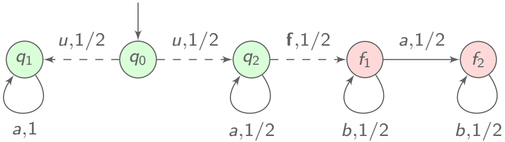

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a^n is likely to be observed $\mathbb{P}(a^n) = \frac{1}{2} + \frac{1}{2^n} + \frac{1}{2^{n-1}}$

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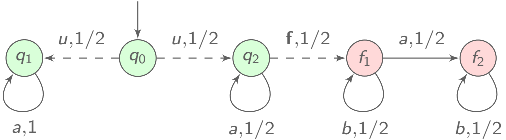

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However, a^ω is surely correct: $q_0 \xrightarrow{u} q_1(\xrightarrow{a} q_1)^\omega, q_0 \xrightarrow{u} q_2(\xrightarrow{a} q_2)^\omega$

Many possible specifications

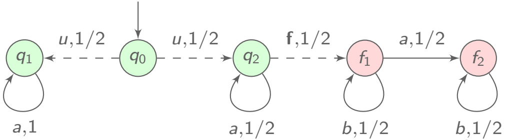
Verdict: information provided

Faulty runs or all ambiguous runs?

Correctness: accuracy of the verdict

Exact, approximate or accurate approximate?

Reactivity: delay before a verdict is given



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Almost sure, uniform almost sure or infinite?

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Each combination of features defines a diagnoser notion

Many possible specifications

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Each combination of features defines a diagnoser notion

$\rightarrow$ Semantical analysis of the relations

Formalising diagnosability notions

Verdict: Detection of faulty runs

Reactivity: Finite delay

Formalising diagnosability notions

Verdict: Detection of faulty runs

Reactivity: Finite delay

Reactivity / Correctness	Uniform almost sure	Almost sure
Exact	Uniform FF-diagnosability	FF-diagnosability $\lim_{n\to\infty} \mathbb{P}(FAmb_n) = 0$
Accurate approximate	Uniform AFF-diagnosability	AFF-diagnosability $\forall \varepsilon > 0, \lim_{n\to\infty} \mathbb{P}(FAmb_n^{\varepsilon}) = 0$
Approximate	Uniform εFF-diagnosability	εFF-diagnosability

Formalising diagnosability notions

Verdict: Detection of faulty runs

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Stochastic model

- Finite Markov chain

Specification

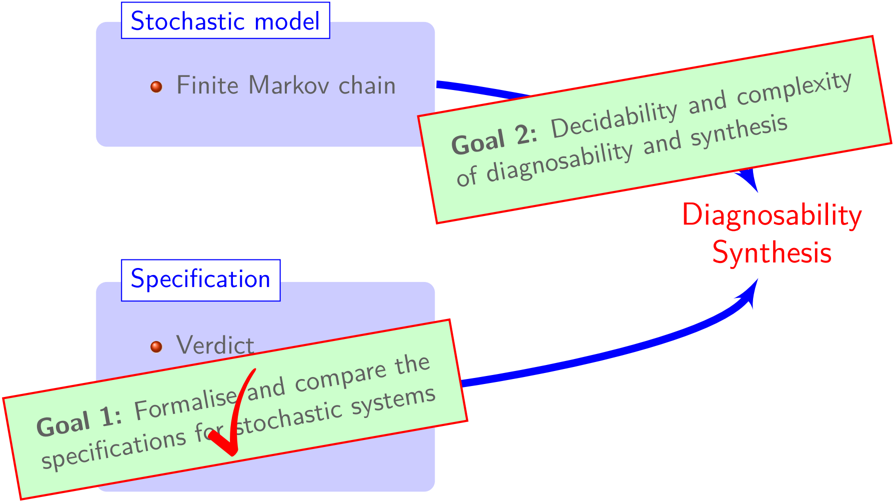
- Verdict

Goal 2: Decidability and complexity of diagnosability and synthesis

Goal 1: Formalise and compare the specifications for stochastic systems

Diagnosability
Synthesis

Challenges



Stochastic model
Finite Markov chain
Specification
Verdict
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Diagnosability
Synthesis
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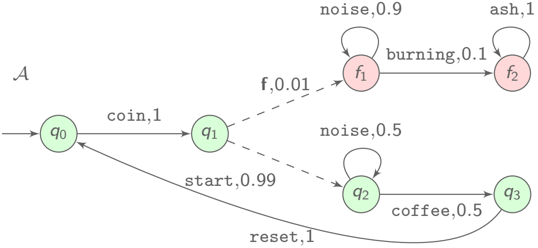
FF-diagnosability

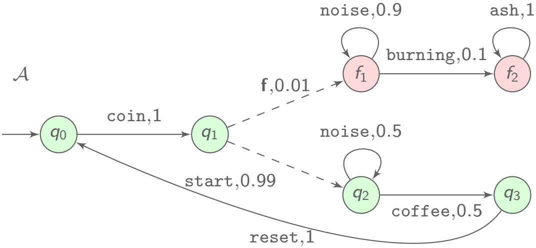
Definition

The probability of faulty ambiguous runs converges to 0



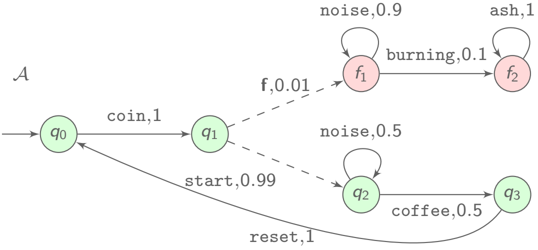
Faulty ambiguous runs: ending with $(f_1 \xrightarrow{noise} f_1)^*$

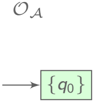
The belief construction



$\mathcal{O}_\mathcal{A}$: sequence of observations $\mapsto$ set of possible current states

The belief construction





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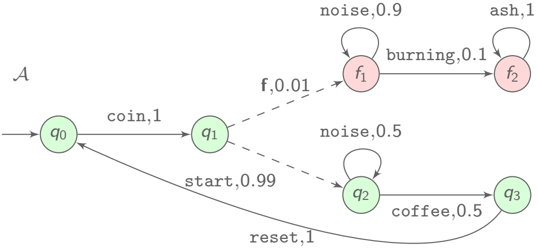

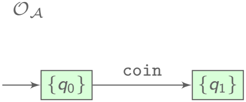

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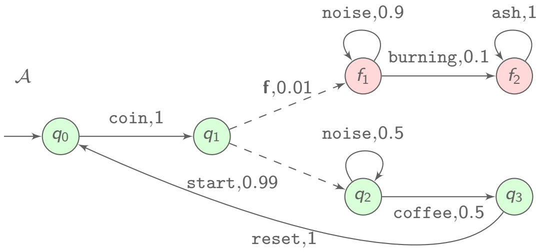

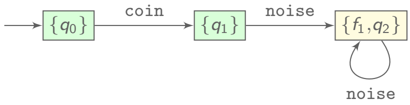

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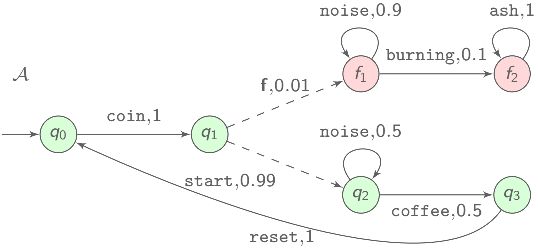
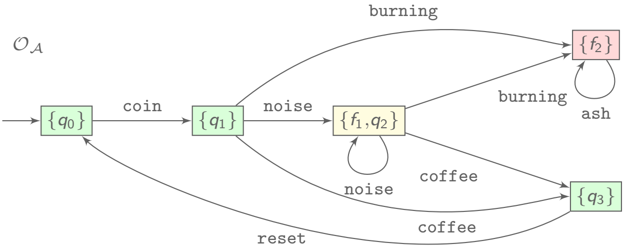
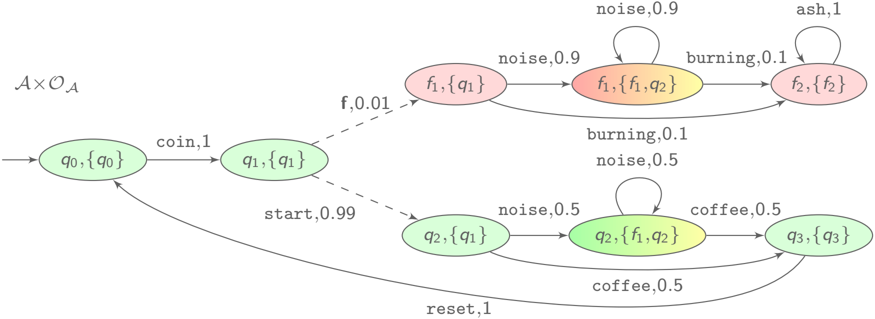




Synchronised product



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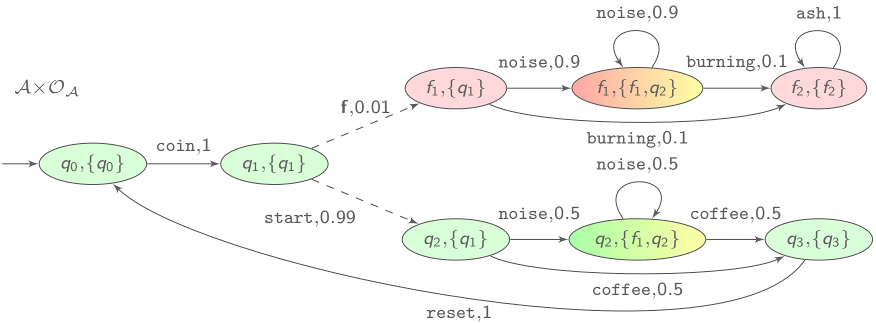
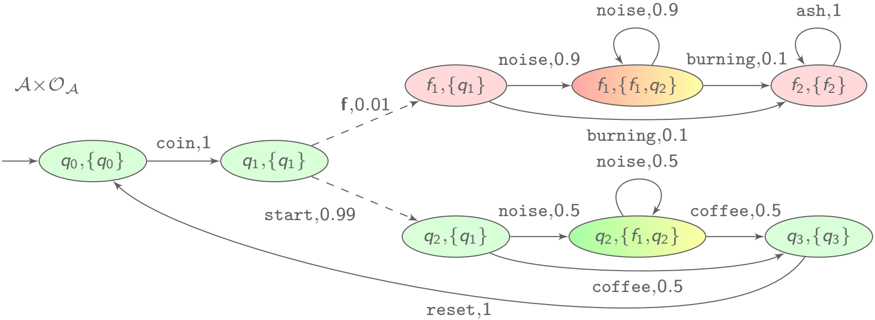


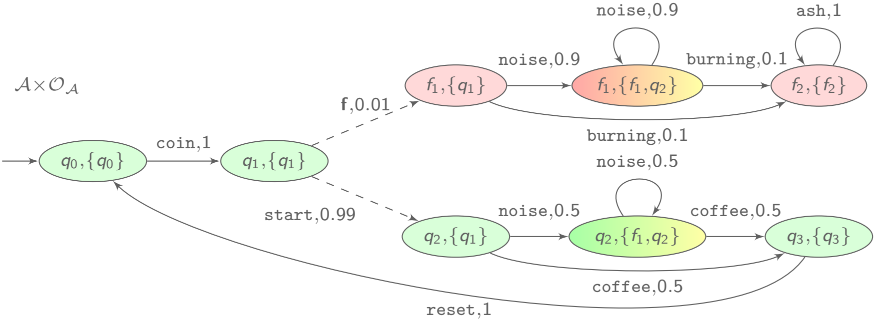
- Same stochastic behaviour as $\mathcal{A}$

Synchronised product



- Same stochastic behaviour as $\mathcal{A}$
- Ambiguity of a run deduced from its last state

Synchronised product



- Same stochastic behaviour as $\mathcal{A}$
- Ambiguity of a run deduced from its last state
- Possibly exponential in the size of $\mathcal{A}$

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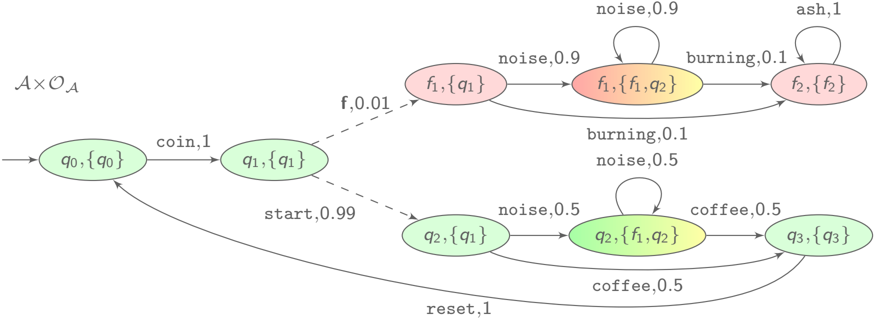

- Same stochastic behaviour as $\mathcal{A}$
- Ambiguity of a run deduced from its last state
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FF-diagnosable iff
no BSCC contains a faulty ambiguous state

Complexity of FF-diagnosability

Verdict: Detection of faulty runs

Reactivity: Finite delay

Reactivity / Correctness	Uniform almost sure	Almost sure
Exact	Uniform FF-diagnosability [TT05] [BHL18]	FF-diagnosability PSPACE-complete [BHL14][BHL18]
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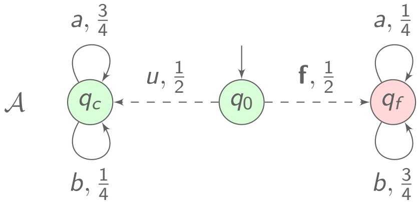
AFF-diagnosability

Definition

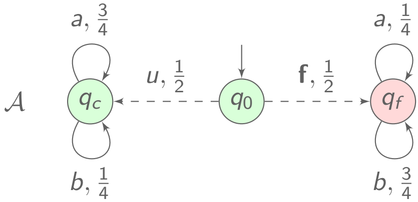
Faults are almost surely detected with arbitrarily small probability of false positive



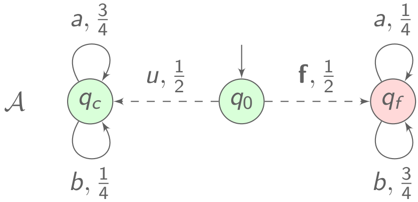
$\mathbb{P}(\text{correct} \mid bba) = \frac{1}{4}$

$\mathbb{P}(\text{correct} \mid bbab) = \frac{1}{10}$

High proportion of $b \Rightarrow$ small probability of being correct



Distance between q_c and q_f: $\sup\limits_{E \subseteq \{a,b\}^\omega} \mathbb{P}_{q_f}(E) - \mathbb{P}_{q_c}(E)$.



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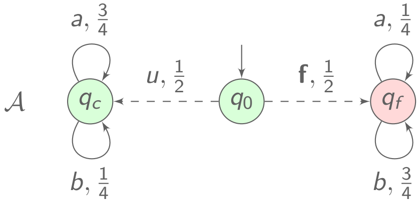
$E = \{$infinite words with proportion of b greater than half$\}$

Distance between states



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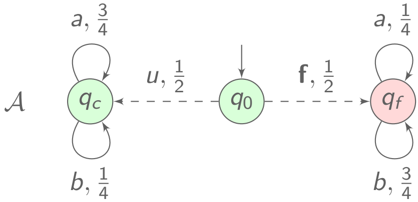
E separates q_c and q_f: $\mathbb{P}_{q_c}(E) = 0$ and $\mathbb{P}_{q_f}(E) = 1$



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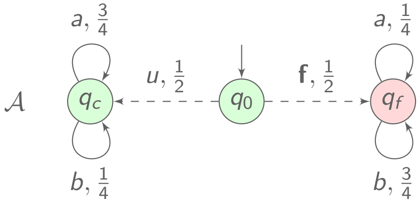
E separates q_c and q_f: $\mathbb{P}_{q_c}(E) = 0$ and $\mathbb{P}_{q_f}(E) = 1$

$\longrightarrow$ The distance between q_c and q_f is 1



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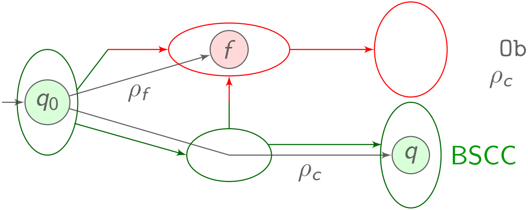
$\longrightarrow$ The distance between q_c and q_f is 1

$\longrightarrow$ $\mathcal{A}$ is AFF-diagnosable

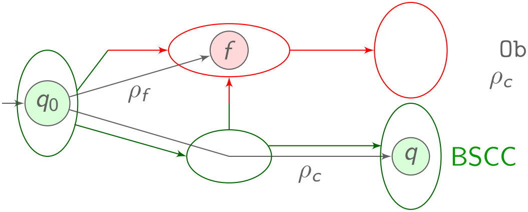
- Identifying **relevant pairs** of states



$\mathtt{Obs}(\rho_c) = \mathtt{Obs}(\rho_f)$
ρ_c correct, ρ_f faulty

Solving AFF-diagnosability

- Identifying **relevant pairs** of states



$\mathtt{Obs}(\rho_c) = \mathtt{Obs}(\rho_f)$
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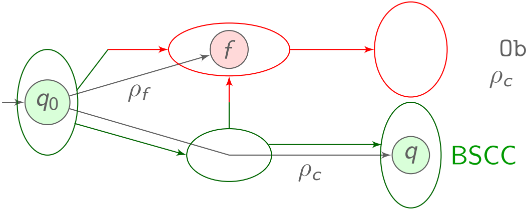
- Checking distance 1 for all relevant pairs

Solving AFF-diagnosability

- Identifying **relevant pairs** of states



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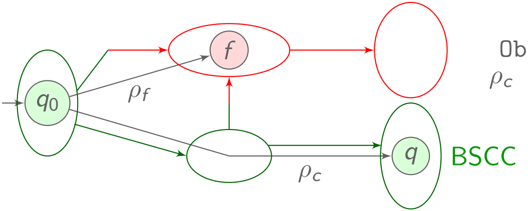
AFF-diagnosable iff distance 1 for all relevant pairs

Solving AFF-diagnosability

- Identifying **relevant pairs** of states



$\mathtt{Obs}(\rho_c) = \mathtt{Obs}(\rho_f)$
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- Checking distance 1 for all relevant pairs

AFF-diagnosable iff distance 1 for all relevant pairs

- The distance 1 problem is in PTIME [CK14]

[CK14] Chen and Kiefer, *On the Total Variation Distance of Labelled Markov Chains*, CSL-LICS, 2014.

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Challenges

Stochastic model

- Finite Markov chain

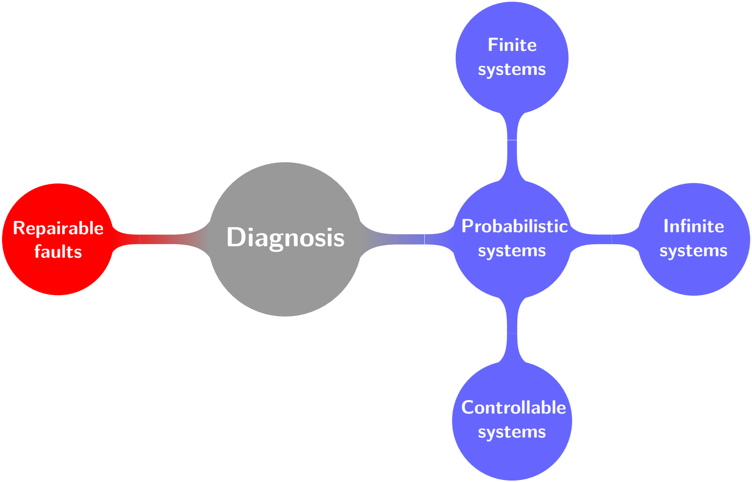
Specification

- Verdict

Diagnosability
Synthesis

Goal 2: Decidability and complexity of diagnosability and synthesis ✓

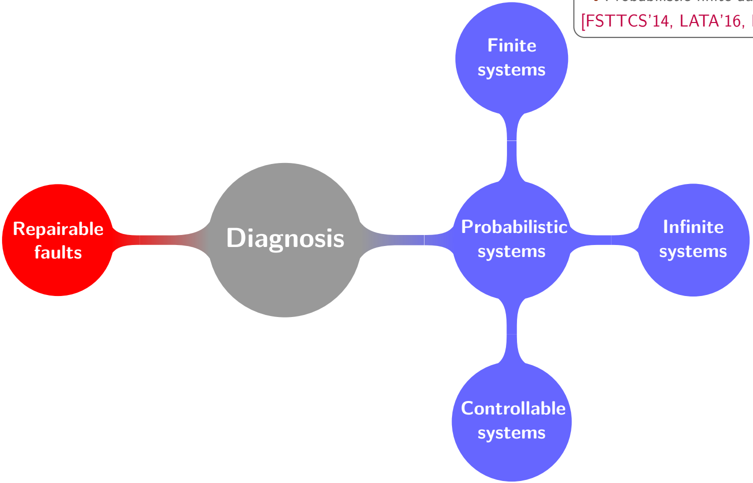
Goal 1: Formalise and compare the specifications for stochastic systems ✓


Repairable faults
Diagnosis
Probabilistic systems
Finite systems
Infinite systems
Controllable systems

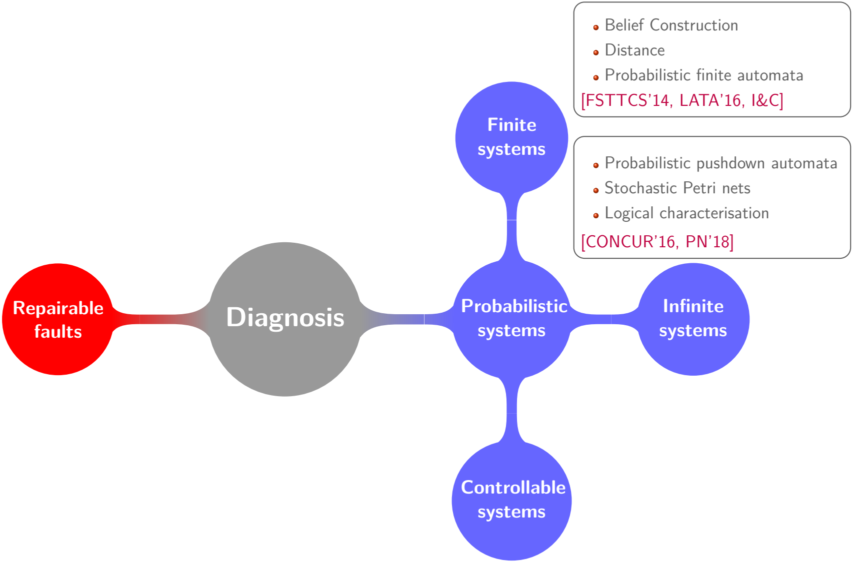
Contributions

- Belief Construction
- Distance
- Probabilistic finite automata

[FSTTCS'14, LATA'16, I&C]



Contributions



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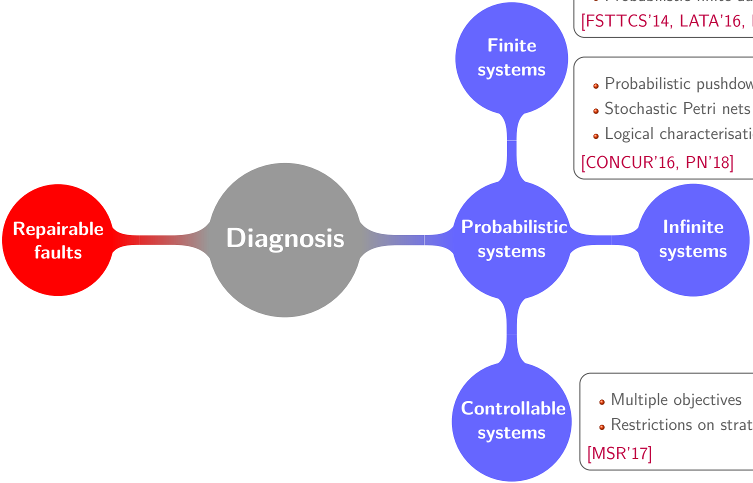


- Belief Construction
- Distance
- Probabilistic finite automata

[FSTTCS'14, LATA'16, I&C]

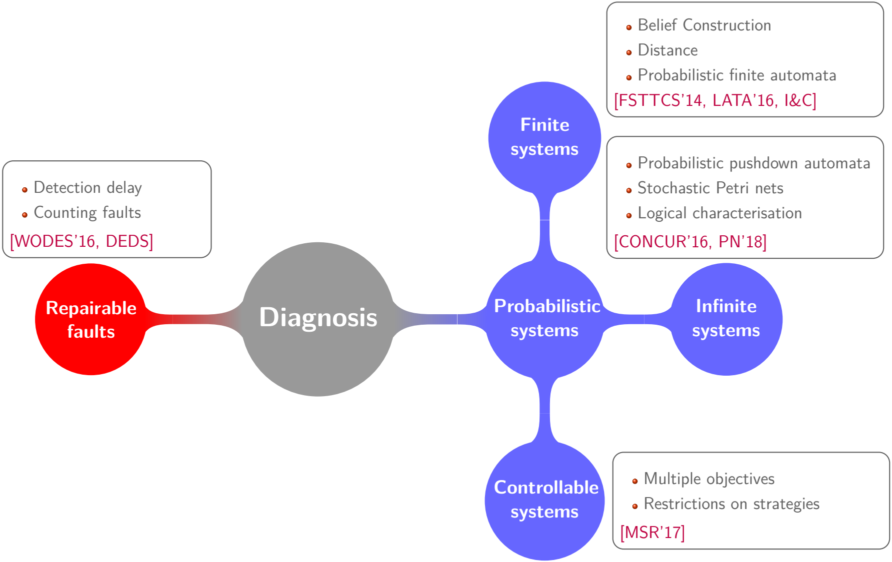
- Probabilistic pushdown automata
- Stochastic Petri nets
- Logical characterisation

[CONCUR'16, PN'18]

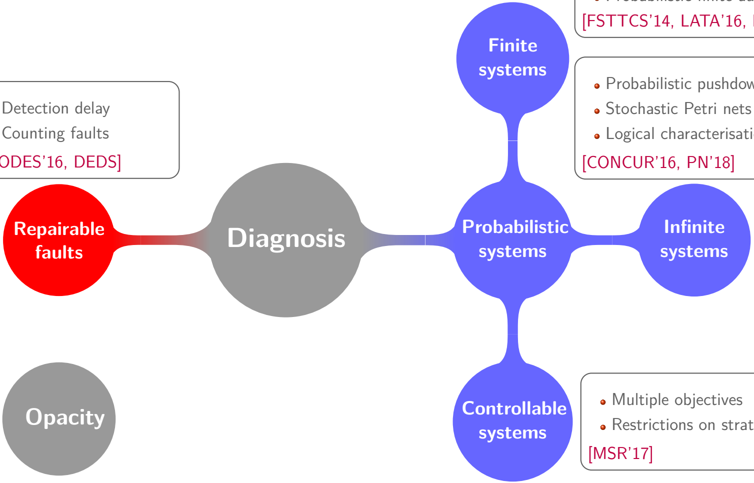
- Multiple objectives
- Restrictions on strategies

[MSR'17]

Contributions



Contributions



- Belief Construction
- Distance
- Probabilistic finite automata

[FSTTCS'14, LATA'16, I&C]

- Probabilistic pushdown automata
- Stochastic Petri nets
- Logical characterisation

[CONCUR'16, PN'18]

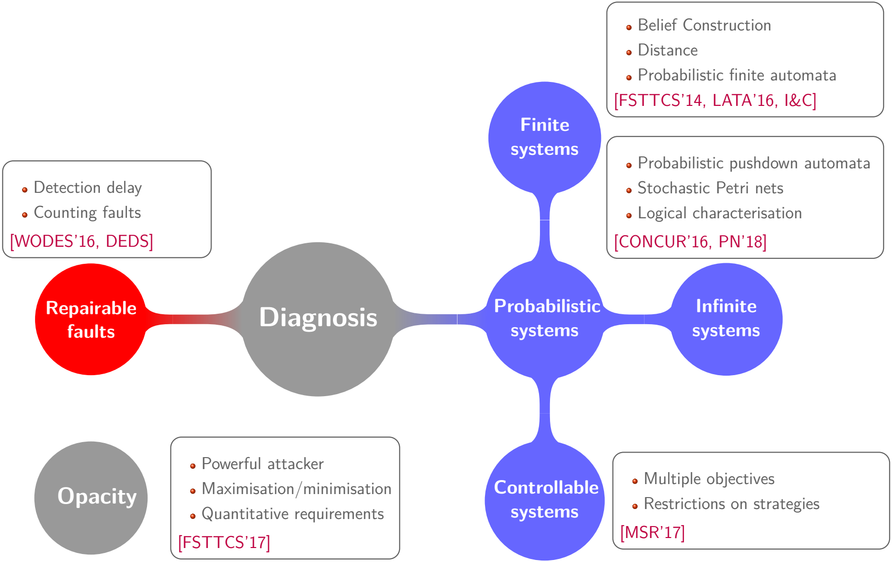
- Detection delay
- Counting faults

[WODES'16, DEDS]

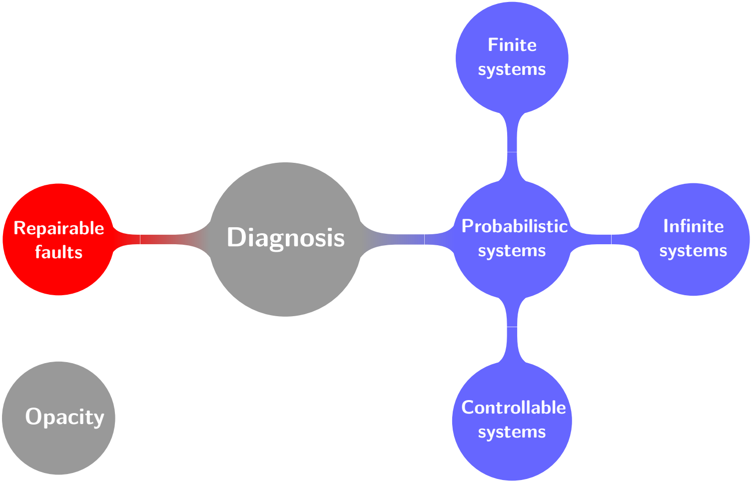
- Multiple objectives
- Restrictions on strategies

[MSR'17]

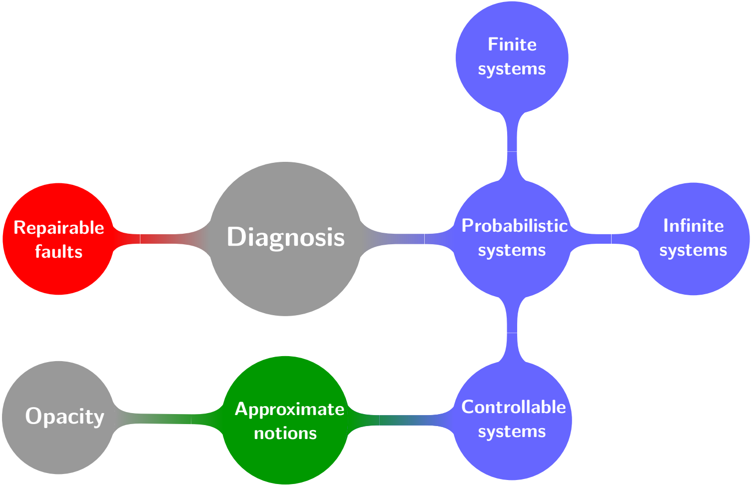
Contributions



Perspectives



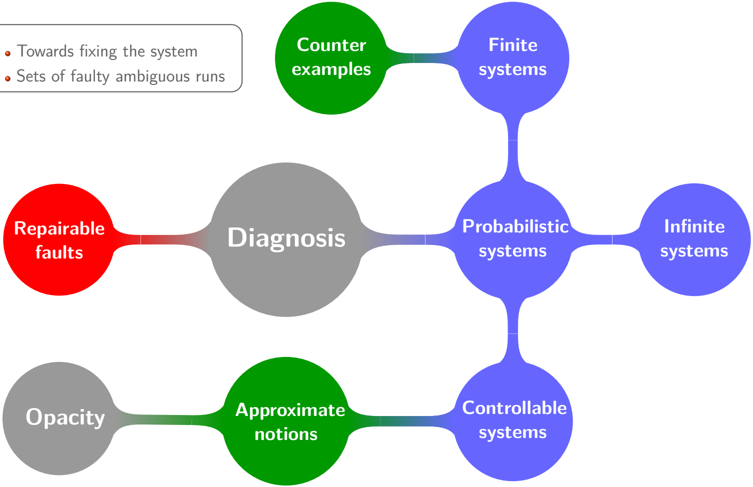
Perspectives



- Realistic
- Risk of undecidability

Perspectives

- Towards fixing the system
- Sets of faulty ambiguous runs



- Realistic
- Risk of undecidability

Perspectives