# Fault diagnosis for Probabilistic Systems a semantical and algorithmic journey

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based on joint work with Éric Fabre, Stefan Haar, Serge Haddad, Loïc Hélouët and Engel Lefaucheux

# Two tales of smoke and observation

Original idea by Stefan Schwoon

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Assuming the behaviour of a system is known, an observer may deduce the occurrence of internal events from the outputs.

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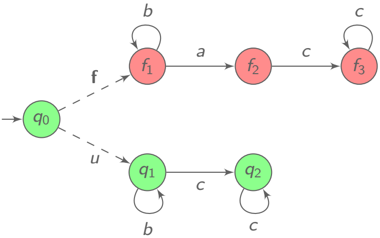
Diagnosis, non-interference, information flow, opacity, etc.

# Outline

# Fault diagnosis in discrete event systems [SSLST95]

**Objective**: tell whether a fault occurred, based on observations.

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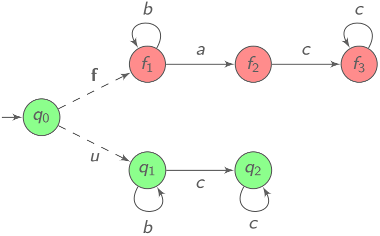


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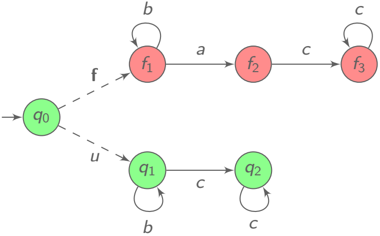


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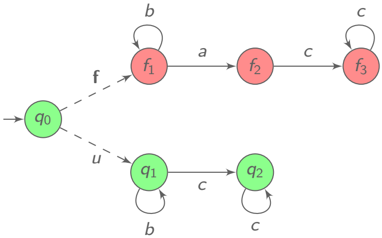


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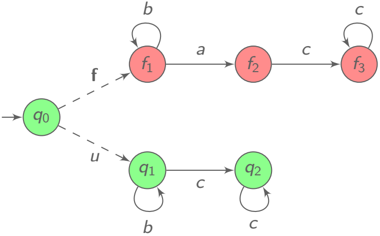


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Remark: w.l.o.g. state space partitionned into correct and faulty states

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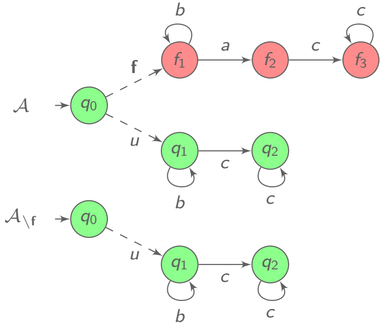

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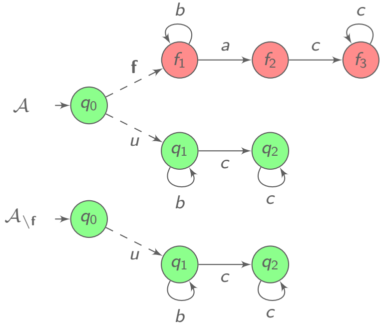


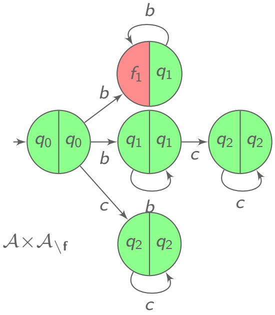

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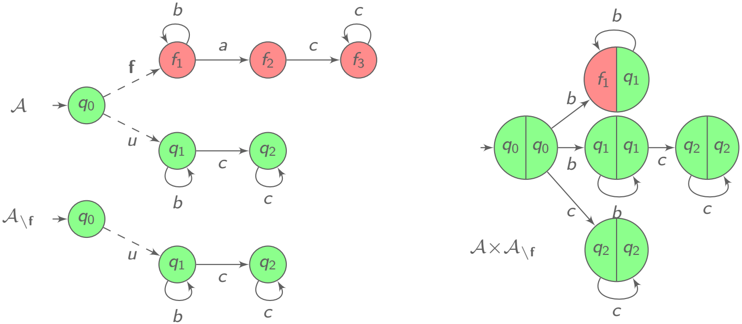


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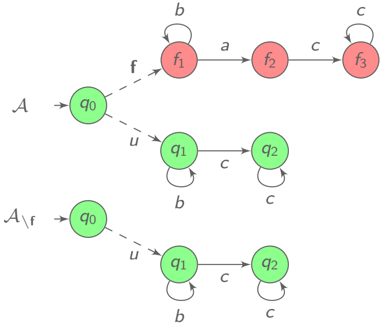


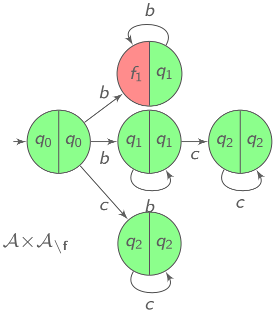


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**Decidability and complexity of diagnosability** [JHCK01]
Diagnosability is decidable in PTIME.

[JHCK01] Jiang, Huang, Chandra and Kumar, *A polynomial algorithm for testing diagnosability of discrete-event systems*, TAC, 2001.

# Diagnosers

**Diagnoser**: assigns verdicts to observed sequences $D : \Sigma_o^* \rightarrow \{✓, ✗, ?\}$

Diagnoser requirements

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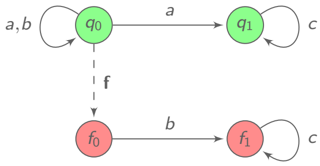


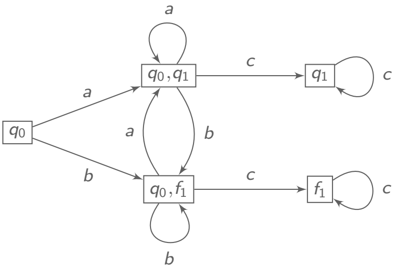

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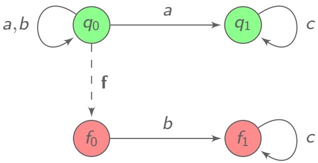


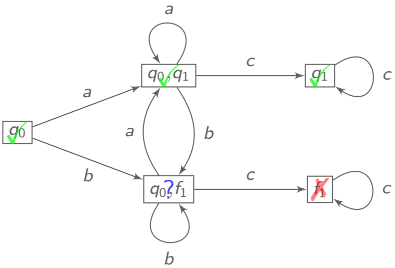

# Diagnoser synthesis

**Complexity of diagnoser synthesis**
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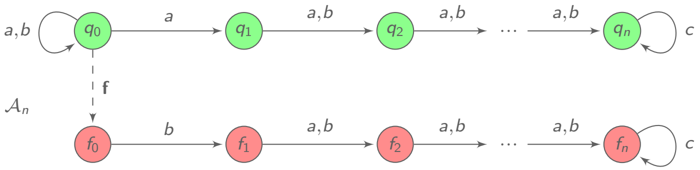
There is a family $(\mathcal{A}_n)$ of diagnosable systems such that $\mathcal{A}_n$ has $2n+2$ states and any diagnoser needs $2^n$ states.




diagnoser must remember the last $n$ events: $2^n$ possibilities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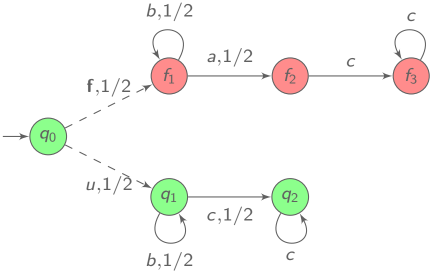
# Outline

# Diagnosis of probabilistic systems



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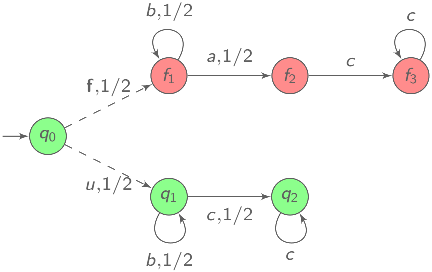


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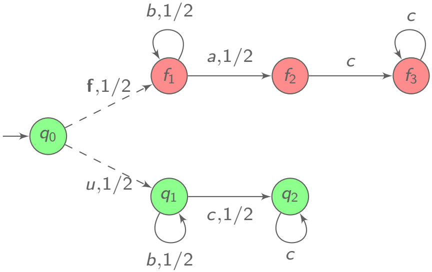


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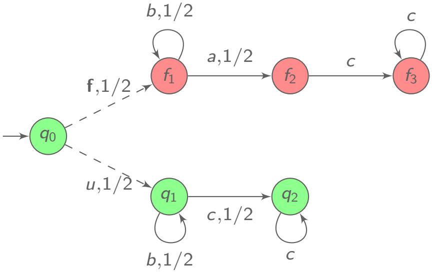


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How to adapt the framework to probabilistic systems?

- diagnosability notion(s)
- soundness and correctness for diagnosers
- algorithms for diagnosability checking and diagnoser synthesis


[TT05] Thorsley and Teneketzis, *Diagnosability of stochastic discrete-event systems*, TAC, 2005.
[CK13] Chen and Kumar, *Polynomial test for stochastic diagnosability of dicrete-event systems*, TASE, 2013.
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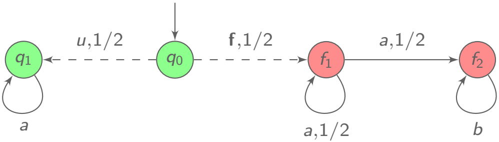


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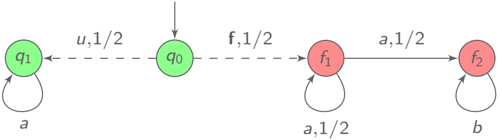


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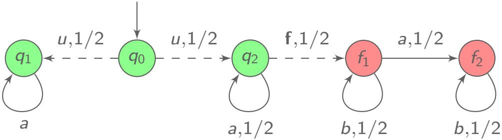
2. Consider infinite observed sequences or their finite prefixes?




Infinite sequence $a^\omega$ is surely correct.

For every $N$, $a^N$ is ambiguous, and has probability greater than $\frac{1}{2}$.

# Four diagnosability specifications

| Diagnosability | All runs | | Faulty runs |
|---|---|---|---|
| Finite prefixes | FA | $\Rightarrow$ $\not\Leftarrow$ | FF |
| | $\Downarrow$ $\not\Uparrow$ | | $\Downarrow\Uparrow^*$ |
| Infinite sequences | IA | $\Rightarrow$ $\not\Leftarrow$ | IF |

* assuming finitely-branching models

# Characterizing diagnosability

*e.g.* FA-diagnosability
disambiguation of All runs, relying on Finite observation sequences.

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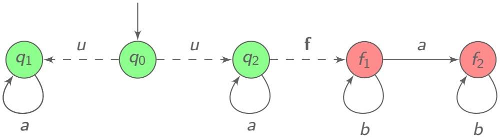

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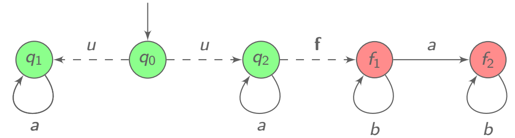


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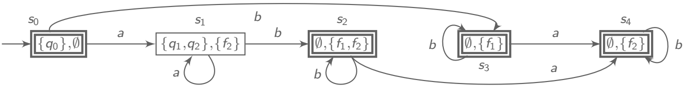

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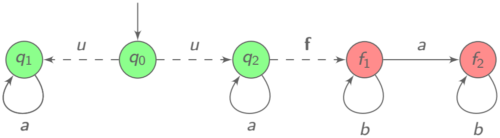


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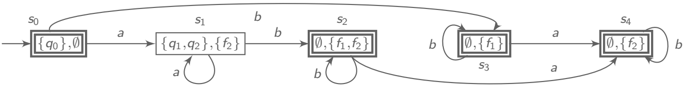


$\mathcal{A}$ is not FA-diagnosable iff
there exists a BSCC of $\mathcal{A} \times \mathcal{O}_{\mathcal{A}}$ where every state $(q, C, F)$ satisfies
$q$ faulty and $C \neq \emptyset$ or $q$ correct and $F \neq \emptyset$.

[BHL14] **B.**, Haddad and Lefaucheux, *Foundation of diagnosis and predictability in probabilistic systems*, FSTTCS'14.

# Solving diagnosability

Methodology to decide all diagnosability notions for probabilistic systems:

- build a deterministic observer $\mathcal{O}_\mathcal{A}$ by an *ad hoc* subset construction
- form the product $\mathcal{A} \times \mathcal{O}_\mathcal{A}$ to recover probabilistic behaviour
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Diagnosability is PSPACE-complete for probabilistic systems. [BHL14]

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For every diagnosable system with $n$ states
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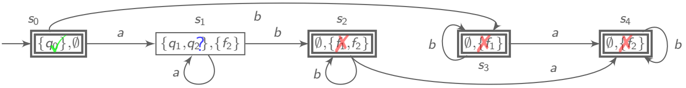
Diagnoser derived from observer $\mathcal{O}_\mathcal{A}$:

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# Outline

Introduction to fault diagnosis

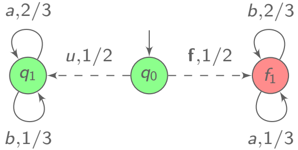
Diagnosability in probabilistic systems

- Exact Diagnosis
- Approximate diagnosis

Control for probabilistic diagnosability

Conclusion

# Motivation for approximate diagnosis



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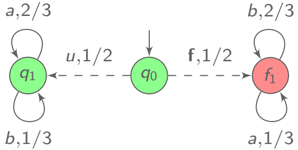


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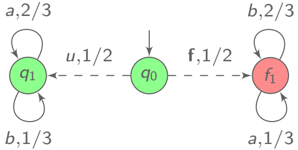


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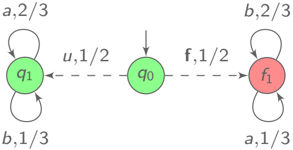


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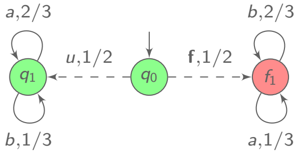
Relaxed soundness: if a fault is claimed, the probability of error is small.

[TT05] Thorsley and Teneketzis, *Diagnosability of stochastic discrete-event systems*, TAC, 2005.

# Formalisation of accurate approximate diagnosability

**Correcness proportion** of an observation sequence $\sigma$

$$\mathrm{CorP}(\sigma) = \frac{\mathbb{P}(\{\pi^{-1}(\sigma) \cap \mathsf{correct}\})}{\mathbb{P}(\{\pi^{-1}(\sigma)\})}$$

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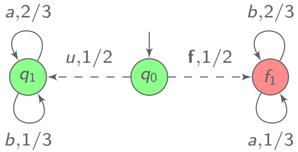


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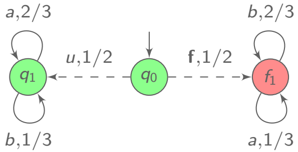


$\mathrm{CorP}(a) = 2/3$, $\mathrm{CorP}(ab) = 1/2$, $\mathrm{CorP}(abb) = 1/3$, $\mathrm{CorP}(abbb) = 1/5$, ...

# Accurate approximate diagnosers

$\varepsilon$-Diagnoser requirements

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- **Uniformity** (optional): the convergence rate for reactivity is independent of the sample faulty run.

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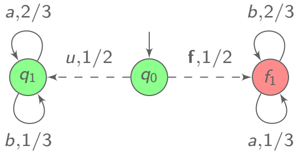
- **Uniformity** (optional): the convergence rate for reactivity is independent of the sample faulty run.




admits $\varepsilon$-diagnoser, for every $\varepsilon > 0$
has no uniform $\varepsilon$-diagnoser, for any $\varepsilon > 0$

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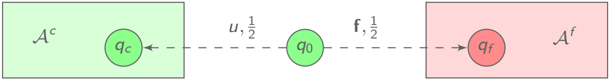


$\mathcal{A}$ is accurate approximate diagnosable iff $\text{dist}(\mathcal{A}^c, \mathcal{A}^f) = 1$
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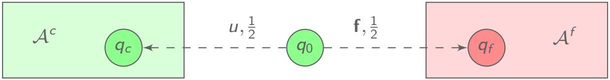


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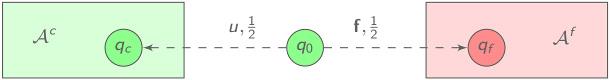


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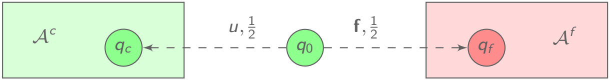


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Uniform accurate approximate diagnosability is undecidable. [BHL16]

[CK14] Chen and Kiefer, *On the Total Variation Distance of Labelled Markov Chains*, CSL-LICS'14.
[BHL16] **B.**, Haddad and Lefaucheux, *Accurate approximate diagnosability of stochastic systems*, LATA'16.

# Outline

# From passive to active diagnosis

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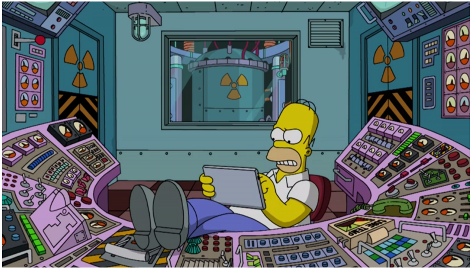
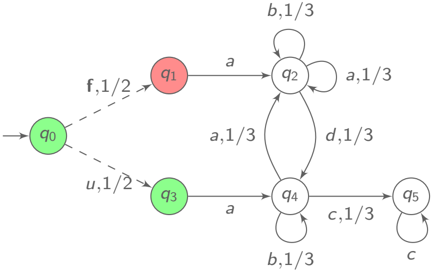


Original idea by Stefan Schwoon

# Active probabilistic diagnosis

**Objective**: control the probabilistic system so that it is diagnosable



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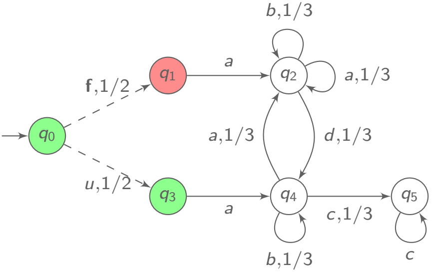


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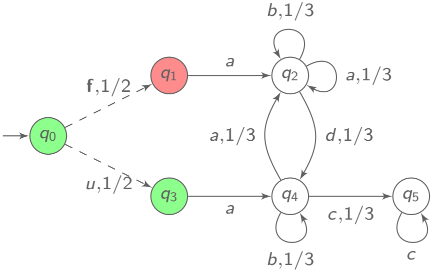


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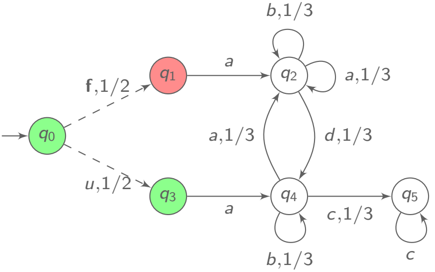


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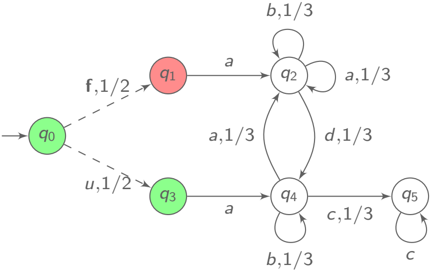


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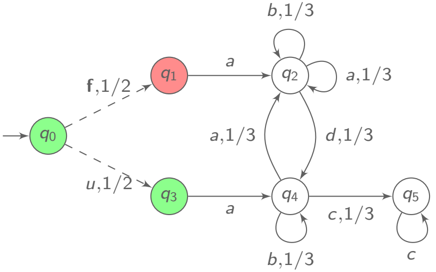


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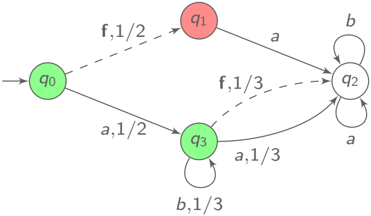


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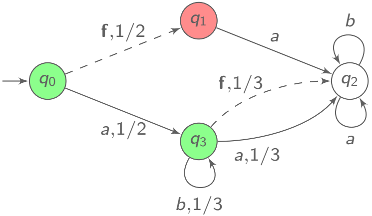


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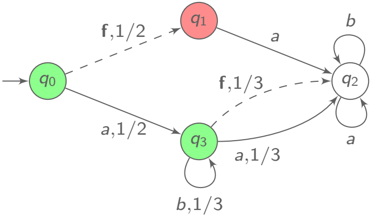


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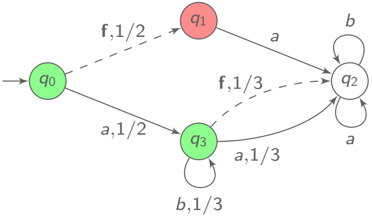


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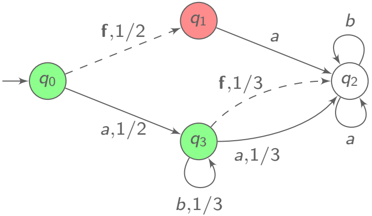


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The safe active probabilistic diagnosis problem restricted to **finite memory controllers** is EXPTIME-complete.

[BFHHH14] **B.**, Fabre, Haar, Haddad and Hélouët, *Active diagnosis for probabilistic systems*, FoSSaCS'14.

# Outline

Introduction to fault diagnosis

Diagnosability in probabilistic systems
- Exact Diagnosis
- Approximate diagnosis

Control for probabilistic diagnosability

Conclusion

# Concluding remarks

Contributions: Foundations of stochastic diagnosis

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Perspectives: Towards more quantitative questions

- Bounded-delay diagnosis
  tradeoff: delay *vs* diagnosability precision
- Space and time optimisation of observations
  tradeoff: observation cost *vs* diagnosability probability
- Challenge: control, partial observation, quantitative properties