A Foundation for Runtime Monitoring

The Secret Life of Monitors

Adrian Francalanza · March 20, 2018

More than one way to skin a cat

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Verification Techniques

- Testing
- Model Checking
- Type Checking
- Theorem Proving
- ...

What if...

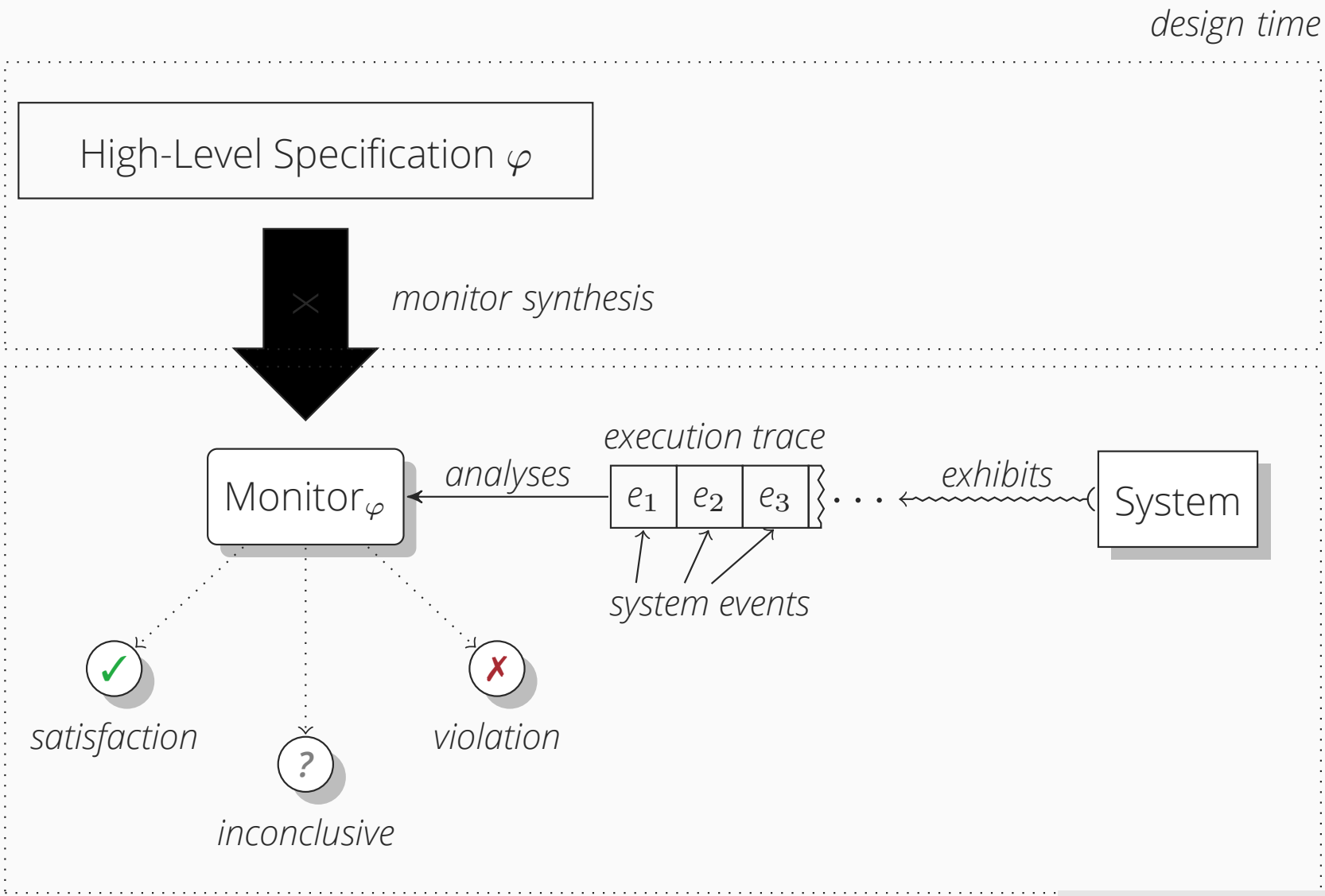
...Building a model is not worthwhile?

- Building a model is very **expensive** and/or **complex**.
- The model may need to **change often**.

...Building a model is not possible?

- The system should be viewed as a **black box**.
- Parts of the system are third-party or **closed source**.
- Parts of the system are **dynamically** loaded at runtime.

The General Approach



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Where is Monitoring used in Practice?

How: In conjunction with other verification techniques.

Where: Autonomous Vehicles, Financial Transactions, Online Video Games, Machine Learning *etc.*

Main Concerns in Runtime Verification (RV)

1. Efficiency
2. Expressivity
3. Correctness

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The Aims of Our Study

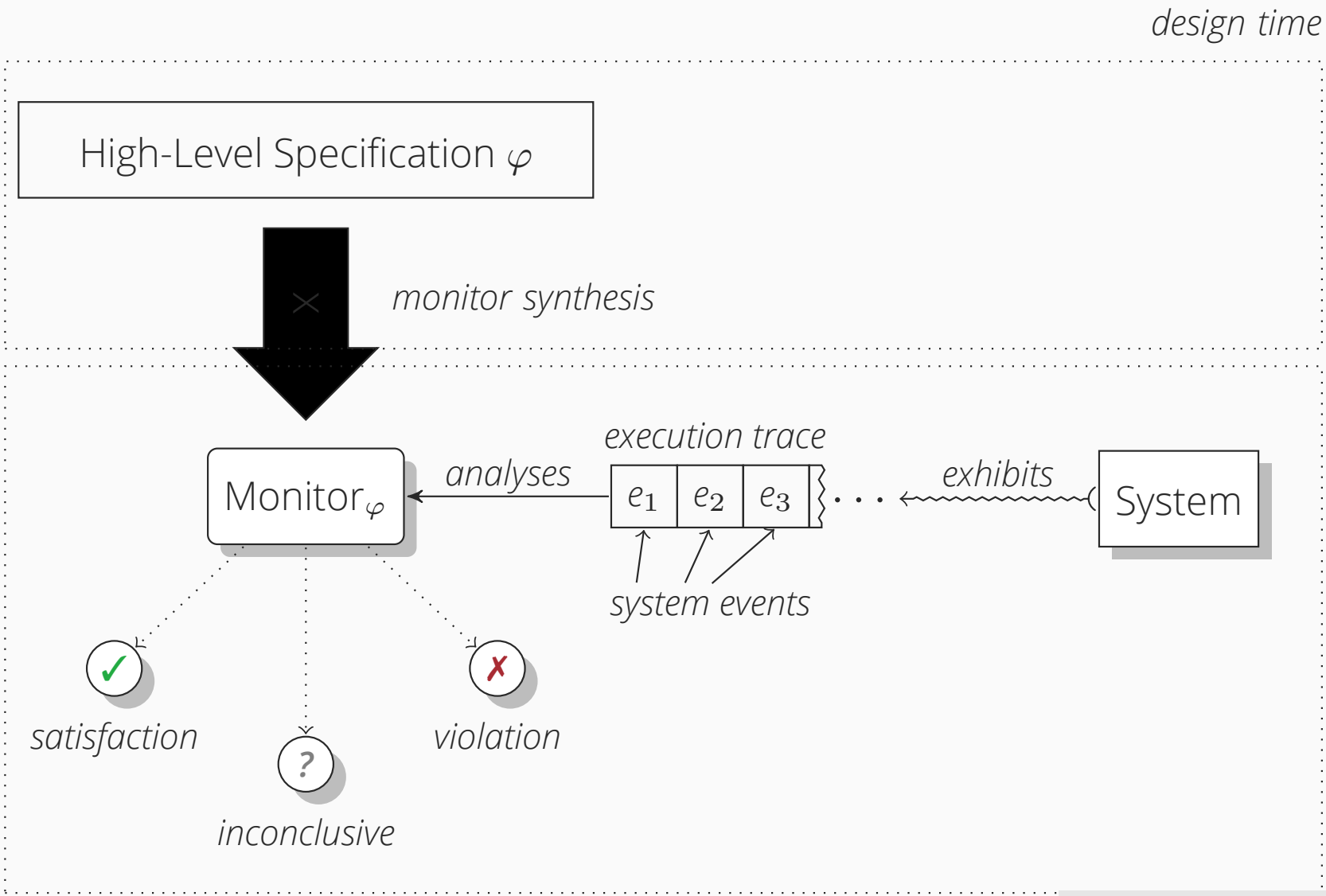
- Understand the **expressivity limits** of RV.
- Identify **correctness criteria** and design **methods** to **ensure correctness**.

Outline

1. Preliminaries
2. Monitors and Instrumentation
3. Monitorability
4. To Monitorabilty...and Beyond!

Preliminaries

The General Approach



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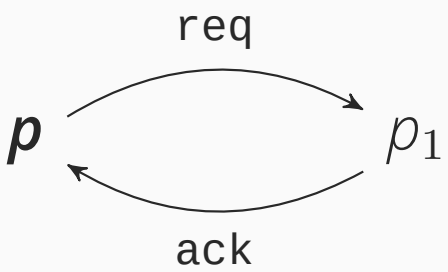

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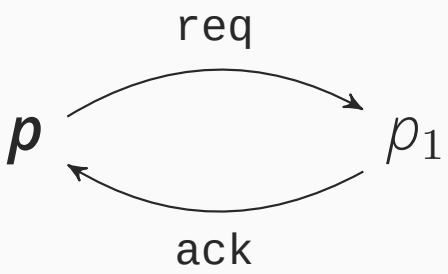

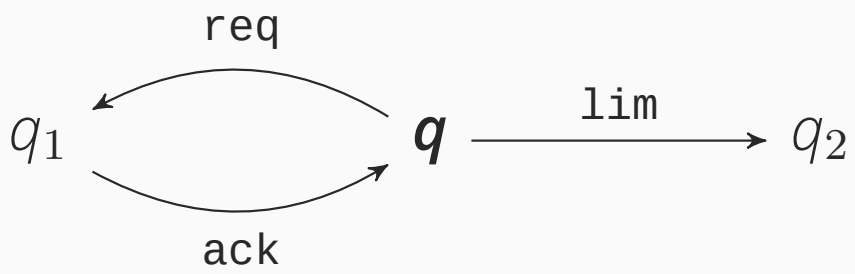

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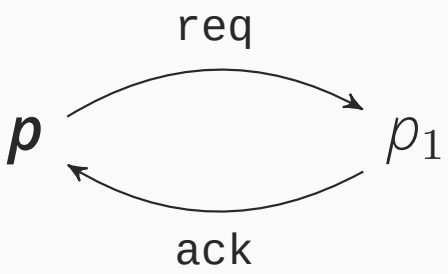

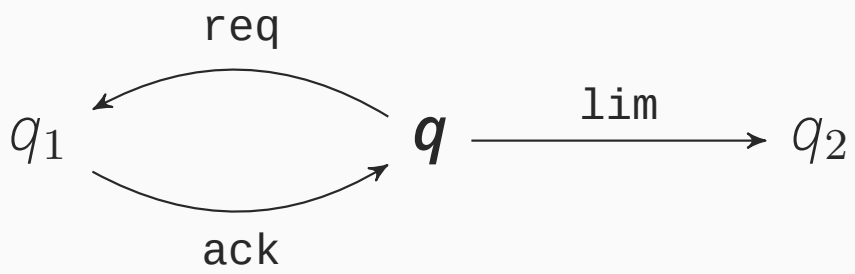

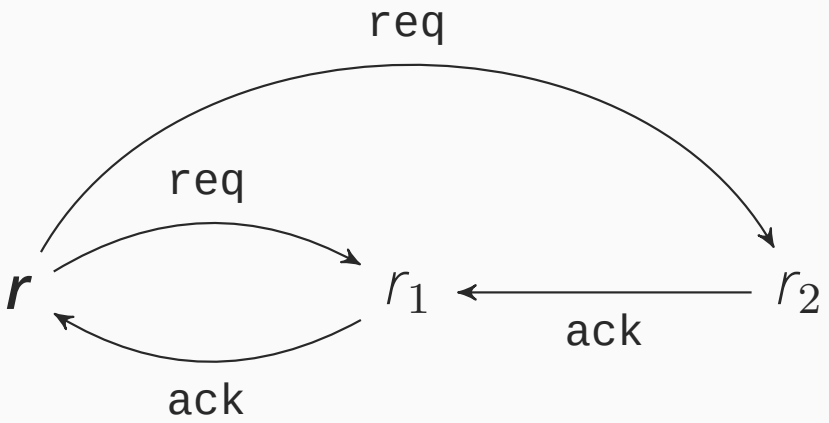

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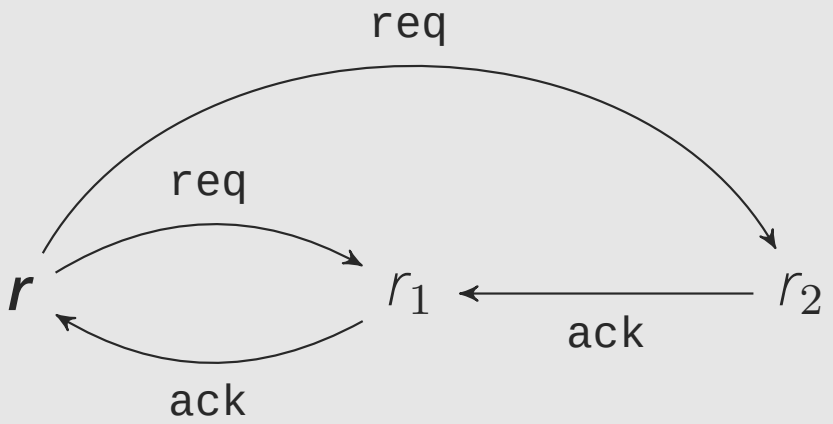
- a ternary **transition relation** between states labelled by actions; we write $p \xrightarrow{\alpha} q$ in lieu of $\langle p, \alpha, q \rangle \in \longrightarrow$.

Systems as LTS



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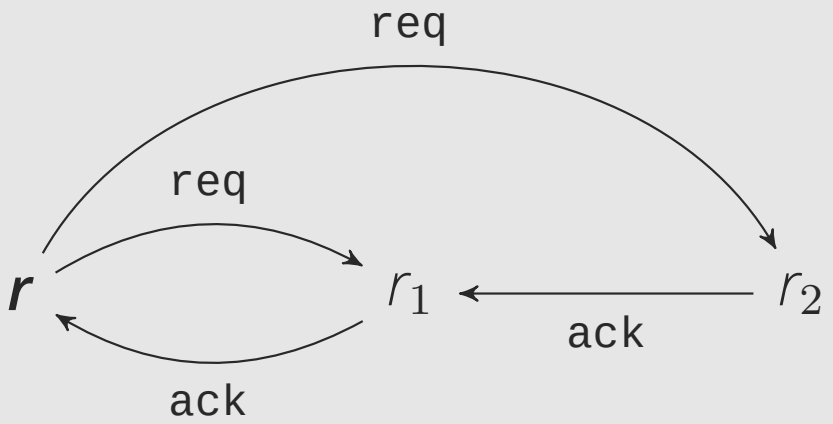

$$\left\langle \begin{array}{l} \{r, r_1, r_2\},\ \{\text{req}, \text{ack}, \tau\} \\ \quad \{r \xrightarrow{\text{req}} r_1,\ r \xrightarrow{\text{req}} r_2,\ r_1 \xrightarrow{\text{ack}} r,\ r_2 \xrightarrow{\text{ack}} r_1\} \end{array} \right\rangle$$

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- We typically assume rooted LTS so both have a unique start state.
- LTSs have a more explicit **delineation** between **internal** and **external** actions (and transitions).
- Automata usually need to specify **explicitly** that their transitions are **non-deterministic**.

The Logic

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Definition (Logic Syntax)

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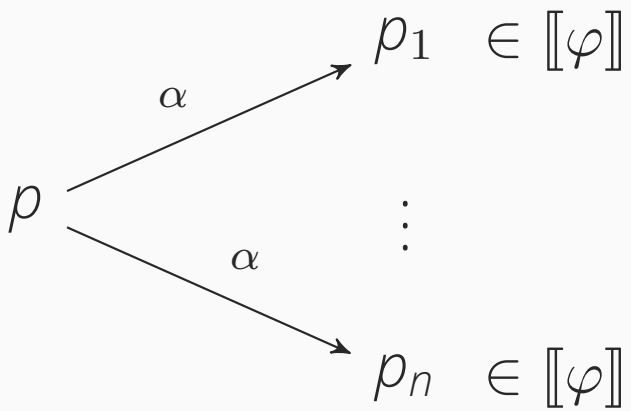

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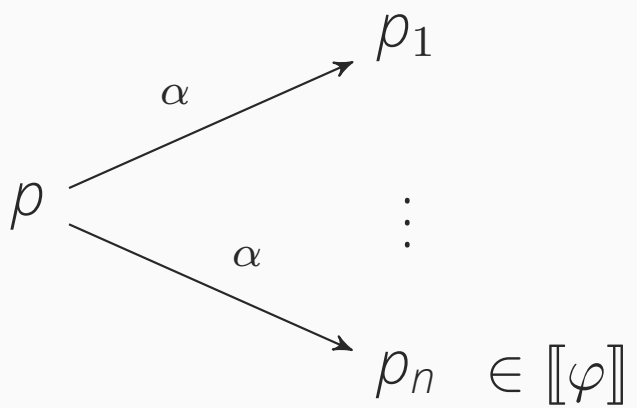

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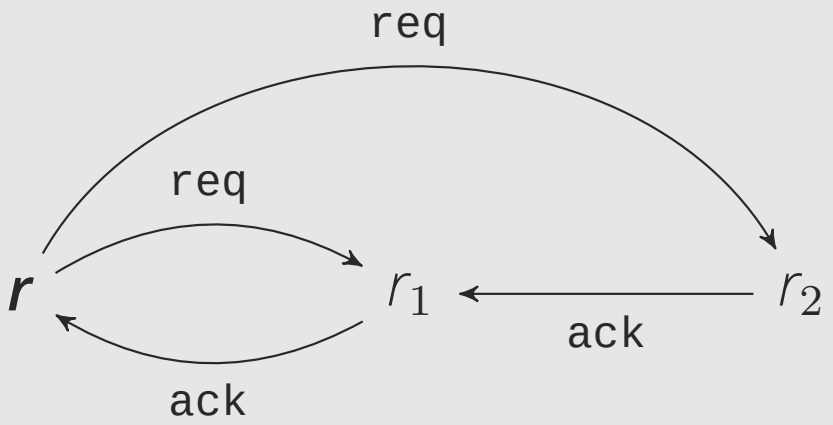

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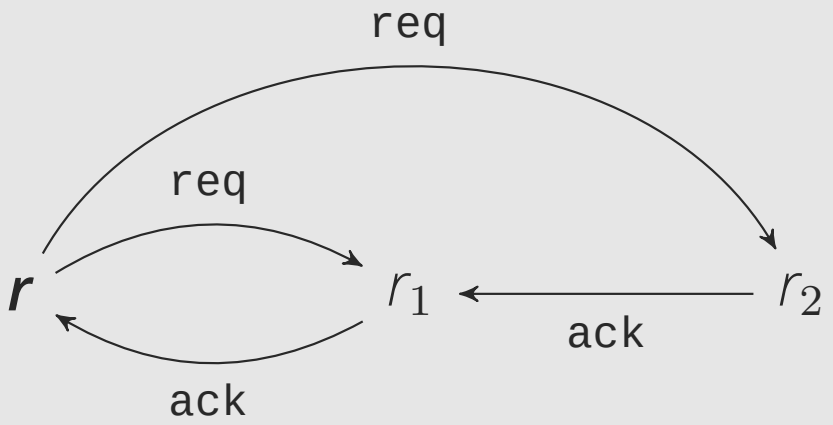

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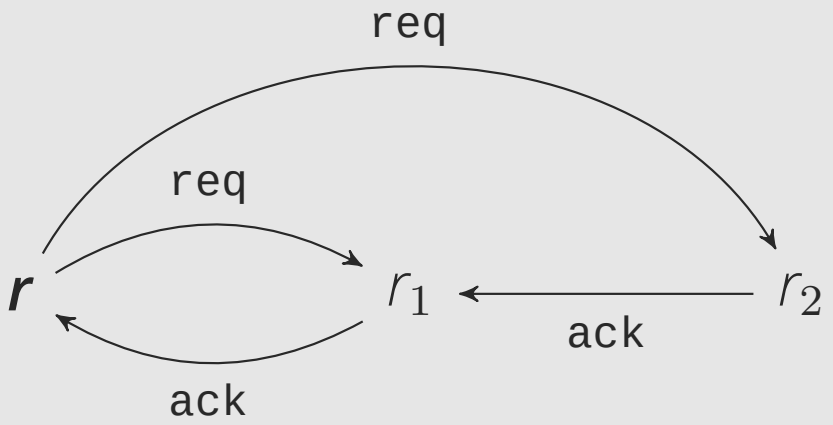

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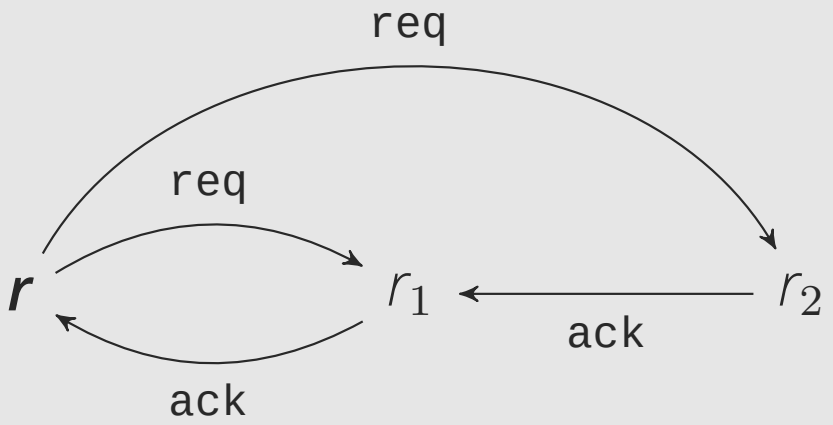

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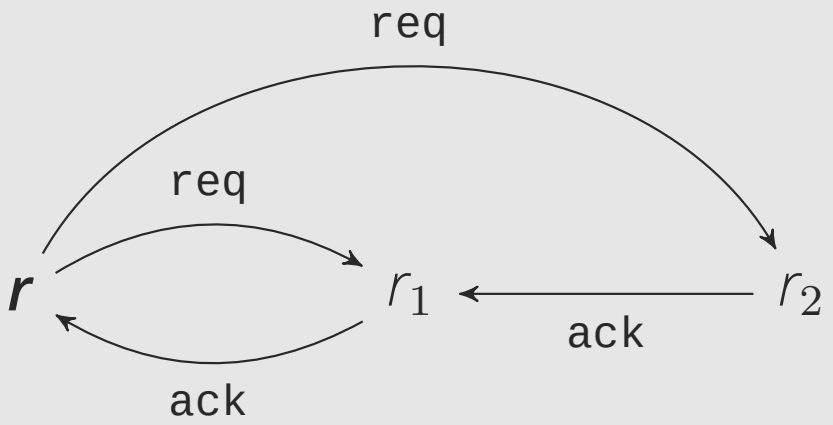

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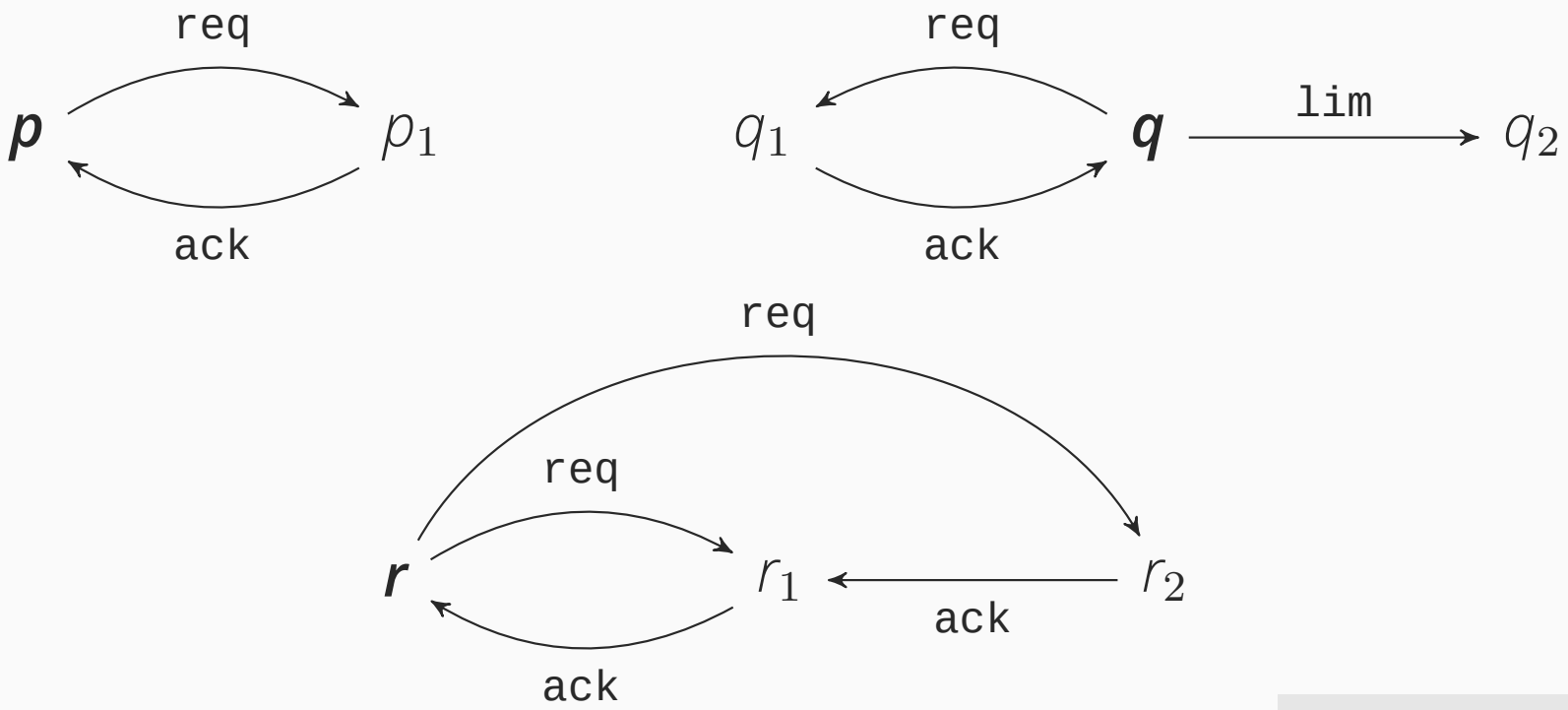

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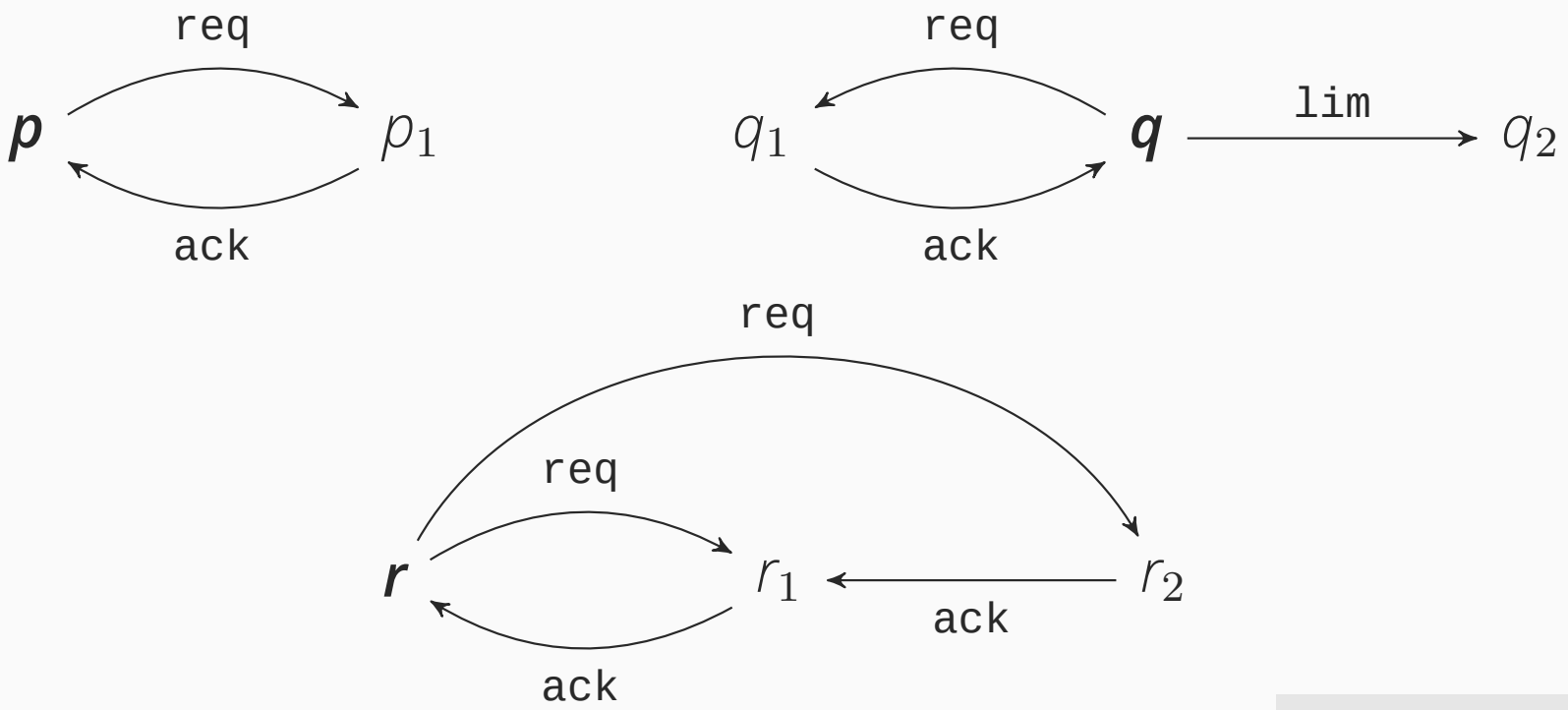

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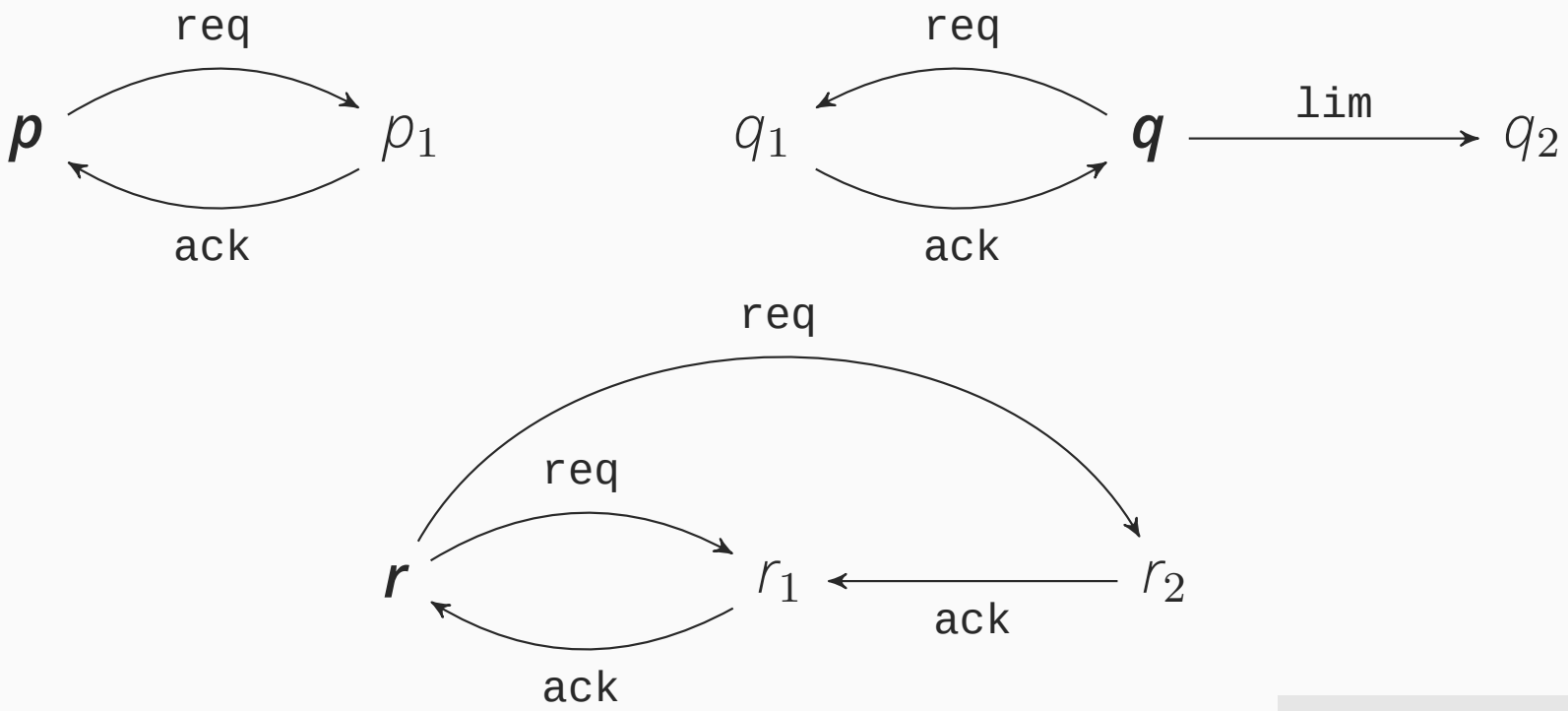

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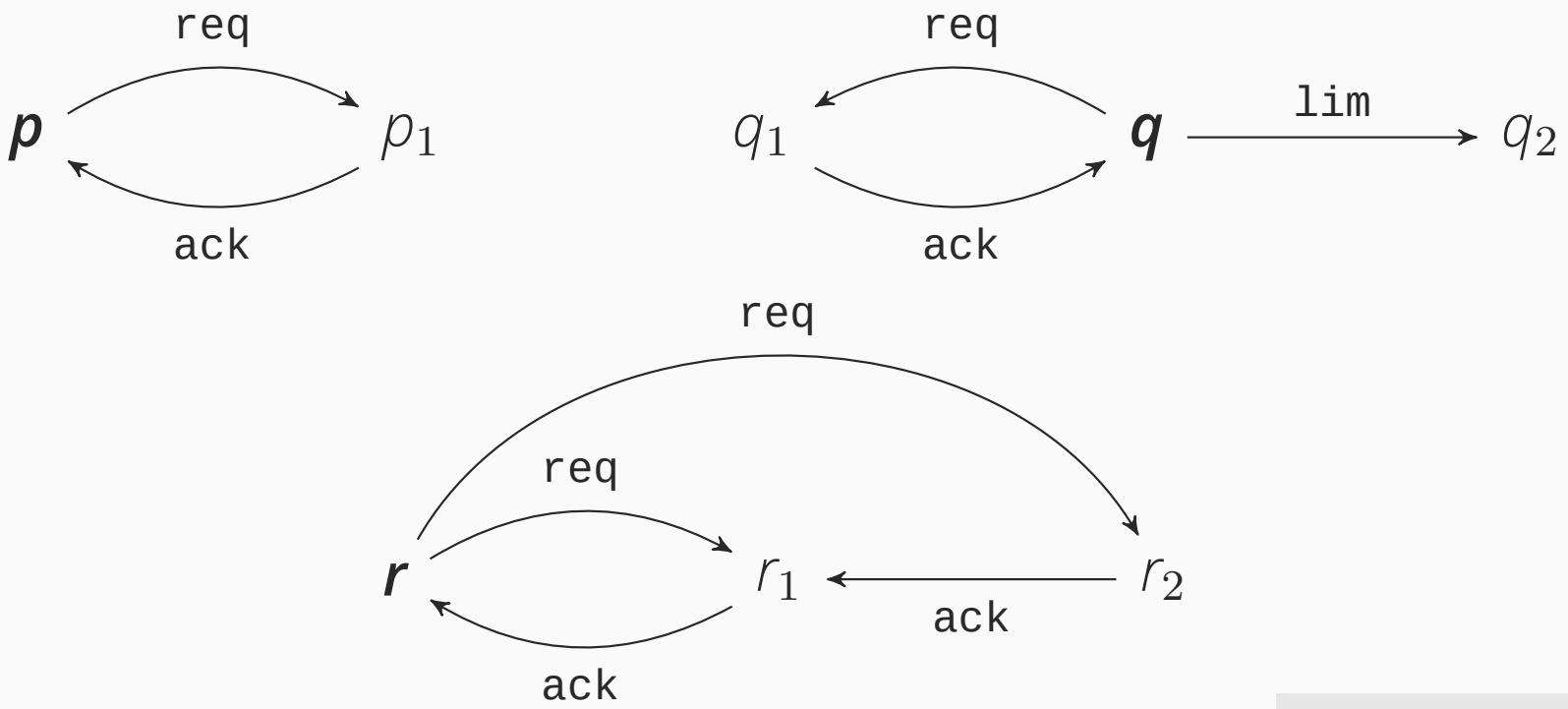

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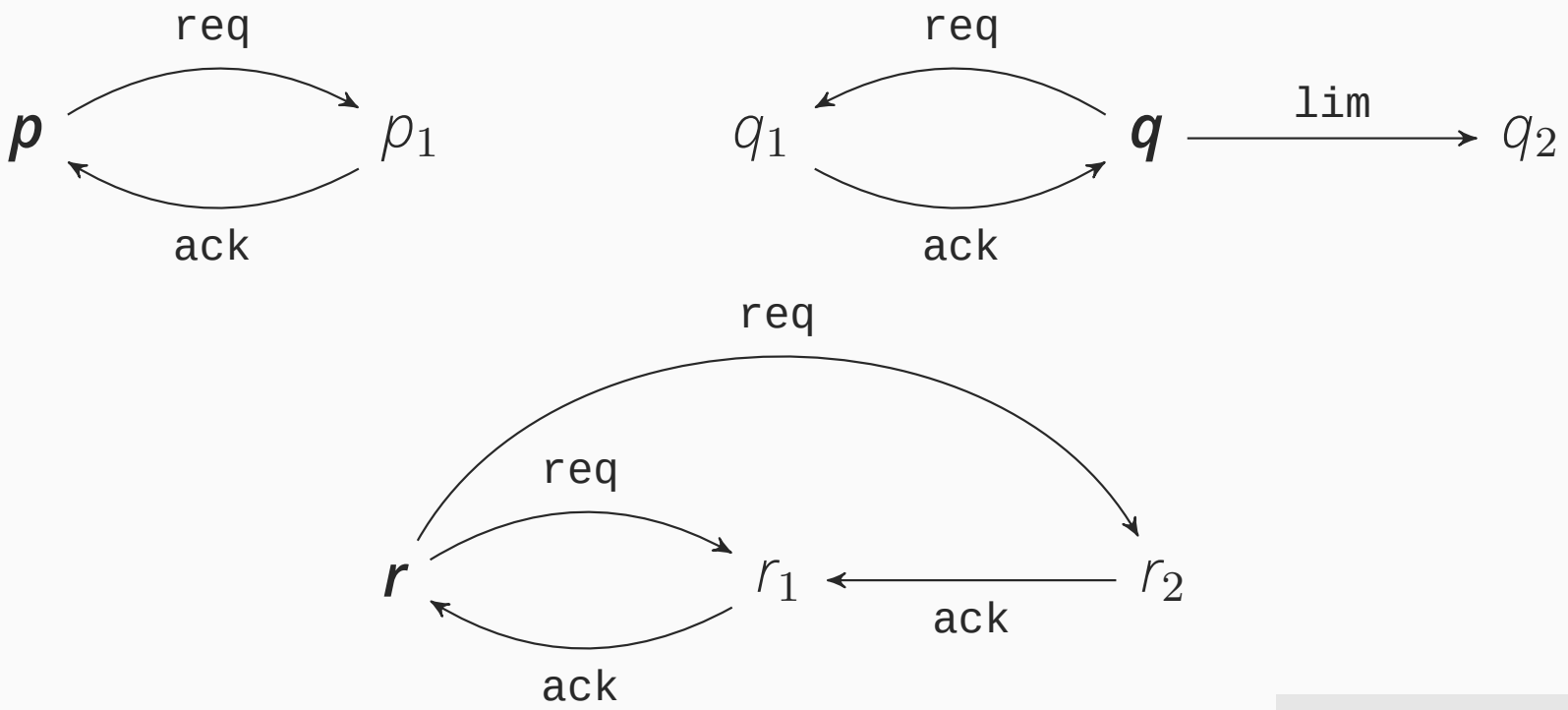

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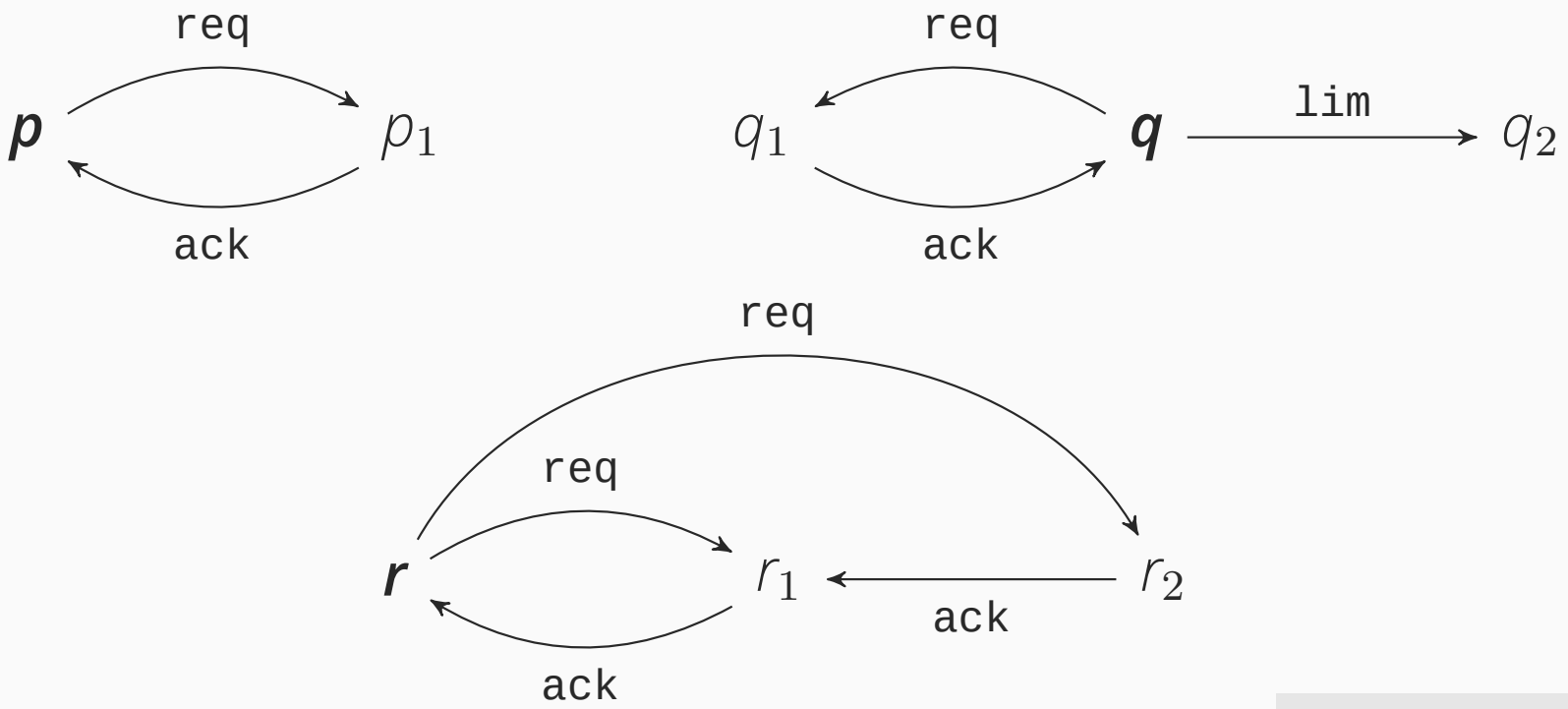

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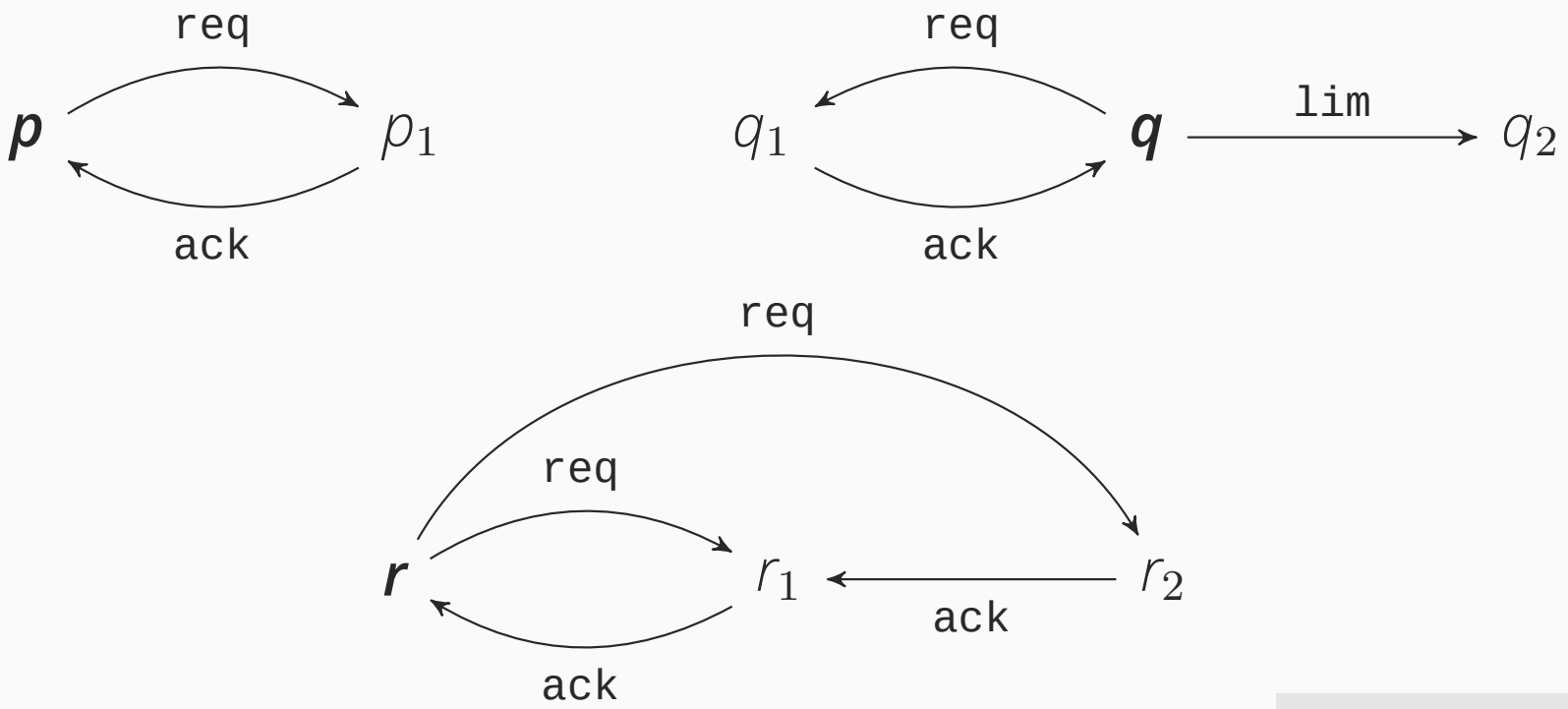

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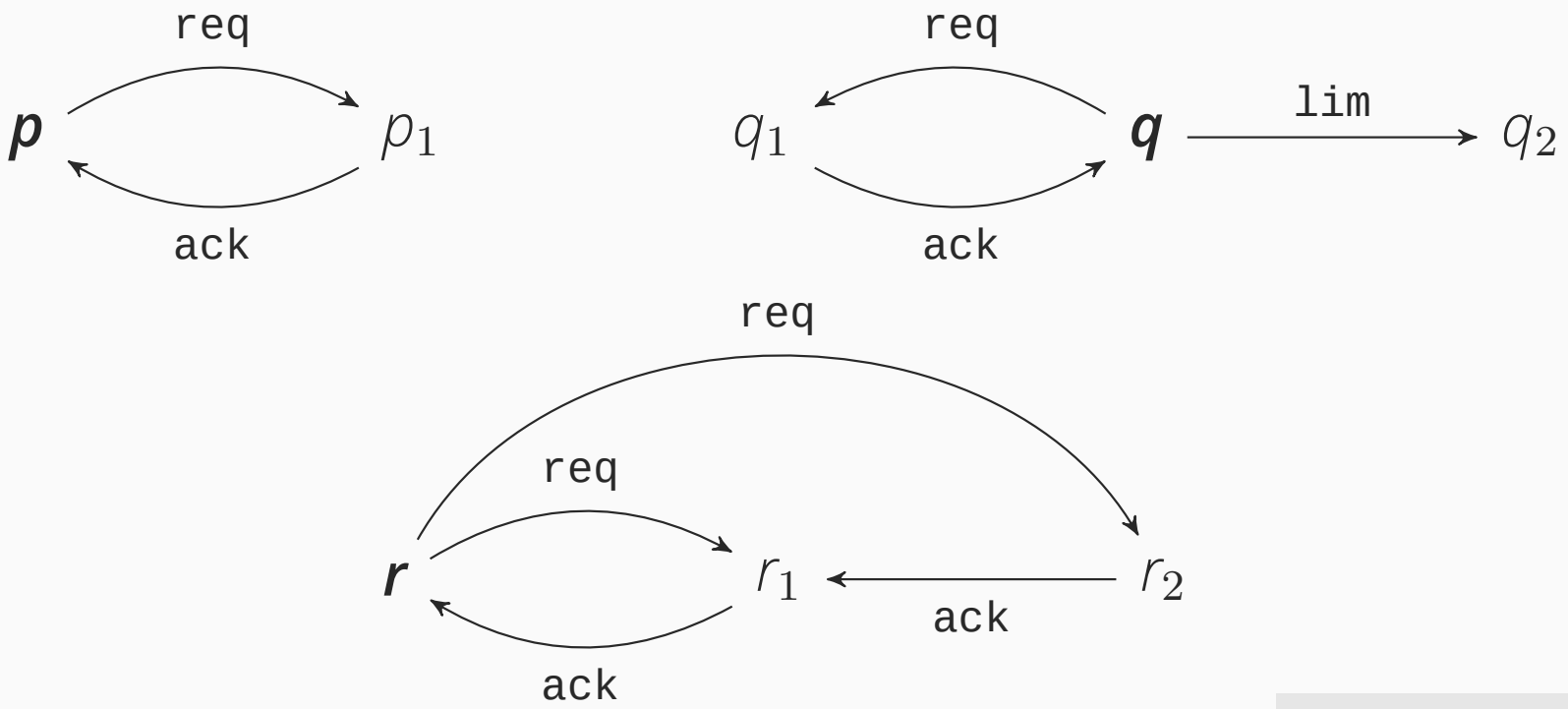

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$$\textbf{pos}(\varphi) \stackrel{\text{def}}{=} \varphi \vee \langle\text{Act}\rangle\varphi \vee \langle\text{Act}\rangle\langle\text{Act}\rangle\varphi \vee \ldots$$

The Logic

Definition (Modalities Over action Sets)

Assume $\text{Act} = \{\alpha_1, \ldots, \alpha_n\}$

$$[\text{Act}]\varphi \stackrel{\text{def}}{=} [\alpha_1]\varphi \wedge \ldots \wedge [\alpha_n]\varphi \qquad \langle\text{Act}\rangle\varphi \stackrel{\text{def}}{=} \langle\alpha_1\rangle\varphi \vee \ldots \vee \langle\alpha_n\rangle\varphi$$

Invariance and Possibility over Act

$$\textbf{inv}(\varphi) \stackrel{\text{def}}{=} (X = \varphi \wedge [\text{Act}]X)$$

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Invariance and Possibility over Act

$$\textbf{inv}(\varphi) \stackrel{\text{def}}{=} (X = \varphi \wedge [\text{Act}]X)$$

$$\textbf{pos}(\varphi) \stackrel{\text{def}}{=} (X = \varphi \vee \langle\text{Act}\rangle X)$$

Quiz

Fix Points in a tiny Nutshell

Solving recursive equations

- Consider the following equations over *Nat*:

Fix Points in a tiny Nutshell

Solving recursive equations

- Consider the following equations over *Nat*:
  - $x = 2 \times x$ has **one** solution $(x = 0)$

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  - $x = 1 + x$ has **???**

Fix Points in a tiny Nutshell

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  - $x = (\{1\} \cup x) \cap \{1\}$ has **one** solution ($x = \{1\}$)

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- Equations over 2^{Nat} (sets of integers)
  - $x = (\{1\} \cup x) \cap \{1\}$ has **one** solution ($x = \{1\}$)
  - $x = \{1\} \cap x$ has **two** solutions (**???**)

Fix Points in a tiny Nutshell

Solving recursive equations

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  - $x = 2 \times x$ has **one** solution ($x = 0$)
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  - $x = \{1\} \cap x$ has **two** solutions ($x = \{1\}$ and $x = \emptyset$)

FixPoints in a tiny Nutshell

Solving recursive equations

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  - $x = 2 \times x$ has **one** solution ($x = 0$)
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  - $x = \{1\} \cap x$ has **two** solutions ($x = \{1\}$ and $x = \emptyset$)
  - $x = \{1\} \cup x$ has **many** solutions (all N where $\{1\} \subseteq N$)

Fix Points in a tiny Nutshell

Solving recursive equations

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  - $x = 2 \times x$ has **one** solution ($x = 0$)
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- Equations over 2^{Nat} (sets of integers)
  - $x = (\{1\} \cup x) \cap \{1\}$ has **one** solution ($x = \{1\}$)
  - $x = \{1\} \cap x$ has **two** solutions ($x = \{1\}$ and $x = \emptyset$)
  - $x = \{1\} \cup x$ has **many** solutions (all N where $\{1\} \subseteq N$)
  - $x = Nat \setminus x$ has **no** solutions!

Fix Points in a tiny Nutshell

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- Formulas over Proc with one free variable can be seen as a **(monotonic) function** $2^{\text{Sys}} \mapsto 2^{\text{Sys}}$.

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For example $[\alpha]X$

Fix Points in a tiny Nutshell

- Formulas over Proc with one free variable can be seen as a **(monotonic) function** $2^{\text{Sys}} \mapsto 2^{\text{Sys}}$.
- $(2^{\text{Sys}}, \subseteq)$ forms a **complete lattice**.

FixPoints in a tiny Nutshell

- Formulas over Proc with one free variable can be seen as a **(monotonic) function** $2^{\text{Sys}} \mapsto 2^{\text{Sys}}$.
- $(2^{\text{Sys}}, \subseteq)$ forms a **complete lattice**.

Theorem (Tarski's Fixed-Point Theorem)

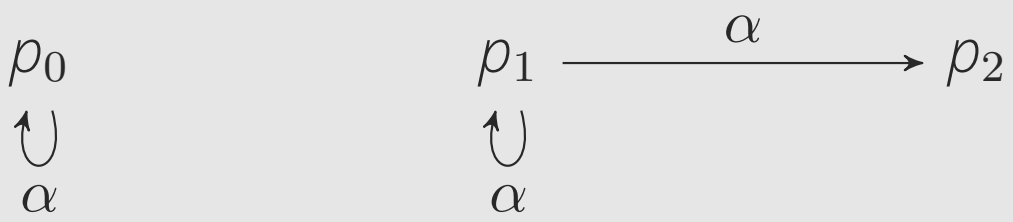
*Let $(D, \subseteq)$ be a complete lattice and $f :: D \mapsto D$ be a monotonic function. Then f has a **unique largest** fixpoint and a **unique smallest** fixpoints, given by:*

$$max \stackrel{def}{=} \bigcup \{x \in D \mid x \subseteq f(x)\}$$

$$min \stackrel{def}{=} \bigcap \{x \in D \mid f(x) \subseteq x\}$$

Simple Sample LTS

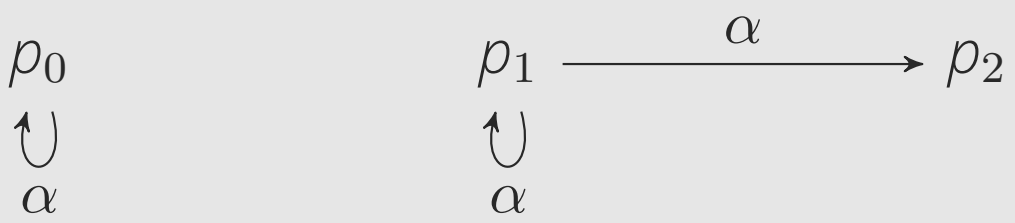
$$\left\langle \{p_0, p_1, p_2\},\ \{\alpha\},\ \left\{ p_0 \xrightarrow{\alpha} p_0, p_1 \xrightarrow{\alpha} p_1, p_1 \xrightarrow{\alpha} p_2 \right\} \right\rangle$$



Largest or Least?

Simple Sample LTS

$$\left\langle \{p_0, p_1, p_2\},\ \{\alpha\},\ \left\{ p_0 \xrightarrow{\alpha} p_0, p_1 \xrightarrow{\alpha} p_1, p_1 \xrightarrow{\alpha} p_2 \right\} \right\rangle$$

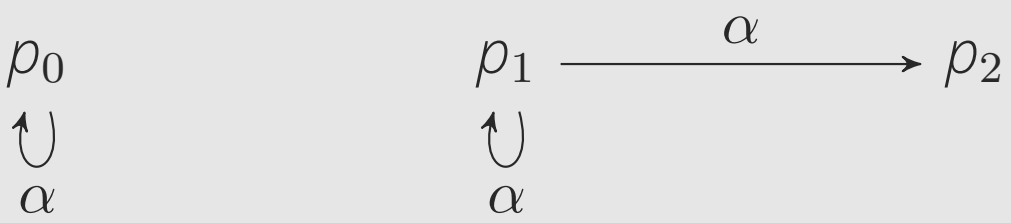


Largest or Least?

inv(φ) expressed as $\quad X = \varphi \wedge [\mathrm{Act}]X$

Simple Sample LTS

$$\left\langle \{p_0, p_1, p_2\},\ \{\alpha\},\ \left\{ p_0 \xrightarrow{\alpha} p_0, p_1 \xrightarrow{\alpha} p_1, p_1 \xrightarrow{\alpha} p_2 \right\} \right\rangle$$



Largest or Least?

inv($\langle\alpha\rangle$**tt**) where Act $= \{\alpha\}$ expressed as $X = \langle\alpha\rangle\mathbf{tt} \wedge [\alpha]X$

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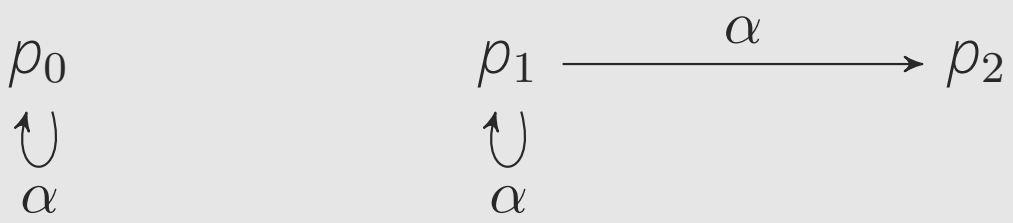
$$\left\langle \{p_0, p_1, p_2\},\ \{\alpha\},\ \left\{ p_0 \xrightarrow{\alpha} p_0, p_1 \xrightarrow{\alpha} p_1, p_1 \xrightarrow{\alpha} p_2 \right\} \right\rangle$$



Largest or Least?

inv($\langle\alpha\rangle$**tt**) where Act $= \{\alpha\}$ expressed as $X = \langle\alpha\rangle\mathbf{tt} \wedge [\alpha]X$

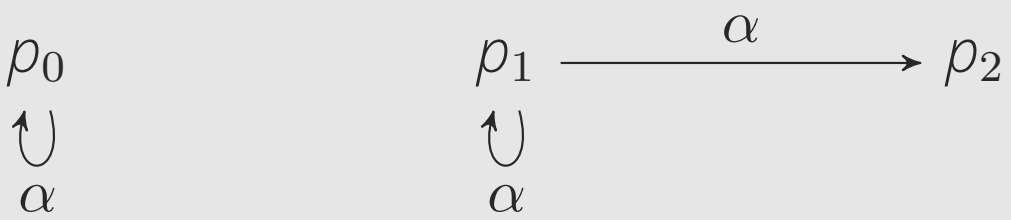
There are two solutions for X:

$$\emptyset \quad \text{or} \quad \{p_0\}$$

We want the **largest** one.

Simple Sample LTS

$$\left\langle \{p_0, p_1, p_2\},\ \{\alpha\},\ \left\{ p_0 \xrightarrow{\alpha} p_0, p_1 \xrightarrow{\alpha} p_1, p_1 \xrightarrow{\alpha} p_2 \right\} \right\rangle$$

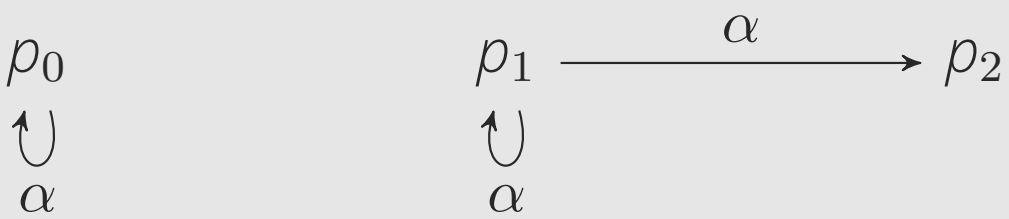


Largest or Least?

pos(φ) expressed as $\quad X = \varphi \ \vee \ \langle \mathrm{Act} \rangle X$

Simple Sample LTS

$$\left\langle \{p_0, p_1, p_2\},\ \{\alpha\},\ \left\{ p_0 \xrightarrow{\alpha} p_0, p_1 \xrightarrow{\alpha} p_1, p_1 \xrightarrow{\alpha} p_2 \right\} \right\rangle$$



Largest or Least?

pos($[\alpha]$**ff**) expressed as $\quad X = [\alpha]\mathbf{ff} \ \vee \ \langle\alpha\rangle X$

Simple Sample LTS

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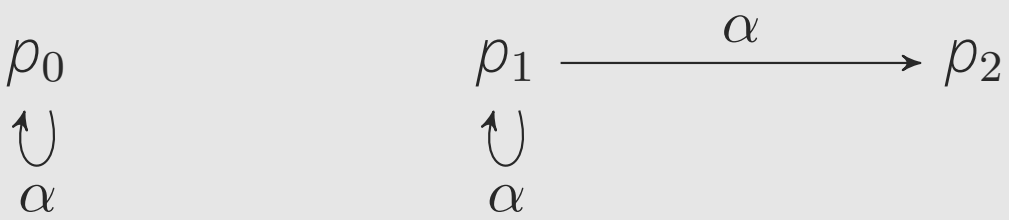


Largest or Least?

pos($[\alpha]$**ff**) expressed as $\quad X = [\alpha]\mathbf{ff} \ \vee \ \langle\alpha\rangle X$

There are two solutions for X:

$$\{p_1, p_2\} \quad \text{or} \quad \{p_0, p_1, p_2\}$$

We want the **least** one.

The Full Logic

Definition (Logic Syntax)

$$
\begin{array}{rlll}
\varphi, \phi \in \mu\text{HML} ::= & \mathbf{ff} & & \text{(falsity)} \\
| & \mathbf{tt} & & \text{(truth)} \\
| & \varphi \wedge \phi & & \text{(conjunction)} \\
| & \varphi \vee \phi & & \text{(disjunction)} \\
| & [\alpha]\varphi & & \text{(necessity)} \\
| & \langle\alpha\rangle\varphi & & \text{(possibility)} \\
| & \mathbf{max}X.\varphi & & \textbf{(maximal fixpoint)} \\
| & \mathbf{min}X.\varphi & & \textbf{(minimum fixpoint)} \\
| & X & & \textbf{(recursion variable)}
\end{array}
$$

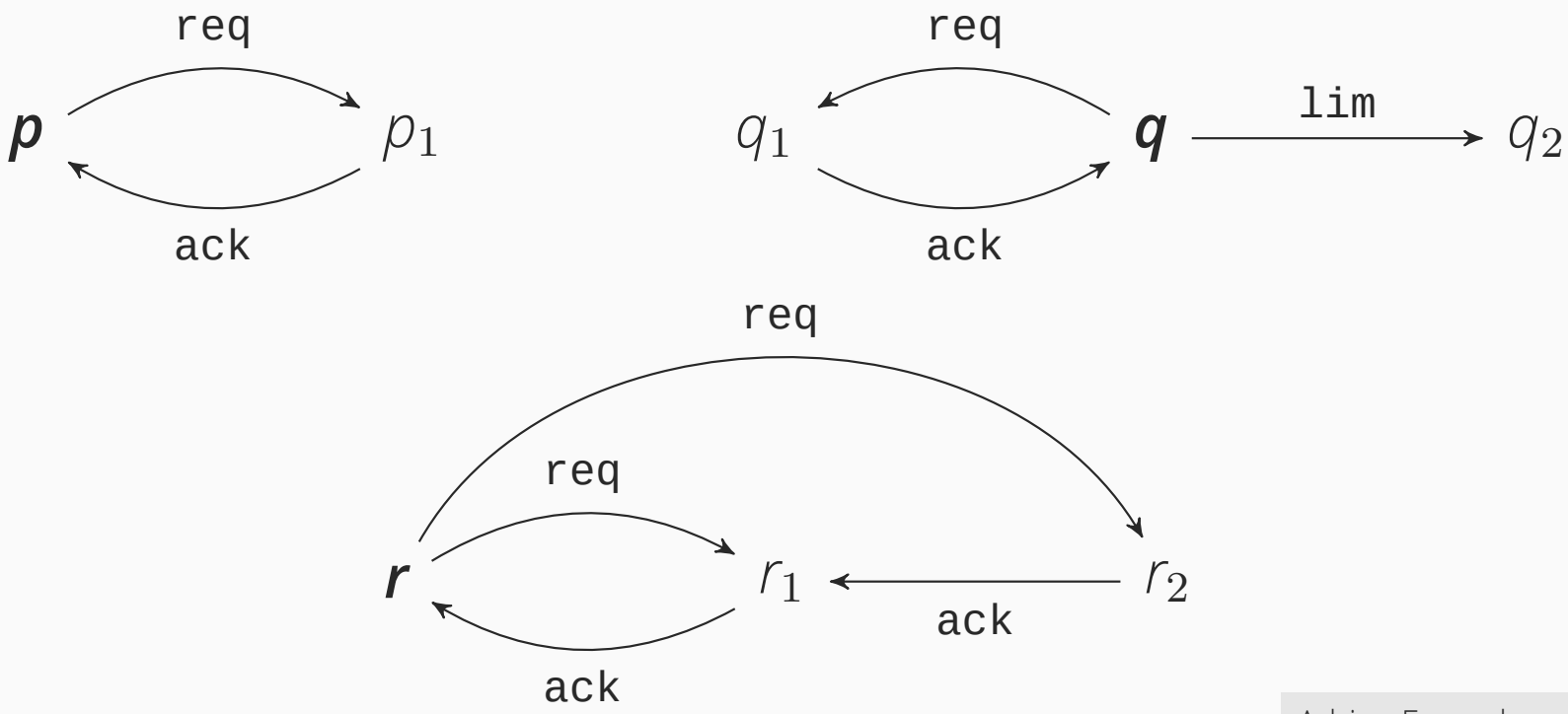
The Logic

Definition (Logic Semantics)

$$
\begin{aligned}
[\![\mathbf{ff}, \rho]\!] &\stackrel{\text{def}}{=} \emptyset \\
[\![\mathbf{tt}, \rho]\!] &\stackrel{\text{def}}{=} \mathrm{Sys} \\
[\![\varphi \wedge \phi, \rho]\!] &\stackrel{\text{def}}{=} [\![\varphi, \rho]\!] \cap [\![\phi, \rho]\!] \\
[\![\varphi \vee \phi, \rho]\!] &\stackrel{\text{def}}{=} [\![\varphi, \rho]\!] \cup [\![\phi, \rho]\!] \\
[\![[\alpha]\varphi, \rho]\!] &\stackrel{\text{def}}{=} \left\{ p \mid \forall p'.\ p \xrightarrow{\alpha} p' \text{ implies } p' \in [\![\varphi, \rho]\!] \right\} \\
[\![\langle\alpha\rangle\varphi, \rho]\!] &\stackrel{\text{def}}{=} \left\{ p \mid \exists p'.\ p \xrightarrow{\alpha} p' \text{ and } p' \in [\![\varphi, \rho]\!] \right\} \\
[\![\mathbf{max}\, X.\varphi, \rho]\!] &\stackrel{\text{def}}{=} \bigcup \{ S \mid S \subseteq [\![\varphi, \rho[X \mapsto S]]\!] \} \\
[\![\mathbf{min}\, X.\varphi, \rho]\!] &\stackrel{\text{def}}{=} \bigcap \{ S \mid [\![\varphi, \rho[X \mapsto S]]\!] \subseteq S \} \\
[\![X, \rho]\!] &\stackrel{\text{def}}{=} \rho(X)
\end{aligned}
$$

System Properties

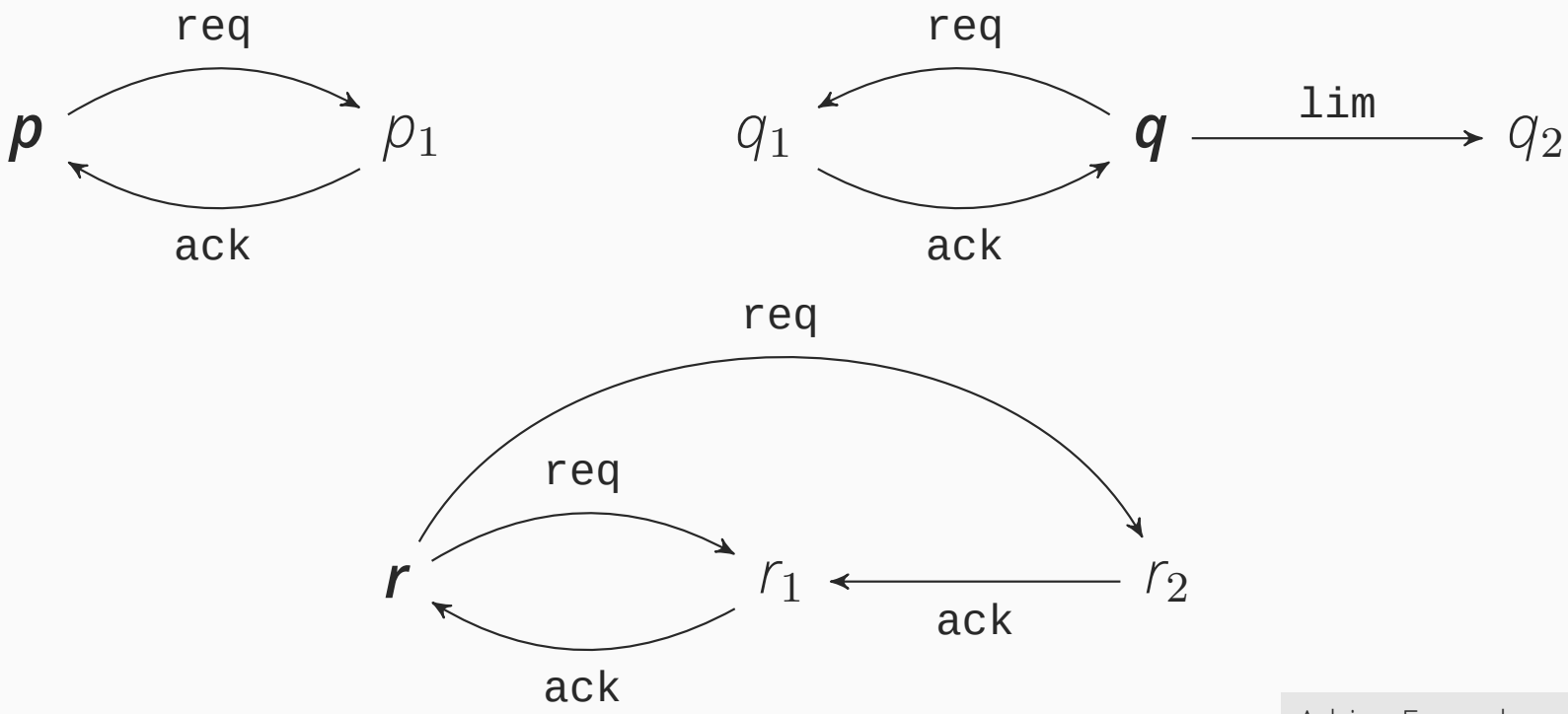
$$\mathbf{max}X.([\mathtt{req}]\,([\mathtt{ack}][\mathtt{ack}]\mathbf{ff} \wedge [\mathtt{ack}]X))$$



The Logic

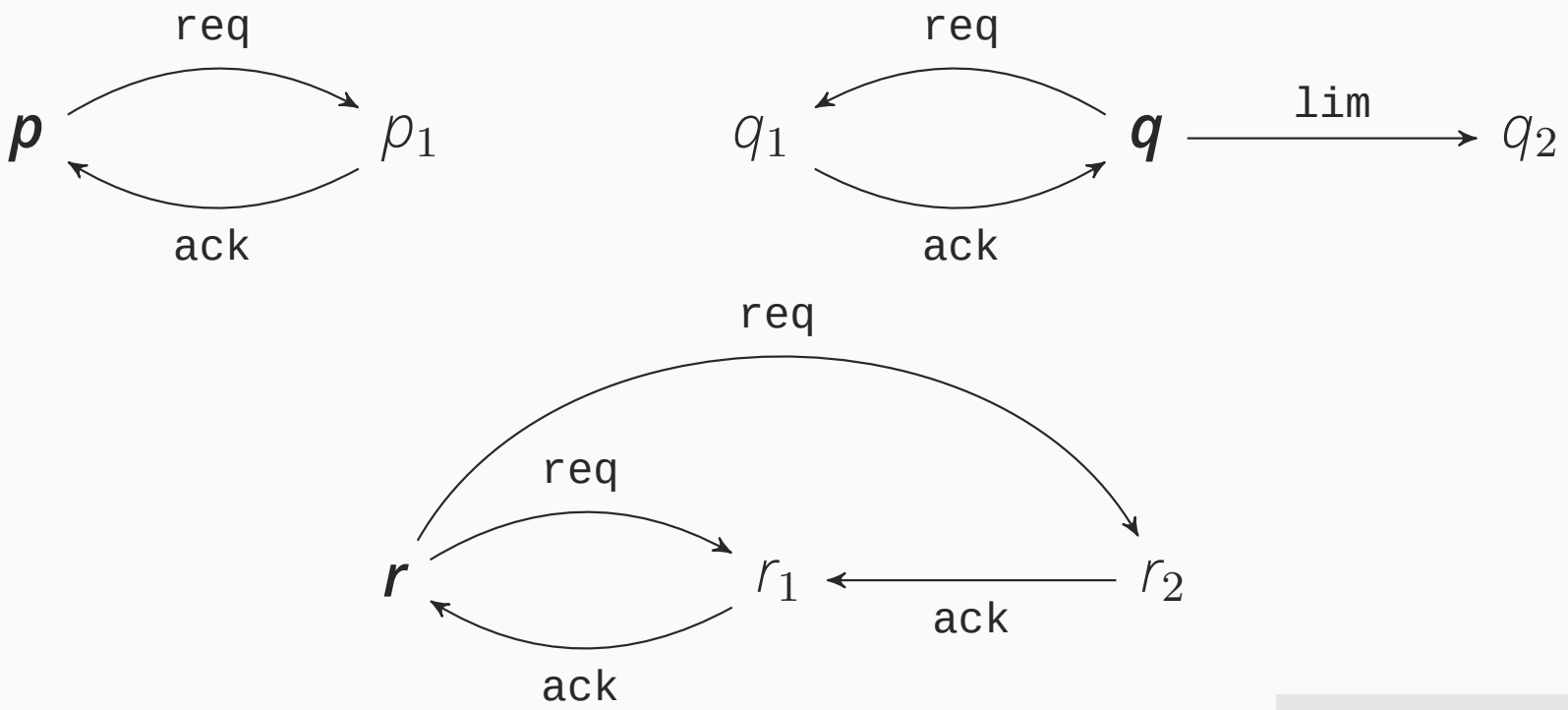
System Properties

$$p, q \in [\![\textbf{max} X.([\texttt{req}]\,([\texttt{ack}][\texttt{ack}]\textbf{ff} \wedge [\texttt{ack}]X))]\!]$$



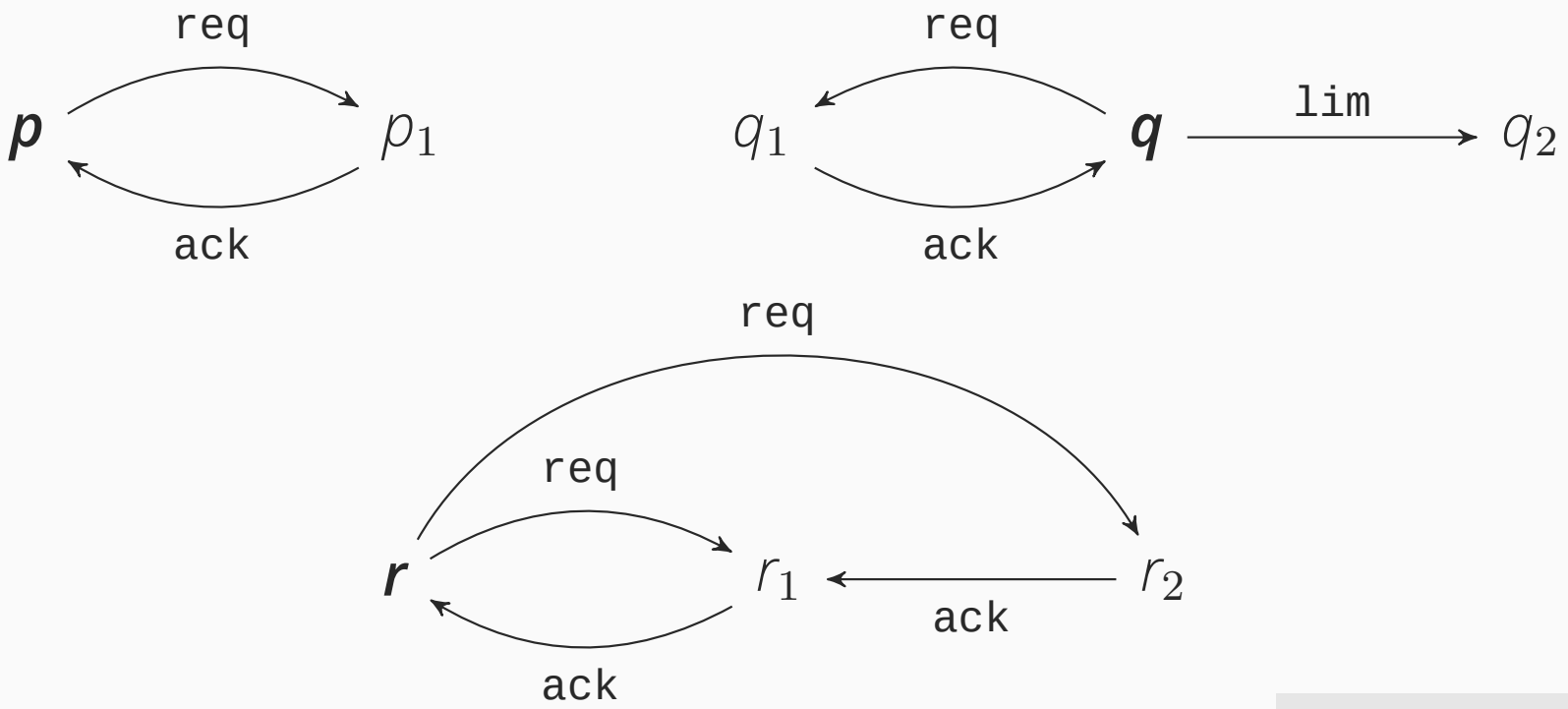
System Properties

$$\mathbf{min}\, X.(\langle \mathtt{lim} \rangle \mathbf{tt} \vee \langle \mathtt{req} \rangle \langle \mathtt{ack} \rangle X)$$



System Properties

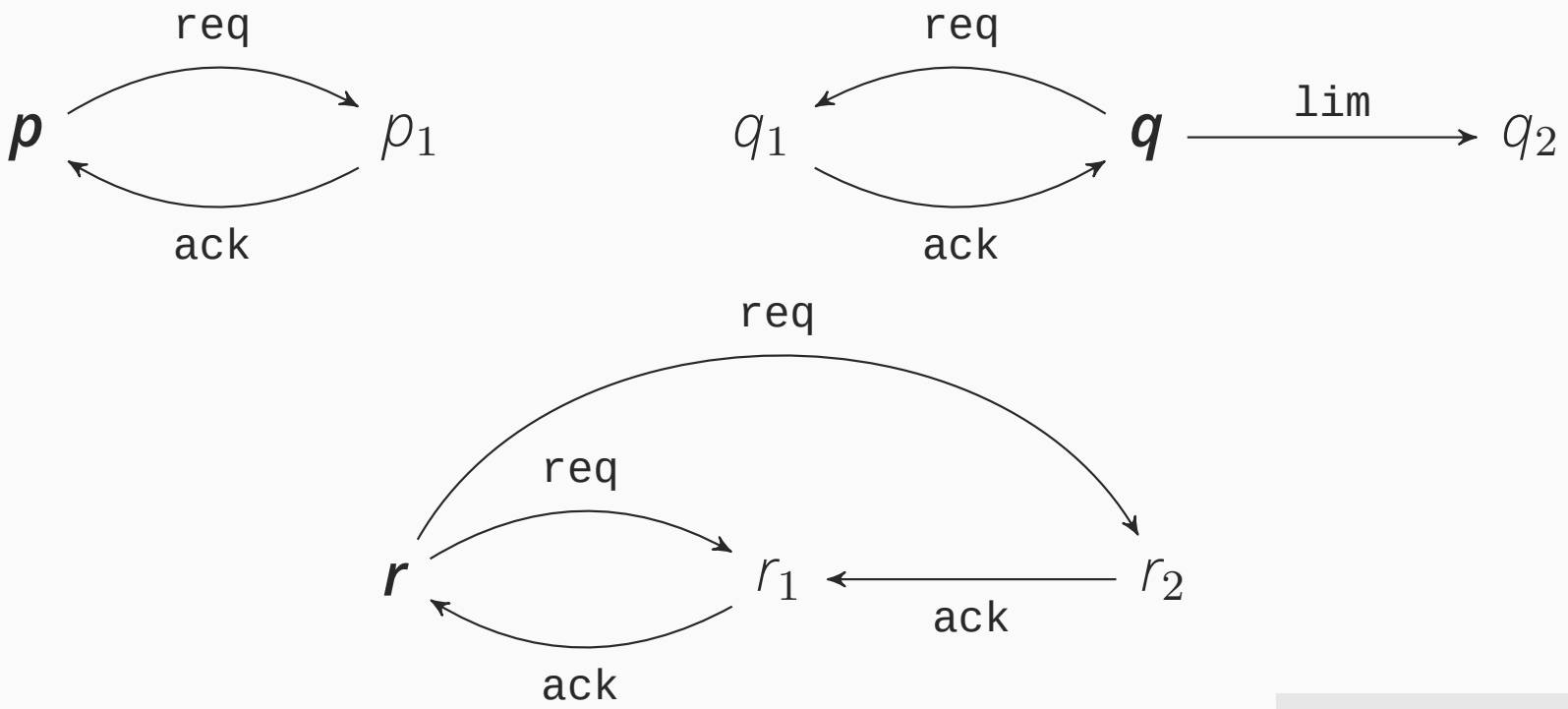
$$q \in [\![\mathbf{min} X.(\langle \mathtt{lim} \rangle \mathbf{tt} \vee \langle \mathtt{req} \rangle \langle \mathtt{ack} \rangle X)]\!]$$



Quiz

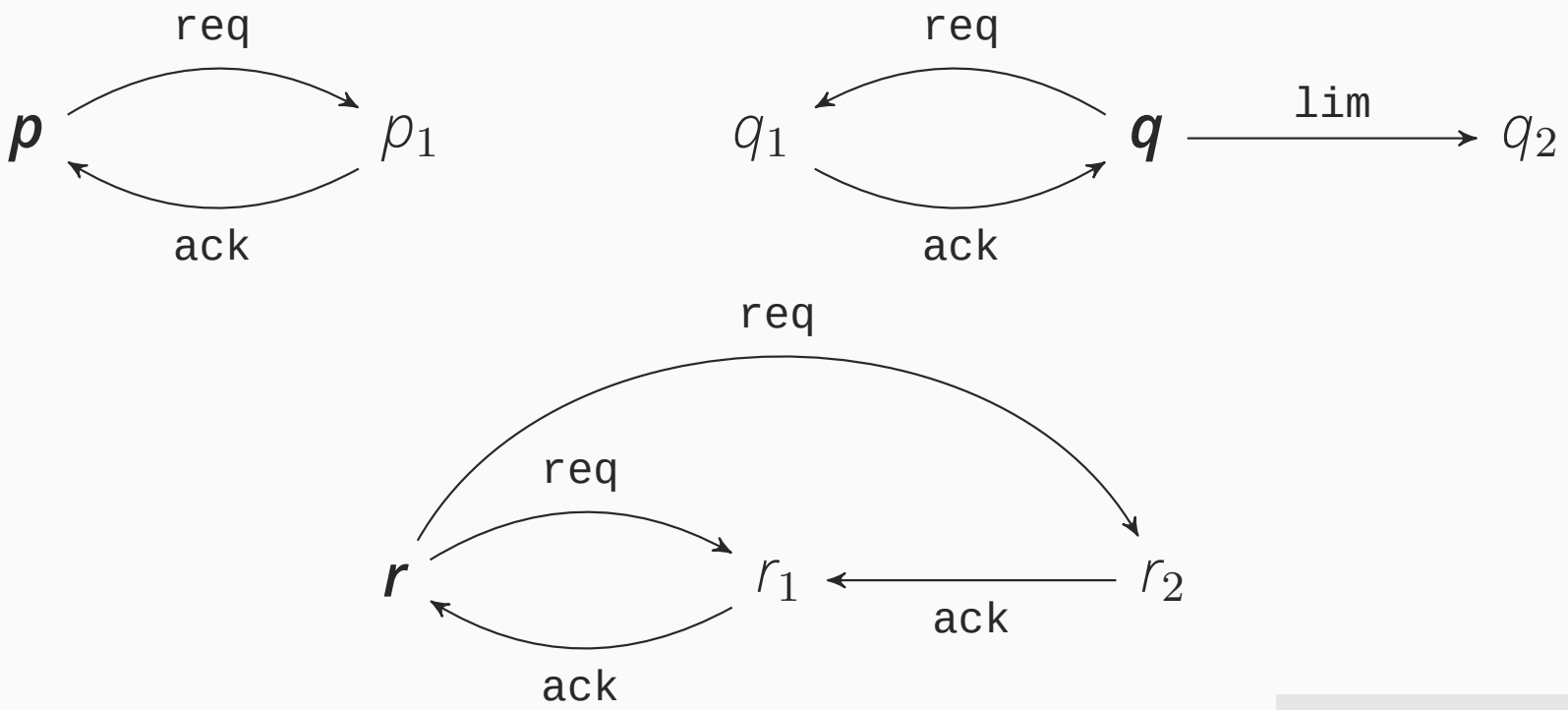
System Properties

$$q \in [\![\textbf{min} X.(\langle \texttt{lim} \rangle \textbf{tt} \vee \langle \texttt{req} \rangle \langle \texttt{ack} \rangle X)]\!]$$



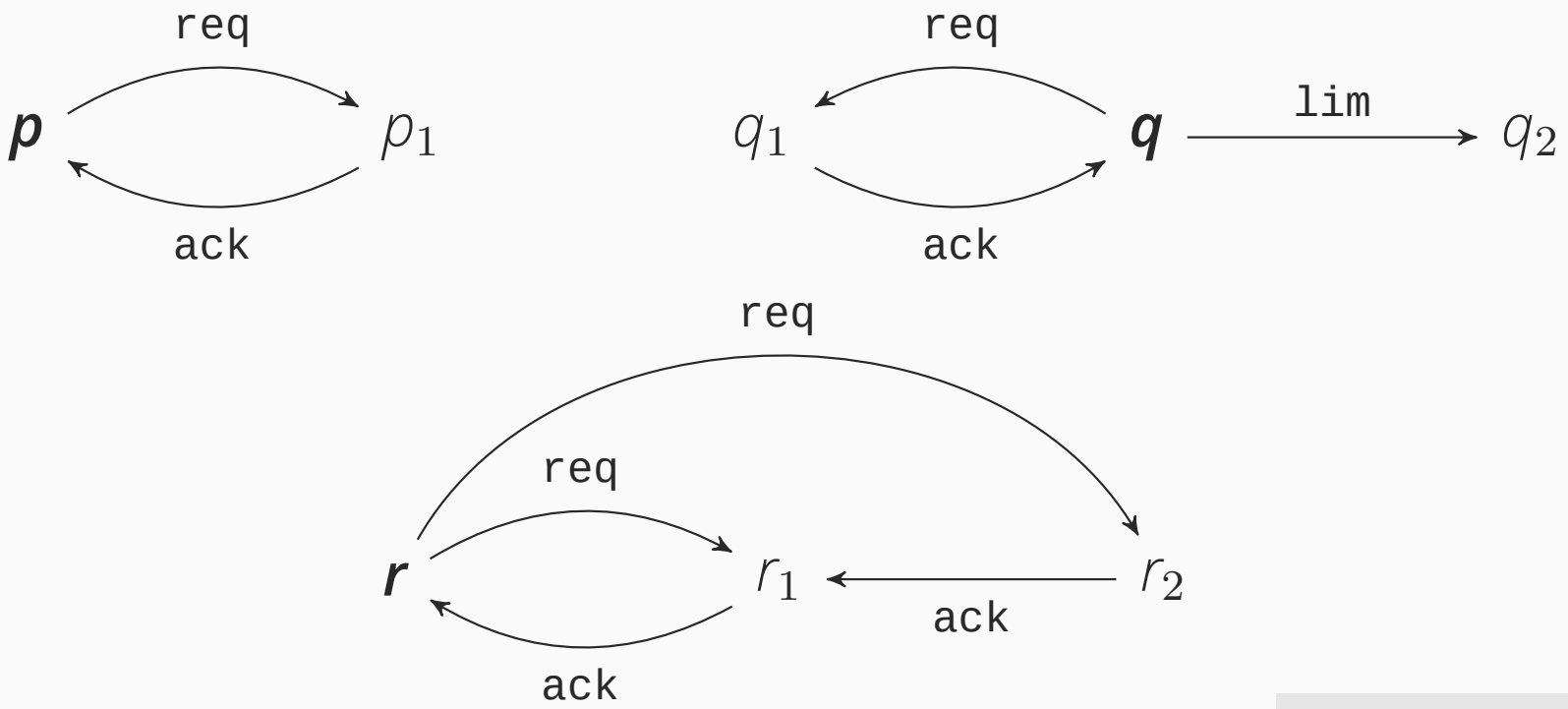
System Properties

$$??? \in [\![\mathbf{max} X.(\langle \texttt{lim} \rangle \mathbf{tt} \vee \langle \texttt{req} \rangle \langle \texttt{ack} \rangle X)]\!]$$



System Properties

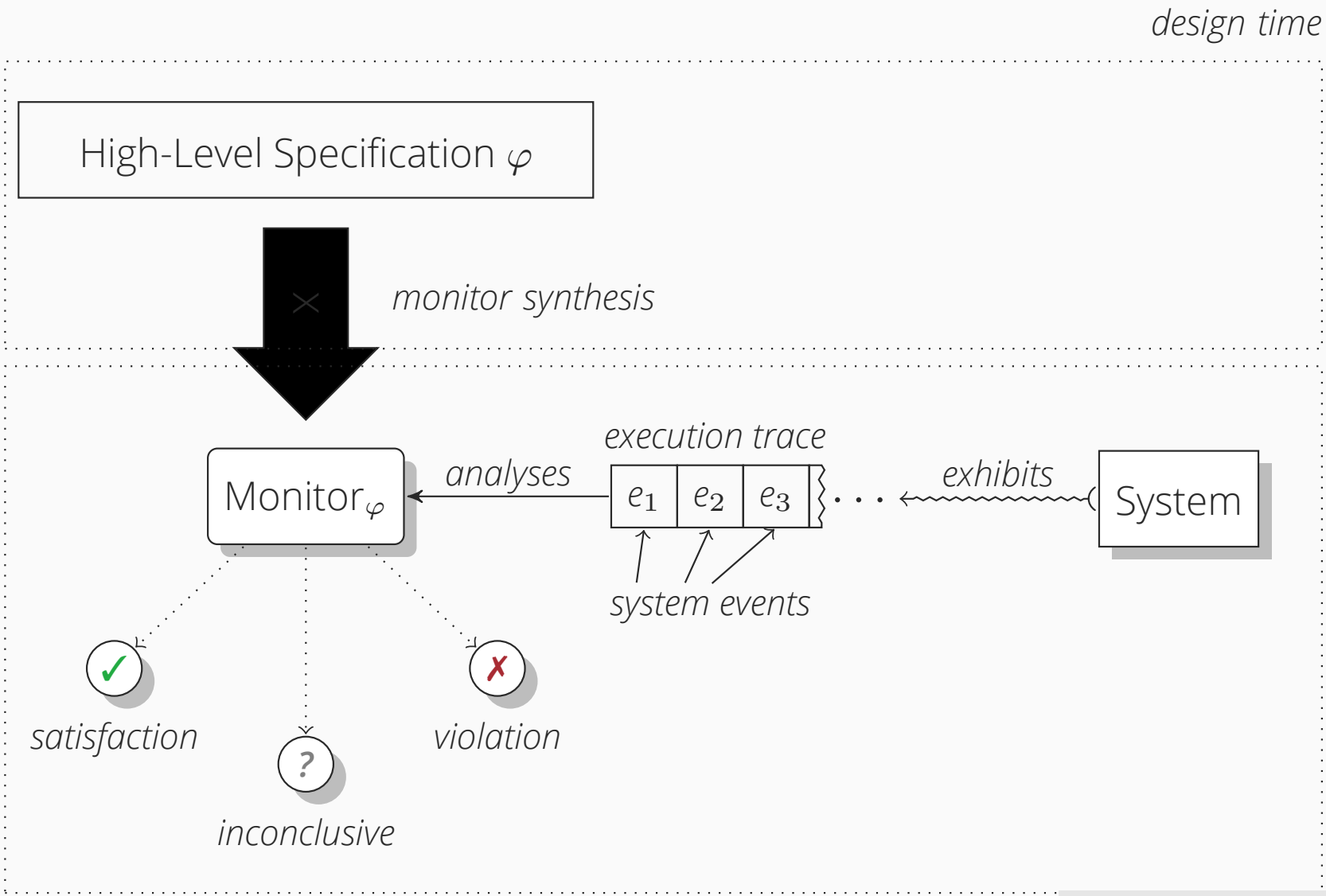
$$p, q, r \in [\![\, \mathbf{max} X.(\langle \mathtt{lim} \rangle \mathbf{tt} \vee \langle \mathtt{req} \rangle \langle \mathtt{ack} \rangle X) \,]\!]$$



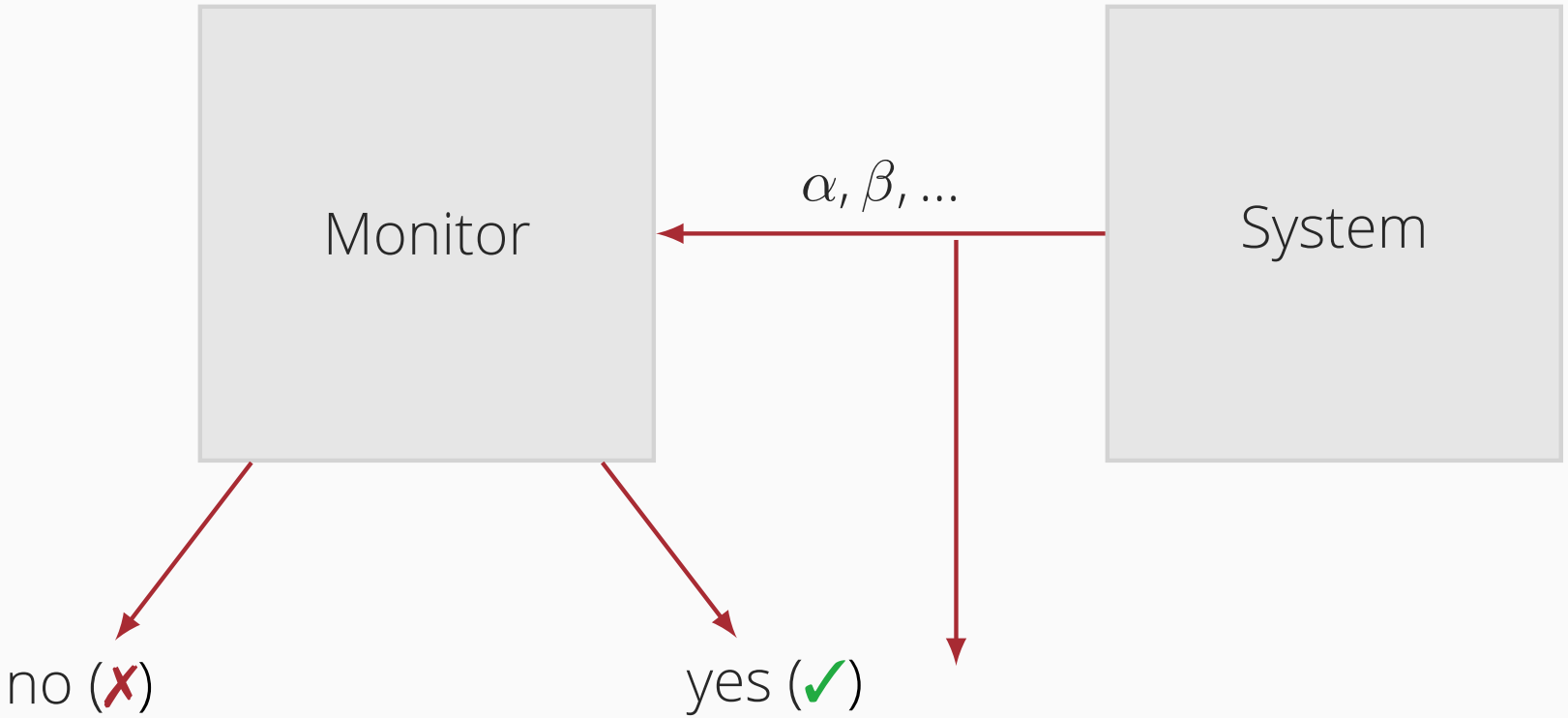
Monitors and Instrumentation

Adrian Francalanza ·

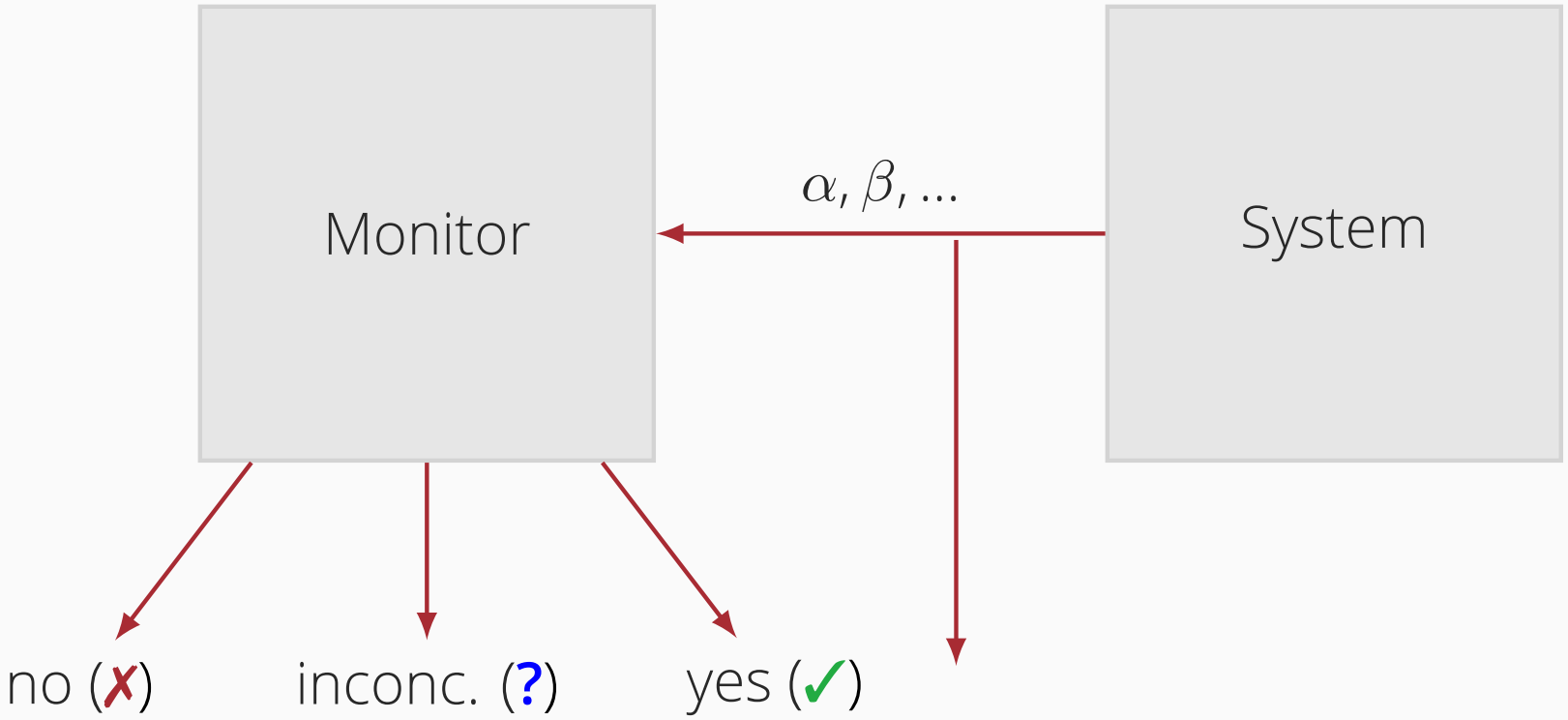
The General Approach



The Basic Setup



The Basic Setup



Monitors

Definition (Monitor Syntax)

$$
\begin{array}{rrllll}
m, n \in \text{Mon} & ::= & v & \mid \alpha.m & \mid m + n & \mid \textbf{rec}\, x.m \quad \mid x \\
v, u \in \text{Verd} & ::= & ? & \mid \times & \mid \checkmark &
\end{array}
$$

Monitors

Definition (Monitor Syntax)

$$m, n \in \text{Mon} ::= v \mid \alpha.m \mid m + n \mid \textbf{rec}\, x.m \mid x$$
$$v, u \in \text{Verd} ::= ? \mid ✗ \mid ✓$$

Monitor Descriptions

$$m_1 = (\texttt{req.ack.ack.}✗ + \texttt{lim.}✓)$$

$$m_2 = \textbf{rec}\, x.(\texttt{lim.}✗ + \texttt{req.ack.}x)$$

Monitors

Definition (Monitor Semantics)

$$\text{mAct}\ \frac{}{\alpha.m \xrightarrow{\alpha} m} \qquad \text{mRec}\ \frac{m[\mathbf{rec}\,x.m/x] \xrightarrow{\alpha} n}{\mathbf{rec}\,x.m \xrightarrow{\alpha} n}$$

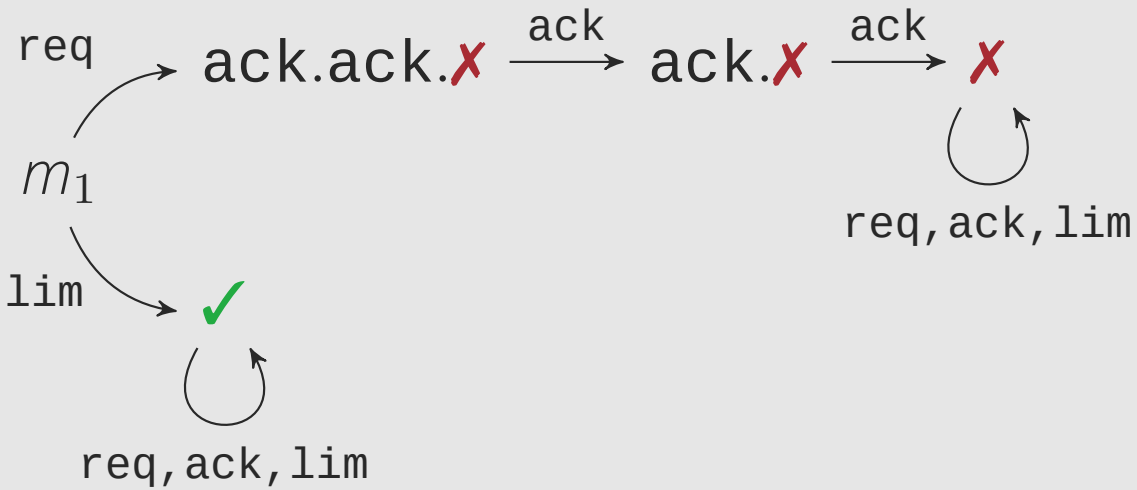
$$\text{mSelL}\ \frac{m \xrightarrow{\alpha} m'}{m + n \xrightarrow{\alpha} m'} \qquad \text{mSelR}\ \frac{n \xrightarrow{\alpha} n'}{m + n \xrightarrow{\alpha} n'}$$

$$\text{mVer}\ \frac{}{v \xrightarrow{\alpha} v}$$

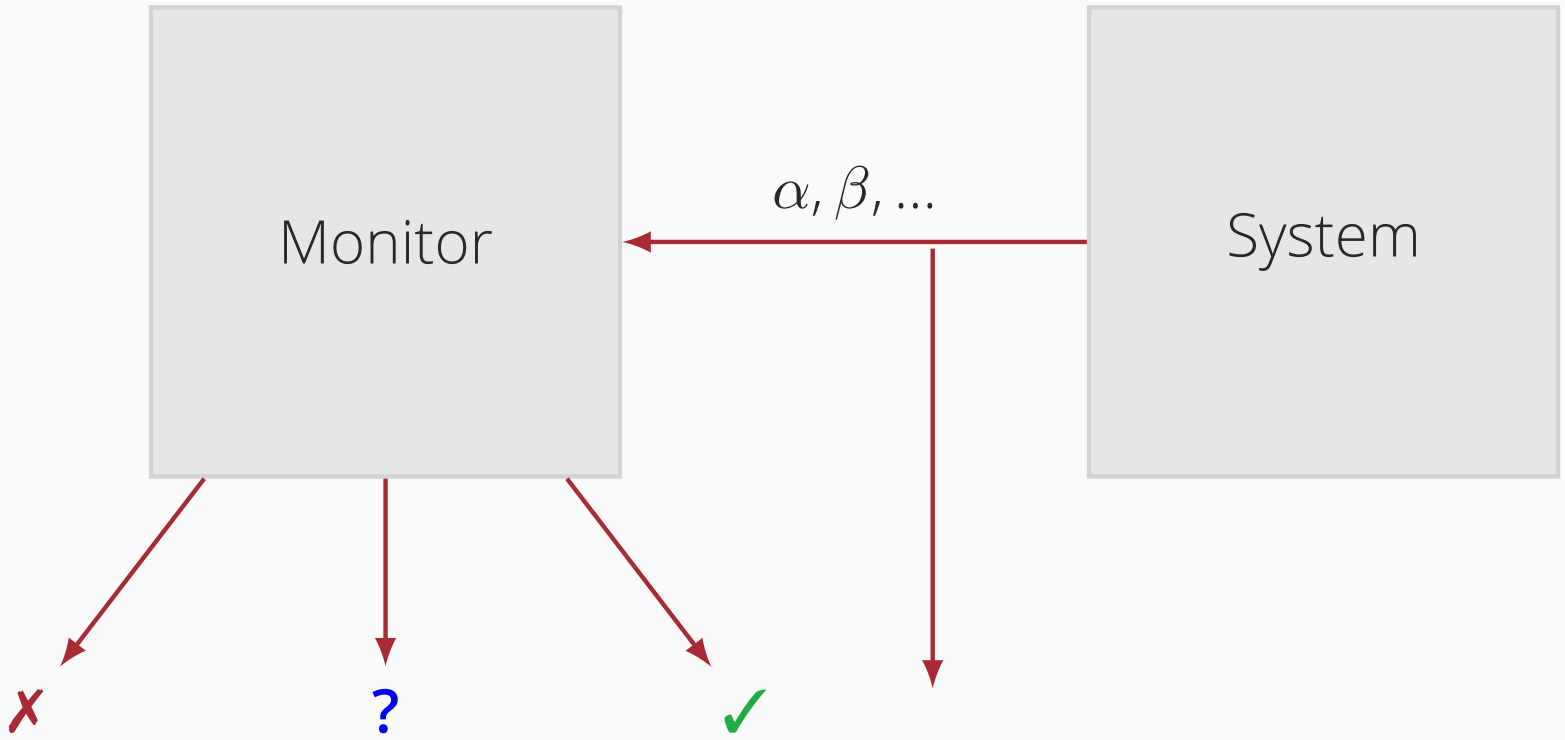
Monitors

From syntax to LTSs

$$m_1 = (\texttt{req.ack.ack.}\times + \texttt{lim.}\checkmark)$$



The Basic Setup



System Instrumentation

Definition (Instrumentation - Simple)

$$\text{Mon}\ \frac{p \xrightarrow{\alpha} p' \qquad m \xrightarrow{\alpha} m'}{m \triangleleft p \xrightarrow{\alpha} m' \triangleleft p'}$$

$$\text{Ter}\ \frac{p \xrightarrow{\alpha} p' \qquad m \not\xrightarrow{\alpha}}{m \triangleleft p \xrightarrow{\alpha} ? \triangleleft p'}$$

System Instrumentation

Definition (Instrumentation - Simple)

$$\text{Mon}\ \frac{p \xrightarrow{\alpha} p' \qquad m \xrightarrow{\alpha} m'}{m \triangleleft p \xrightarrow{\alpha} m' \triangleleft p'}$$

$$\text{Ter}\ \frac{p \xrightarrow{\alpha} p' \qquad m \not\xrightarrow{\alpha}}{m \triangleleft p \xrightarrow{\alpha} ? \triangleleft p'}$$

- The execution **trace** is consumed **incrementally**.
- The monitor is **passive** - the system drives the computation.

System Instrumentation

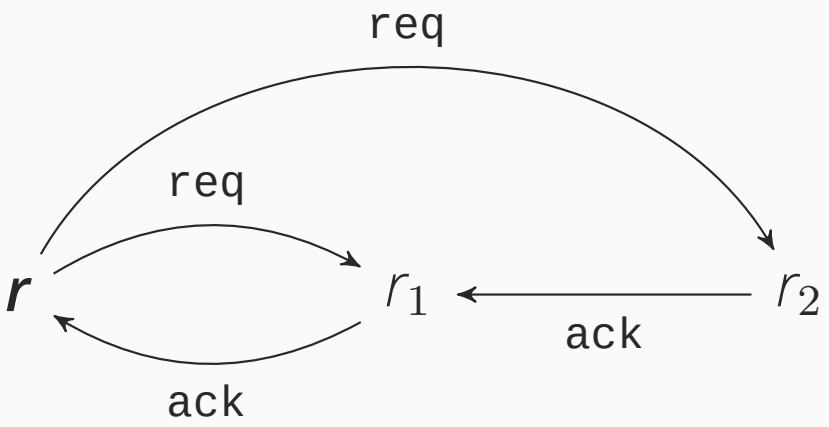
Definition (Instrumentation)

$$\text{Mon}\ \frac{p \xrightarrow{\alpha} p' \qquad m \xrightarrow{\alpha} m'}{m \triangleleft p \xrightarrow{\alpha} m' \triangleleft p'}$$

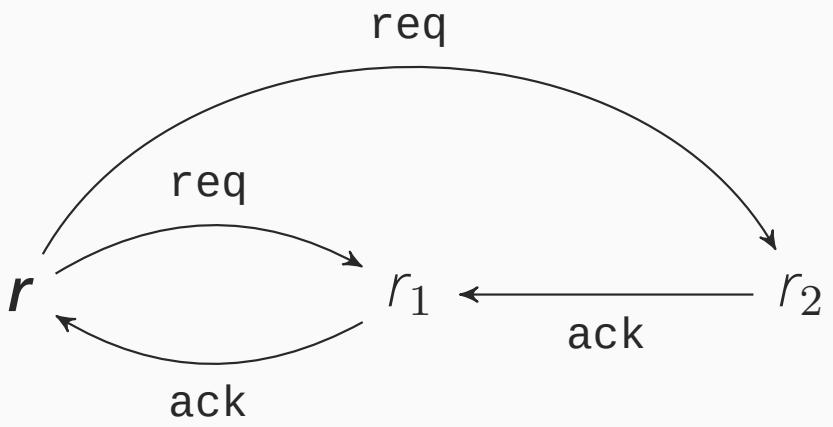
$$\text{Ter}\ \frac{p \xrightarrow{\alpha} p' \qquad m \not\xrightarrow{\alpha} \qquad m \not\xrightarrow{\tau}}{m \triangleleft p \xrightarrow{\alpha} ? \triangleleft p'}$$

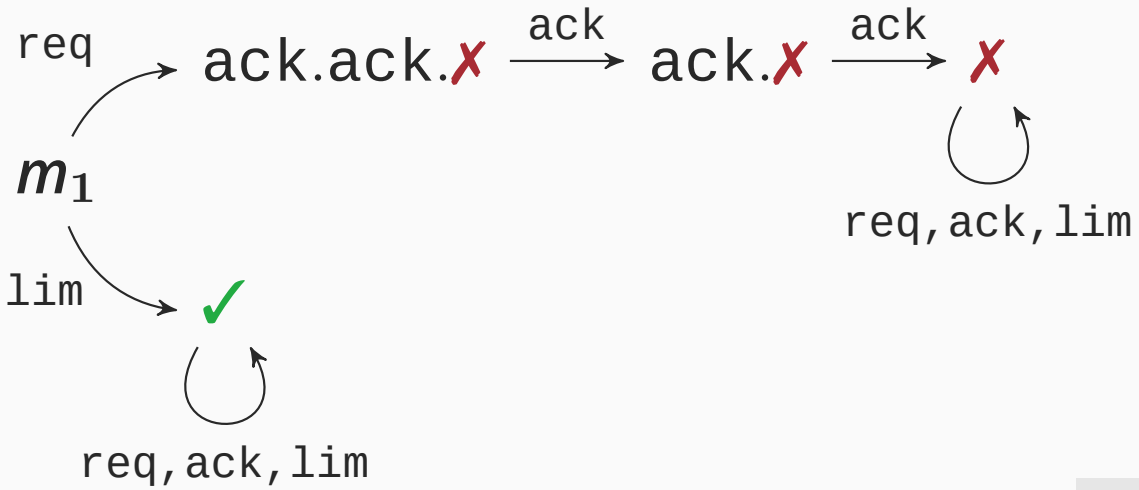
$$\text{AsS}\ \frac{p \xrightarrow{\tau} p'}{m \triangleleft p \xrightarrow{\tau} m \triangleleft p'} \qquad \text{AsM}\ \frac{m \xrightarrow{\tau} m'}{m \triangleleft p \xrightarrow{\tau} m' \triangleleft p}$$

System Instrumentation

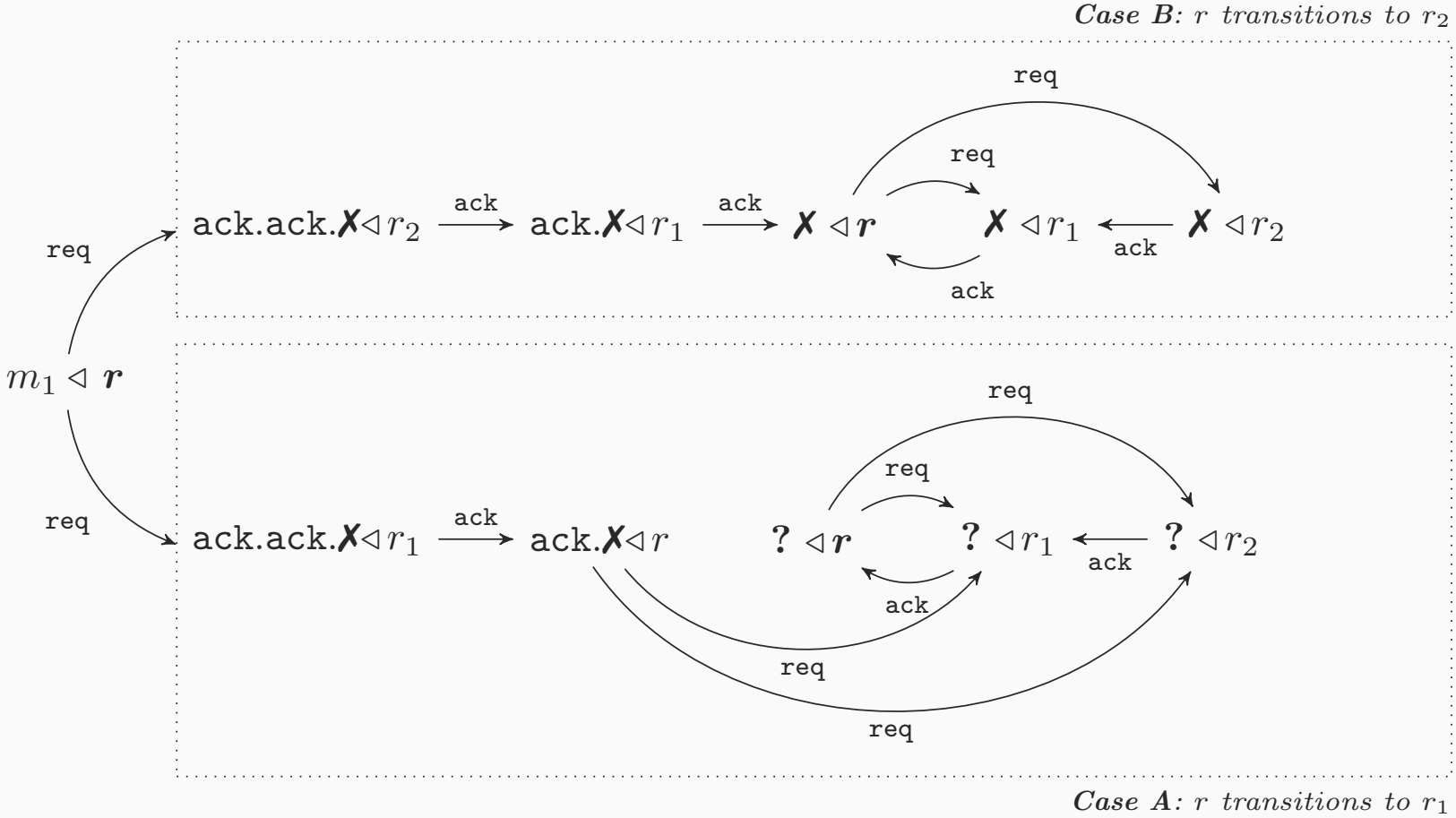


System Instrumentation



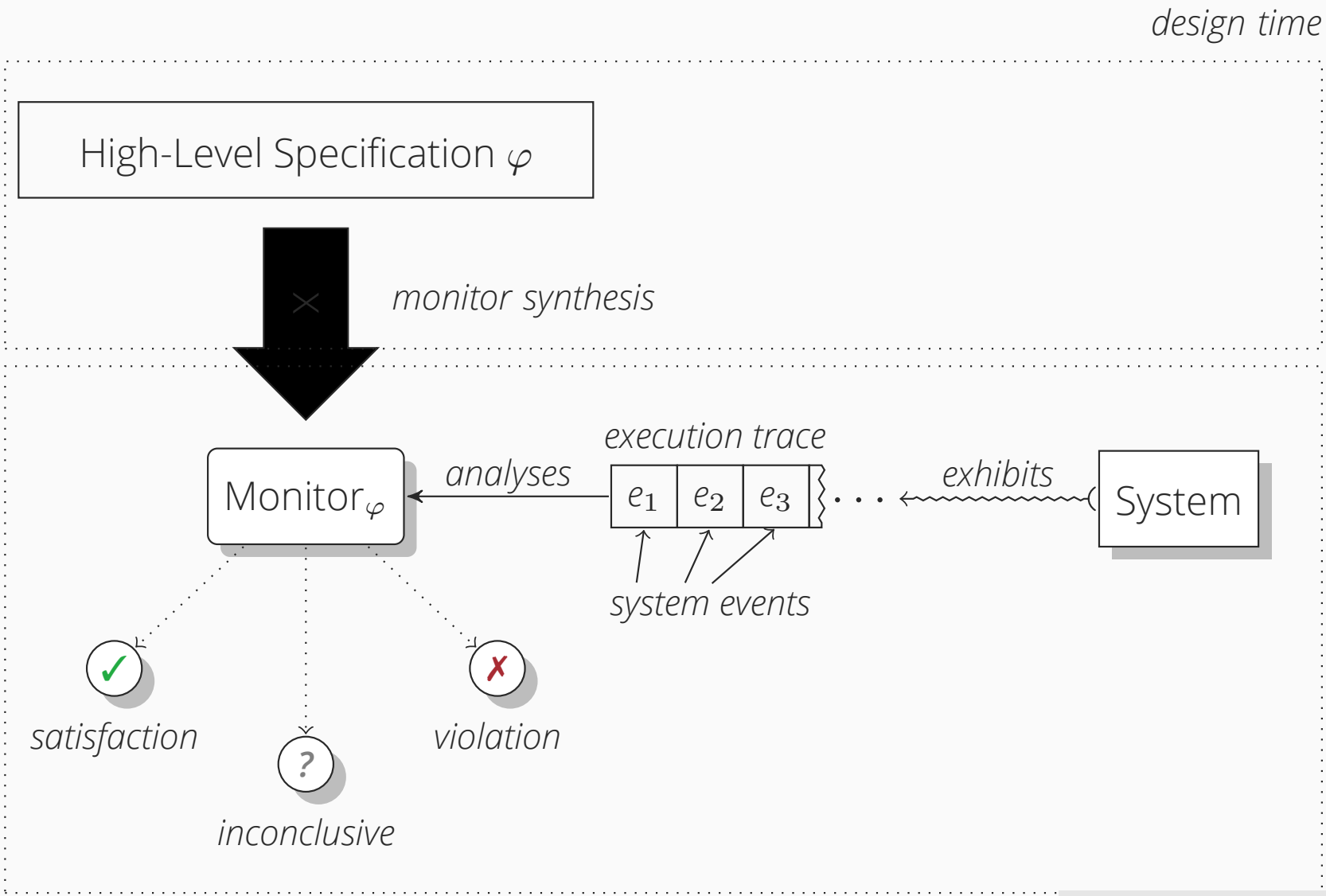


System Instrumentation



Monitorability

The General Approach



Verdicts Vs Satisfactions and Violations

Logic

Monitoring

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Logic

$p \in [\![\varphi]\!]$
$p \notin [\![\varphi]\!]$

Monitoring

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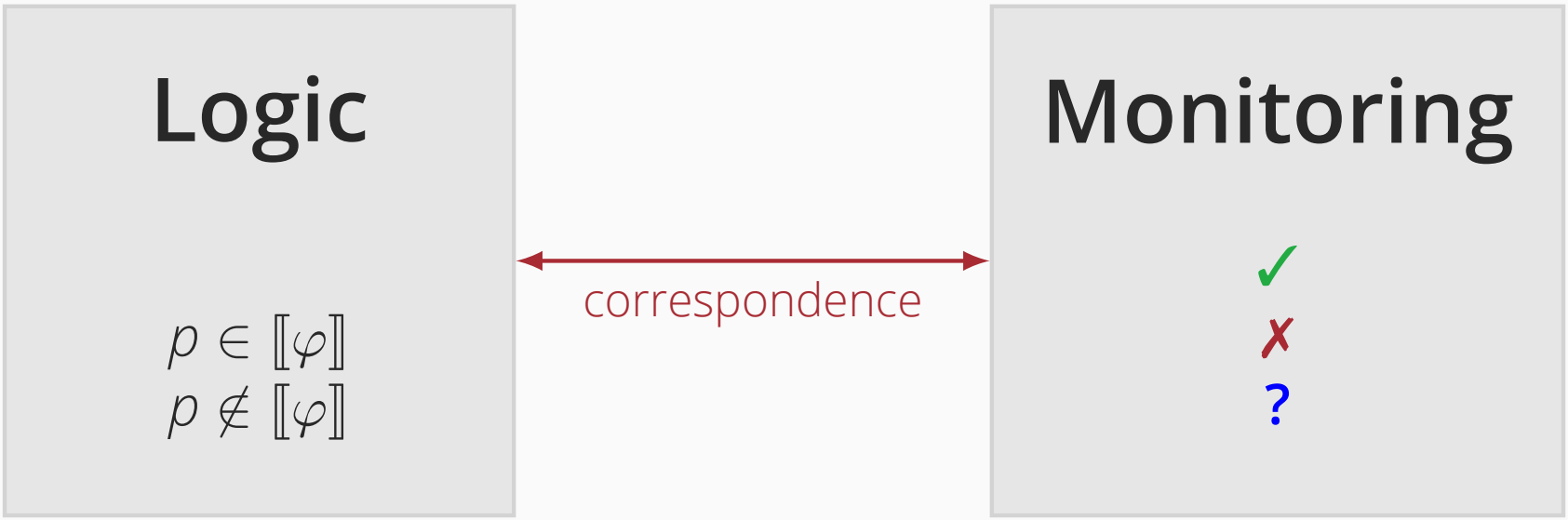
Monitoring

✓
✗
?

Verdicts Vs Satisfactions and Violations



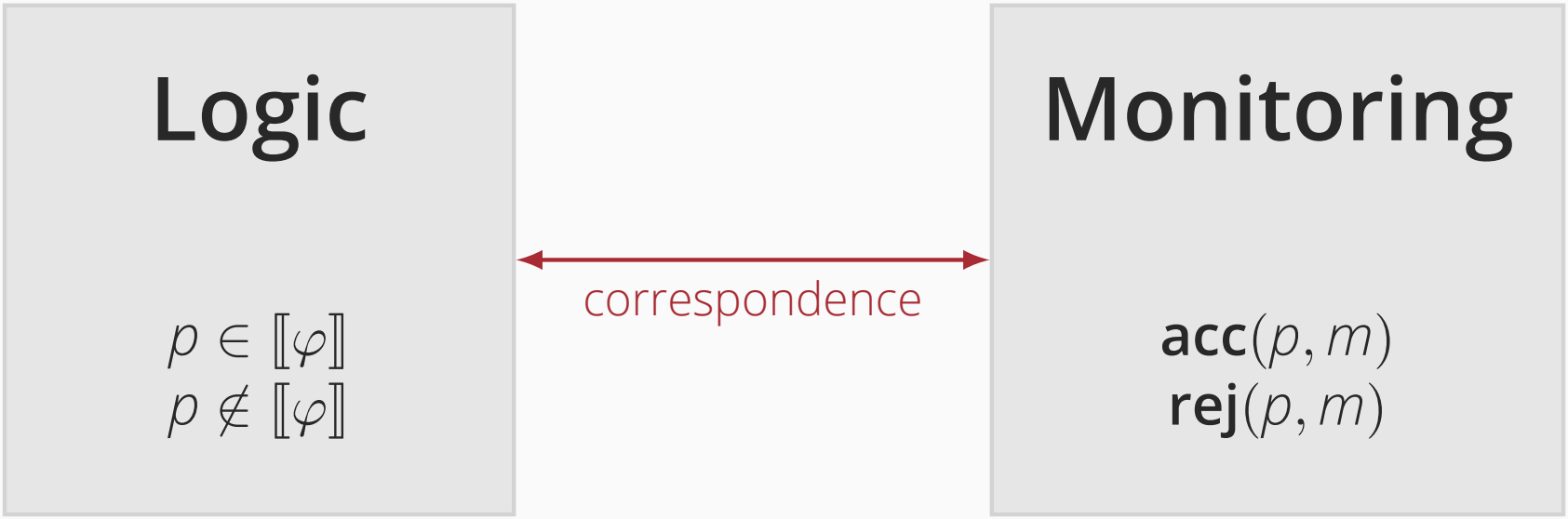
Monitoring Verdicts

Definition (Acceptances and Rejections)

$$\mathbf{acc}(p, m) \stackrel{\text{def}}{=} \exists t, p' \quad \text{such that} \quad m \triangleleft p \stackrel{t}{\Rightarrow} \checkmark \triangleleft p'$$

$$\mathbf{rej}(p, m) \stackrel{\text{def}}{=} \exists t, p' \quad \text{such that} \quad m \triangleleft p \stackrel{t}{\Rightarrow} \times \triangleleft p'$$

Verdicts Vs Satisfactions and Violations



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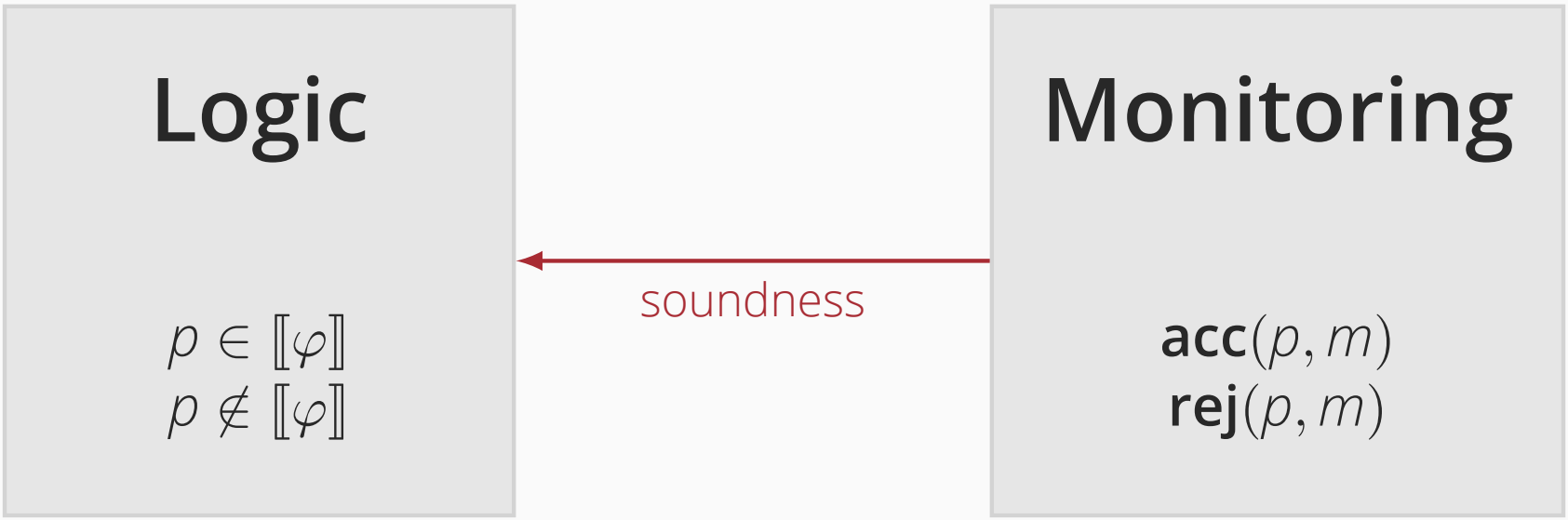

Soundness

Definition (Sound Monitoring)

Monitor m **soundly** monitors for the property φ, denoted as **smon**(m, φ), whenever for **every** system $p \in \mathrm{Sys}$ we have:

- **acc**(p, m) implies $p \in [\![\varphi]\!]$
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Sound Monitors

- $\alpha.$✗ soundly monitors for $[\alpha]\mathbf{ff}$.
- $\alpha.$✓ $+ \beta.$✓ soundly monitors for $\langle\alpha\rangle\mathbf{tt} \vee \langle\beta\rangle\mathbf{tt}$.
- $\alpha.$✗ soundly monitors for $\mathbf{max}\, X.([\alpha]\mathbf{ff} \wedge [\beta]X)$.
- $\mathbf{rec}\, x.(\alpha.$✗ $+ \beta.x)$ soundly monitors for $\mathbf{max}\, X.([\alpha]\mathbf{ff} \wedge [\beta]X)$.

Quiz

Soundness Further Examples

Sound or Unsound?

① $\alpha.\checkmark$??? $[\alpha]\mathbf{ff}.$

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① α.✓ **unsoundly** monitors for $[\alpha]$**ff**.

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Sound Monitors and Inconsistent Verdicts

Definition

- $\textbf{sound}(m) \stackrel{\text{def}}{=} \exists \varphi \cdot \text{smon}(m, \varphi)$
- $\textbf{incons}(m) \stackrel{\text{def}}{=} \exists p \cdot \textbf{acc}(p, m)$ and $\textbf{rej}(p, m)$.

Theorem

sound(m) *implies* $\neg$***incons***(m)

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Proof.

sound(m)	$\Rightarrow \exists \varphi \cdot \text{smon}(m, \varphi)$
Assume $p \in [\![\varphi]\!]$	
Semantics of $[\![\varphi]\!]$	$\Rightarrow \neg(p \notin [\![\varphi]\!])$
smon$(m, \varphi)$and Contrap.	$\Rightarrow \neg(\textbf{rej}(p, m))$

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Soundness is Weak

- Monitor α.✗ soundly monitors for $[\alpha]\textbf{ff} \wedge [\beta]\textbf{ff}$.
- Monitor **?** soundly monitors for every $\varphi \in \mu\text{HML}$ but it is *not* very useful!

Verdicts Vs Satisfactions and Violations

Completeness Predicates

Definition (Satifaction and Violation Complete)

$$\text{scmon}(m, \varphi) \stackrel{\text{def}}{=} \forall p.\, p \in [\![\varphi]\!] \quad \text{implies} \quad \textbf{acc}(p, m)$$

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!!No sound **and** satisfaction-complete monitor for $[\alpha]\mathbf{ff}$ either!!

Runtime Verification Mantra

Half a loaf is better than no bread

(Something is always *better than nothing)*

Monitor-Formula Correspondence (Correctness)

Definition (Partial-Completeness)

A monitor m monitors for formula φ in a **partially-complete** manner, denoted as **cmon**(m, φ), when either scmon(m, φ) **or** vcmon(m, φ) holds.

Definition (Correct Monitors)

A monitor m is said to **monitor for** a formula φ (correctly), denoted as mon(m, φ), if it can do it **soundly**, and in a **partially-complete** manner:

$$\textbf{mon}(m, \varphi) \stackrel{\text{def}}{=} \text{smon}(m, \varphi) \text{ and } \text{cmon}(m, \varphi)$$

Quiz

Monitors For Examples

Does it monitor for it?

1. α.✗ **monitors for** $[\alpha]$**ff**.
2. α.✓ **monitors for** $\langle\alpha\rangle$**tt**.

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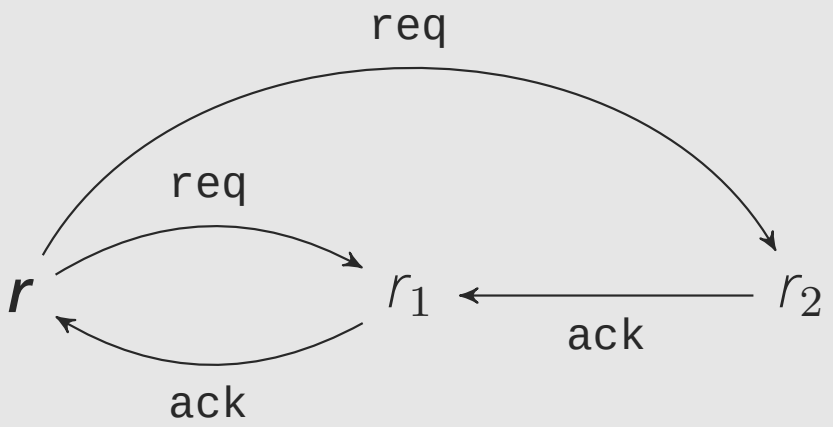
- A **set of formulae** $\mathcal{L} \subseteq \mu\text{HML}$ is monitorable iff **every** formula in the set, $\varphi \in \mathcal{L}$, is monitorable.

Showing that a (sub)logic $\mathcal{L}$ is monitorable requires two universal quantifications:

1. Over all $\varphi \in \mathcal{L}$.
2. Over all $p \in [\![\varphi]\!]$.

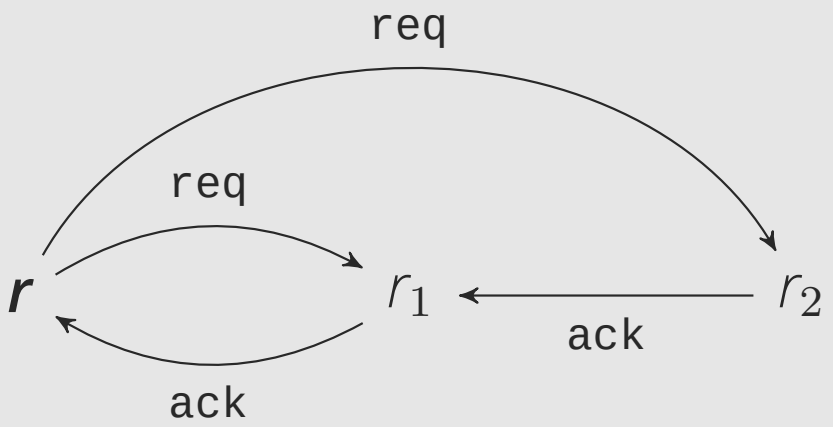
Quiz

Monitorable and Non-monitorable Formulas



$\langle \mathtt{req} \rangle \mathbf{tt}$

Monitorable and Non-monitorable Formulas



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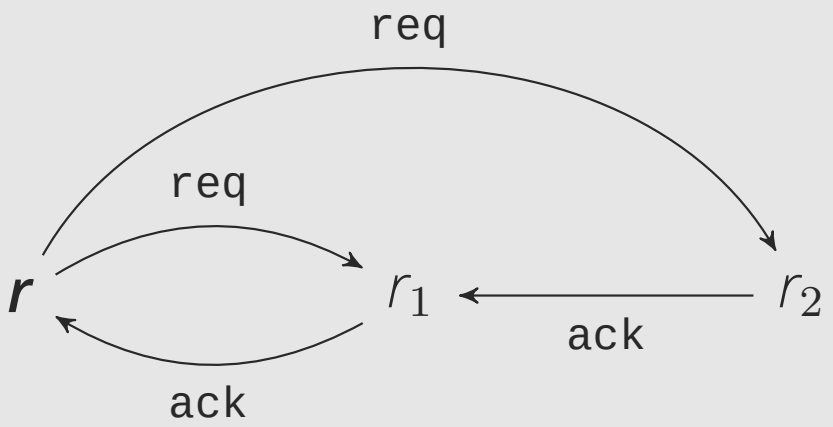

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$m = \text{req}.$✓

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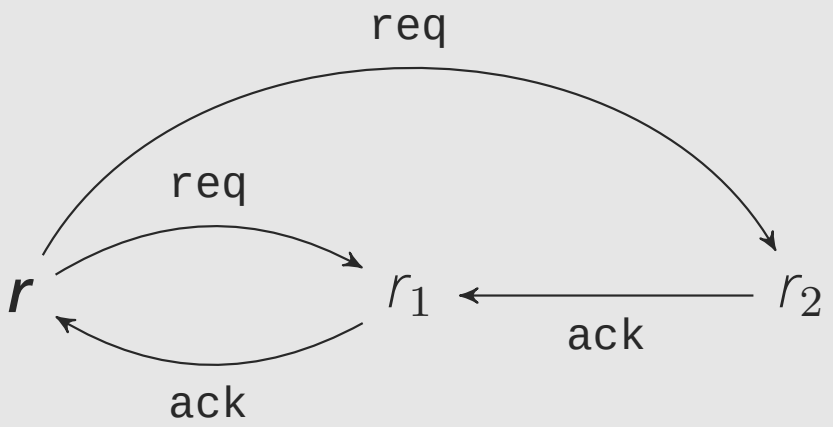

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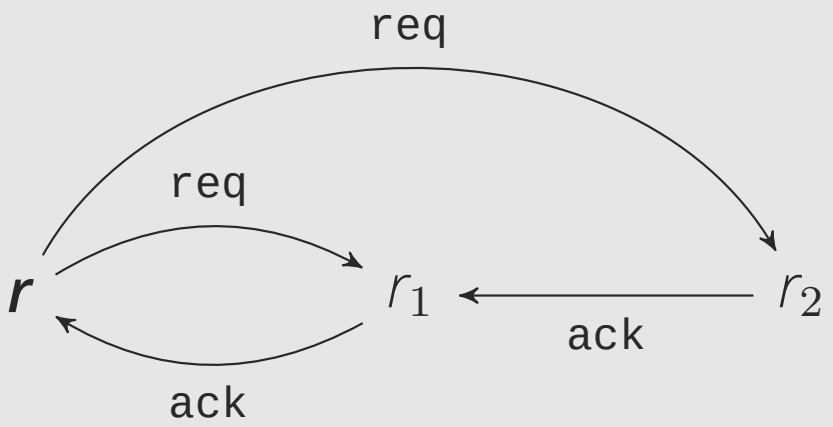

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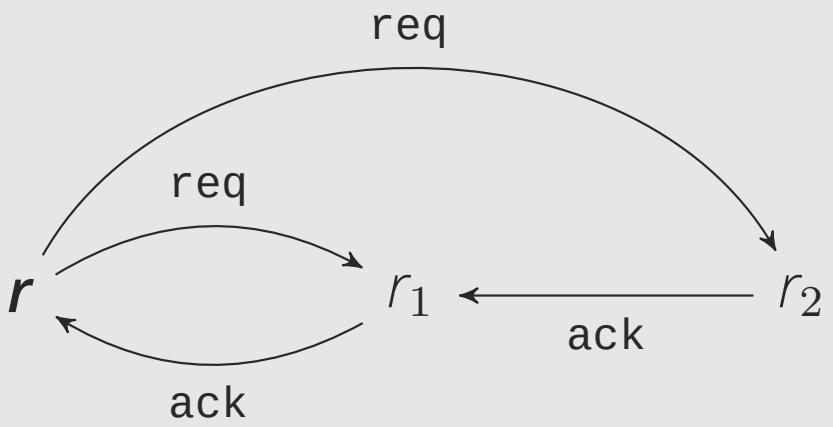

[ack]**ff**

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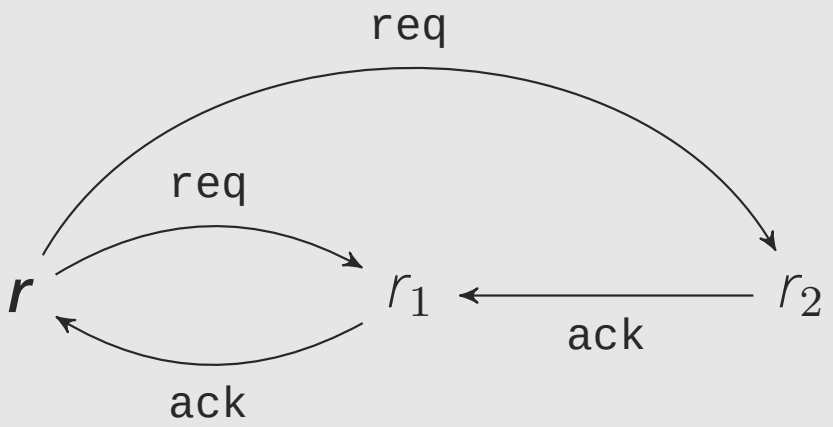

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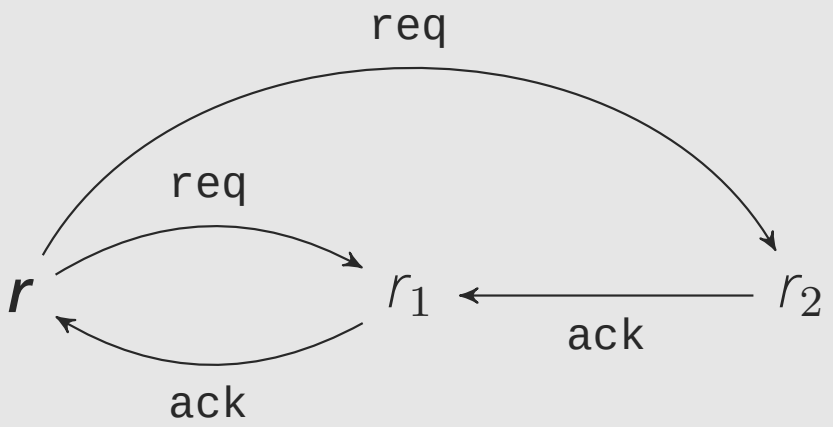

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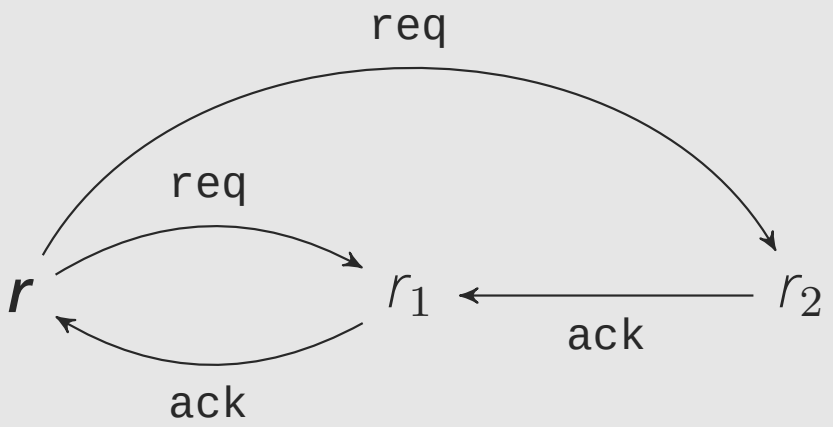

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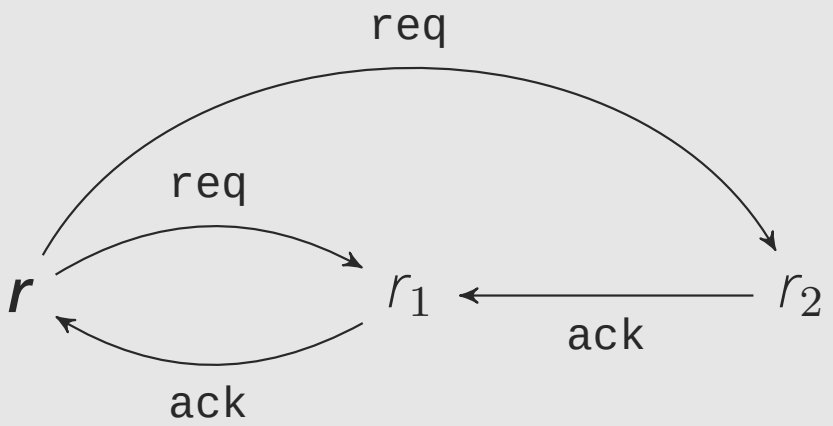

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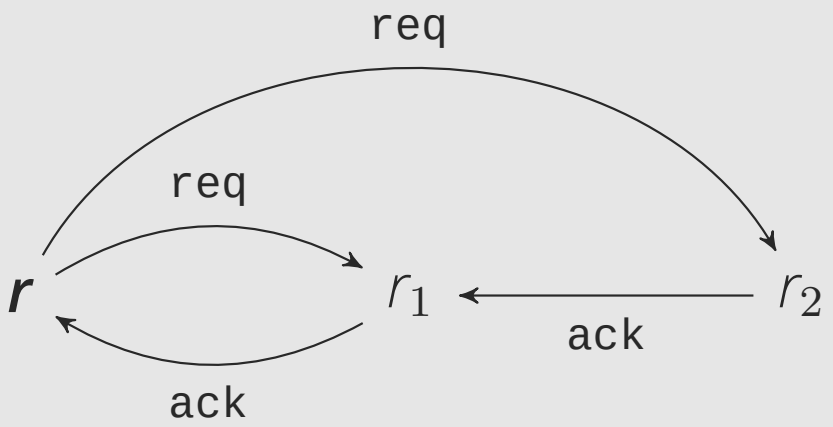

$$[\mathtt{req}]\langle \mathtt{ack} \rangle \mathbf{tt}$$

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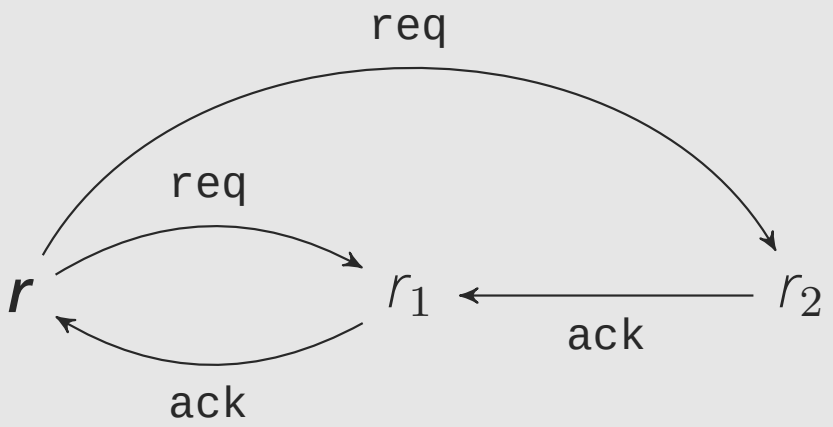

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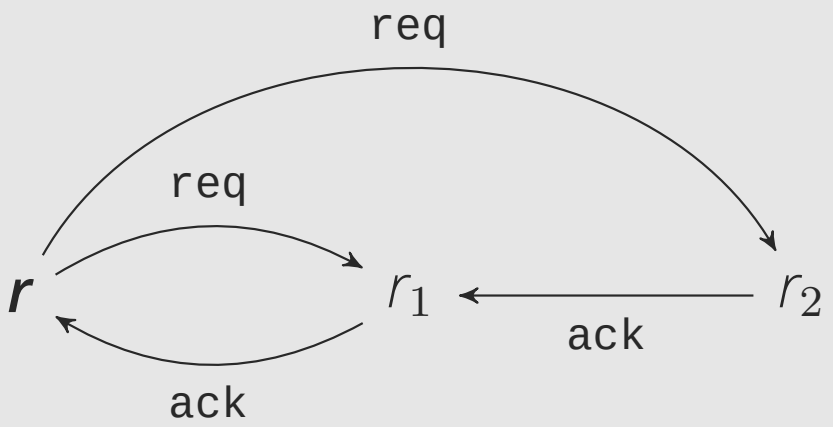

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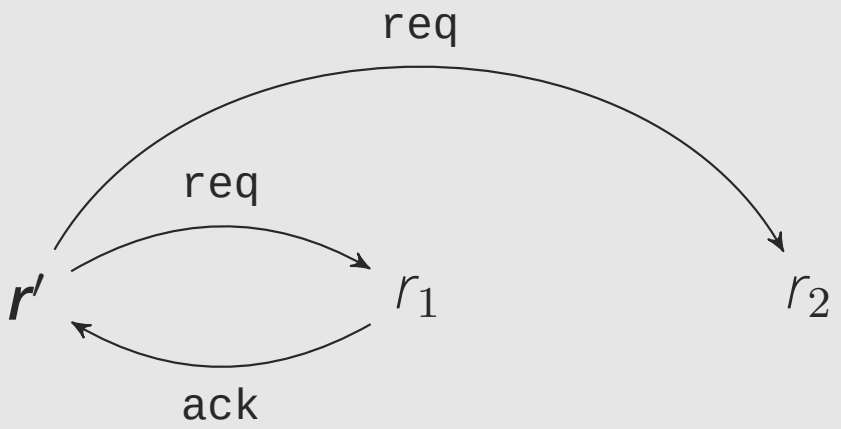

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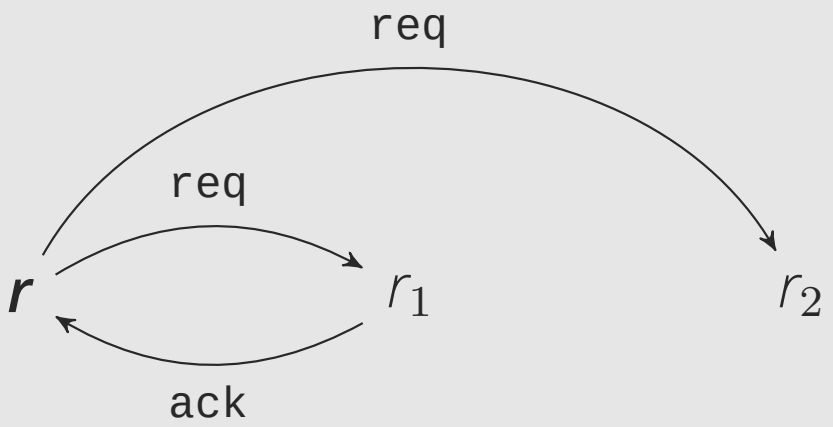

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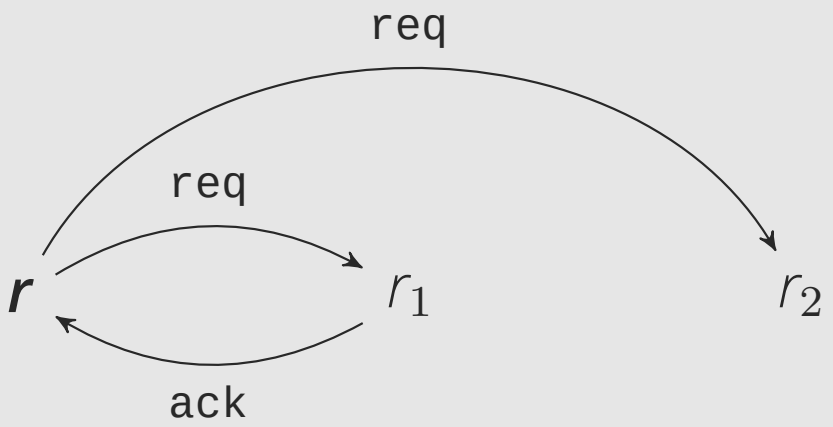
Monitorable and Non-monitorable Formulas



$[\![[\text{req}]\langle\text{ack}\rangle\mathbf{tt}]\!]$

Runtime Verification Mantra

Half a loaf is better than no bread

(Something is always *better than nothing*
...but there not much we can do)

Monitorability

Not all formulas are monitorable

Consider

$$\varphi = [\alpha]\mathbf{ff} \vee [\beta]\mathbf{ff}$$

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Violation Complete: Since $\alpha.\mathbf{0} + \beta.\mathbf{0} \notin [\![[\alpha]\mathbf{ff} \vee [\beta]\mathbf{ff}]\!]$ we should have $\mathbf{rej}(\alpha.\mathbf{0} + \beta.\mathbf{0}, m)$. This means that it must either reject **nil**, $\beta.\mathbf{0}$ or $\alpha.\mathbf{0}$, which is unsound.

A Maximally Monitorable Fragment

Definition (Monitorable Logic)

Let $\mathrm{mHML} = \mathrm{cHML} \cup \mathrm{sHML}$, where

$$\pi, \varpi \in \mathrm{cHML} ::= \mathbf{tt} \mid \mathbf{ff} \mid \pi \vee \varpi \mid \langle\alpha\rangle\pi \mid \mathbf{min}\, X.\pi \mid X$$

$$\theta, \vartheta \in \mathrm{sHML} ::= \mathbf{tt} \mid \mathbf{ff} \mid \theta \wedge \vartheta \mid [\alpha]\theta \mid \mathbf{max}\, X.\theta \mid X$$

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Main Results [FAI17]

- mHML is monitorable.
- mHML is maximally expressive.

How is this useful?

1. Monitor Correctness [FAI15, FAI17, FAA+17]
2. Property specification [FAI15, FAI17, FAA+17]

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$$\langle\alpha\rangle(\langle\beta\rangle\mathbf{tt} \vee [\gamma]\mathbf{ff}) \xrightarrow{\text{refactored as}} (\langle\alpha\rangle\langle\beta\rangle\mathbf{tt}) \vee (\langle\alpha\rangle[\gamma]\mathbf{ff})$$

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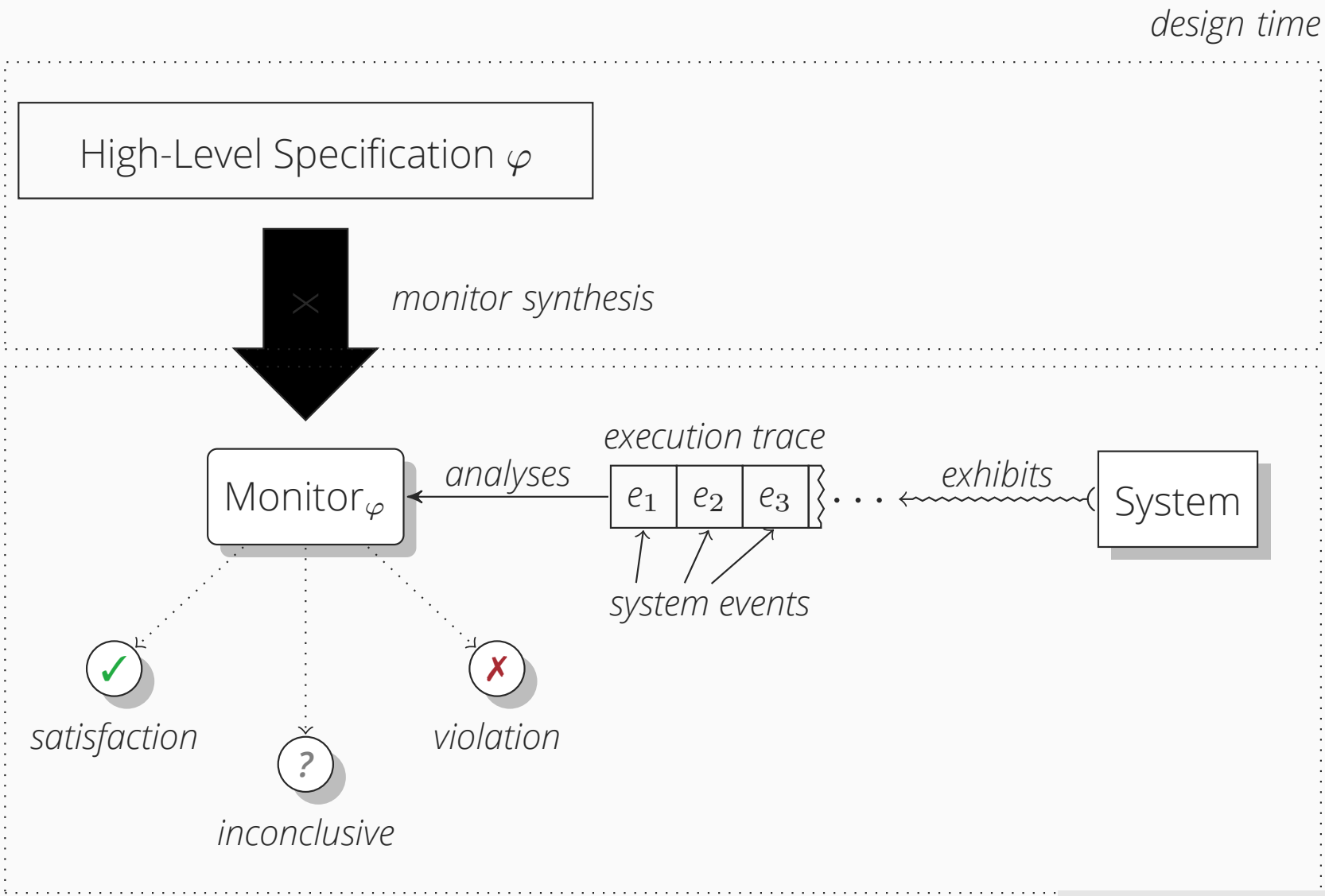
6. Extending monitorability [AF17, AAFI17, AAFI18]

To Monitorabilty...and Beyond!

Know Your Limits



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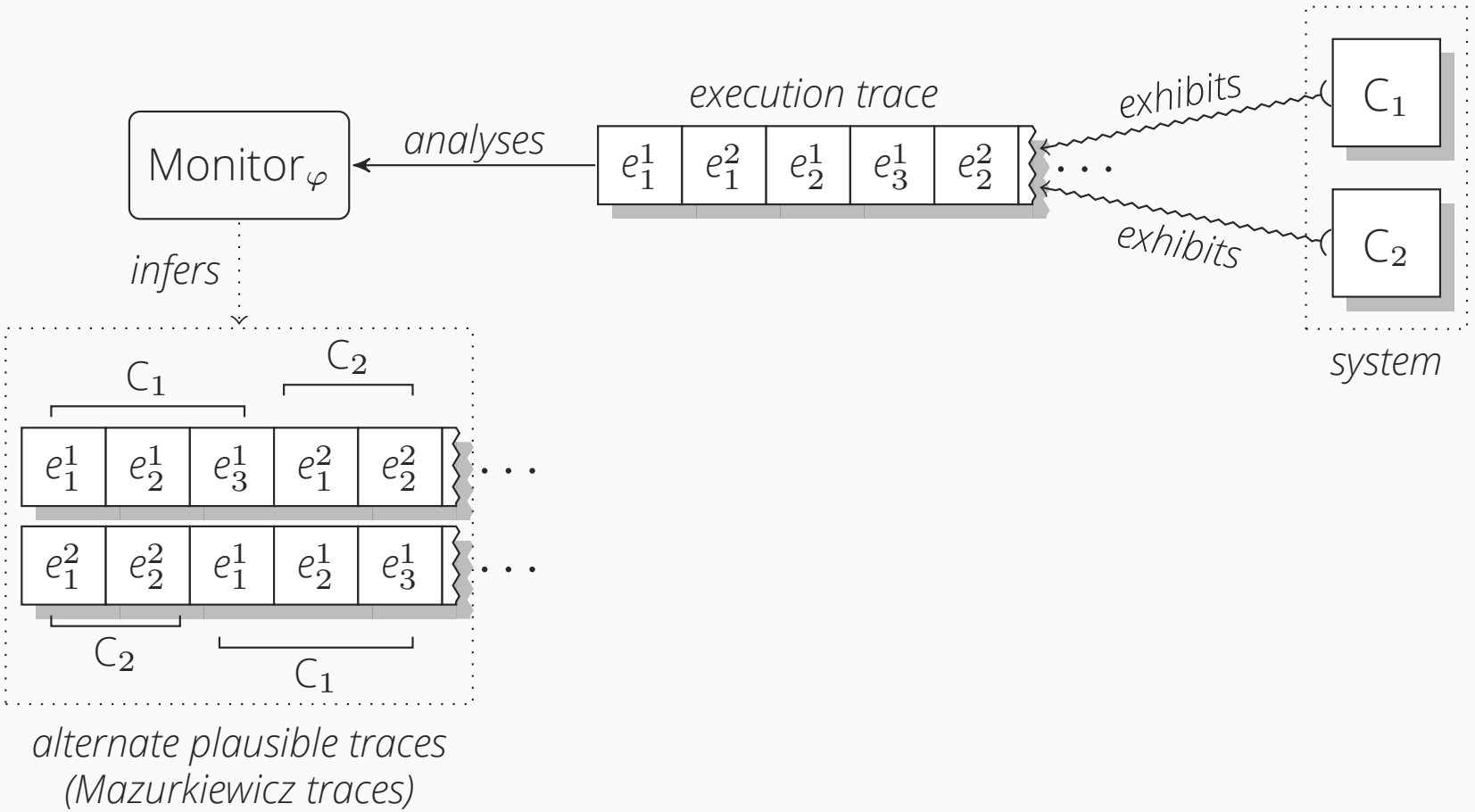
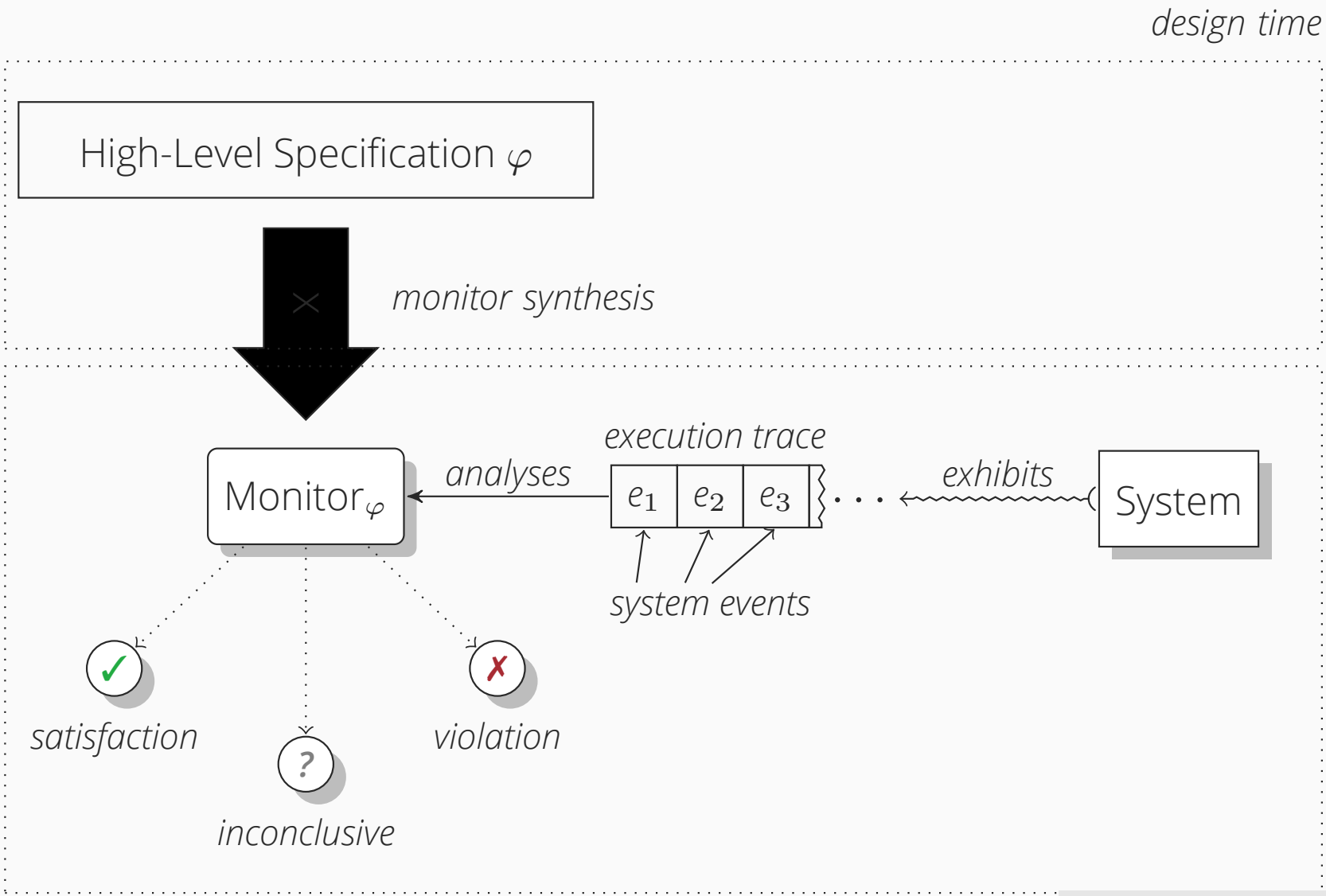
"So...is this it?"

- ponderings of a forty-something

No Limits?


Monitor$_\varphi$
analyses
execution trace
exhibits
exhibits
C_1
C_2
system
infers
C_1
C_2
C_2
C_1
alternate plausible traces
(Mazurkiewicz traces)

Revisiting the Classical Monitoring Setup



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- They could include information from logs **from previously monitored runs**.
- They could also include **descriptions of (depth bounded) trees of computation** at specific points in an execution.

Extended Monitoring Setup

Definition (Extended Monitors)

$$m, n \in \text{Mon} \ ::= \ \ldots \quad \mid !\alpha.m$$

$$\text{Mon}\ \frac{p \xrightarrow{\alpha} p' \qquad m \xrightarrow{\alpha} m'}{m \triangleleft p \xrightarrow{\alpha} m' \triangleleft p'}$$

$$\text{Ter}\ \frac{p \xrightarrow{\alpha} p' \qquad m \not\xrightarrow{\alpha}}{m \triangleleft p \xrightarrow{\alpha} ? \triangleleft p'}$$

$$\text{Neg}\ \frac{p \not\xrightarrow{\alpha} p' \qquad m \xrightarrow{!\alpha} m'}{m \triangleleft p \xrightarrow{\tau} m' \triangleleft p'}$$

Extending the Monitorable Fragment

Recall the safety (monitorable) fragment sHML:

$$\theta, \vartheta \in \text{sHML} ::= \mathbf{tt} \quad | \; \mathbf{ff} \quad | \; \theta \wedge \vartheta \quad | \; [\alpha]\theta \quad | \; \mathbf{max} X.\theta \quad | \; X$$

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In the extended framework, this (maximal) monitorable fragment extends to:

$$\theta, \vartheta \in \text{sHML}^{+} ::= \mathbf{tt} \quad | \ \mathbf{ff} \quad | \ \theta \wedge \vartheta \quad | \ [\alpha]\theta \quad | \ \langle\alpha\rangle\mathbf{tt} \vee \theta \quad | \ \mathbf{max} X.\theta \quad | \ X$$

Extended Monitoring Setup (2)

Definition (Extended Monitors)

$$\eta, \chi \in \mathit{HML} ::= \mathbf{tt} \mid \mathbf{ff} \mid \eta \wedge \chi \mid \eta \vee \chi \mid [\alpha]\eta \mid \langle\alpha\rangle\eta$$
$$m, n \in \mathrm{Mon} ::= \ldots \mid \eta.m$$

$$\mathrm{Mon}\ \frac{p \xrightarrow{\alpha} p' \quad m \xrightarrow{\alpha} m'}{m \triangleleft p \xrightarrow{\alpha} m' \triangleleft p'}$$

$$\mathrm{Ter}\ \frac{p \xrightarrow{\alpha} p' \quad m \not\xrightarrow{\alpha}}{m \triangleleft p \xrightarrow{\alpha} \mathbf{?} \triangleleft p'}$$

$$\mathrm{Frm}\ \frac{p \in [\![\eta]\!] \quad m \xrightarrow{\eta} m'}{m \triangleleft p \xrightarrow{\tau} m' \triangleleft p'}$$

Extending the Monitorable Fragment (2)

Recall the safety (monitorable) fragment sHML:

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Extending the Monitorable Fragment (2)

Recall the safety (monitorable) fragment sHML:

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In the extended framework, this (maximal) monitorable fragment extends to:

$$\begin{aligned} \theta, \vartheta \in \text{sHML}^{++} ::= \ & \mathbf{tt} \quad | \ \mathbf{ff} \quad | \ \theta \wedge \vartheta \quad | \ [\alpha]\theta \\ & | \ \eta \vee \theta \quad | \ \mathbf{max} X.\theta \quad | \ X \end{aligned}$$

Additional Work

- Tool Construction:
  - Automated monitor synthesis [AF16, CF16].
  - Language-Specific instrumentation tools [CFAI17].
- Complexity Results for Monitor Determinisation [AAF+17].
- Automated Formula Refactoring to isolate monitorable parts [DMF15].
- (Correctness) Monitor Preorders for refinement [Fra16].
- (Correctness) Monitor Properties that extend to reactive software in general [Fra17].

Contributors

Luca Aceto, Antonis Achilleos, Duncan Paul Attard, Ian Cassar, Dario Della Monica, Anna Ingolfsdottir, myself (and more researchers will be joining us soon).

What now?

"Verifiers of the world, unite!
You have nothing to lose,
but your own preconceived
verification shackles!"

Further Reading

- The first part of the talk is based on the high-level tutorial paper [FAA+17] available **here**.
- For an in-depth treatment of the topics, consult [FAI17] **here**.
- For the topics discussed in the last section, consult [AAFI18] **here**.
- For a full overview of the work conducted in the TheoFoMon Project, consult **here**.

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