Verifying generalised and structural soundness of workflow nets via relaxations

Philip Offtermatt

Joint work with
Michael Blondin and Filip Mazowiecki

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MAX PLANCK INSTITUTE
FOR SOFTWARE SYSTEMS

UNIVERSITAS VARSOVIENSIS

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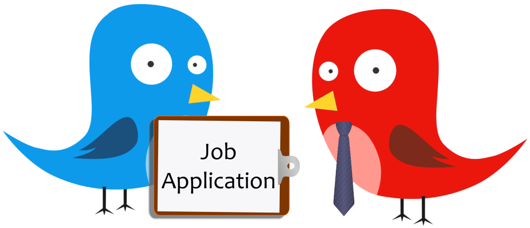
Processes are everywhere!



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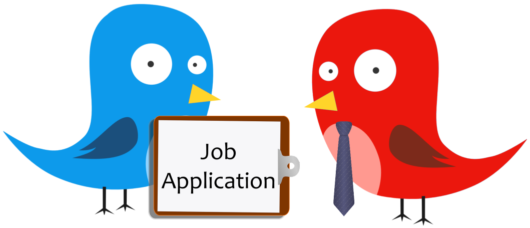

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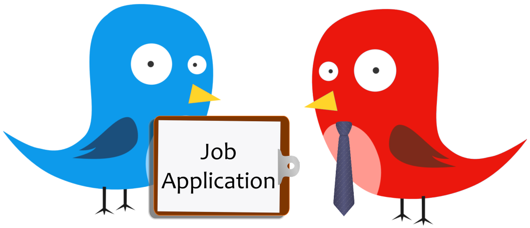

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How many applicants will we need until we find a new hire?

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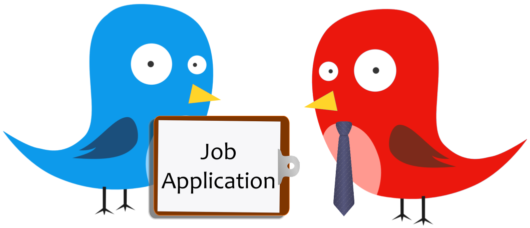

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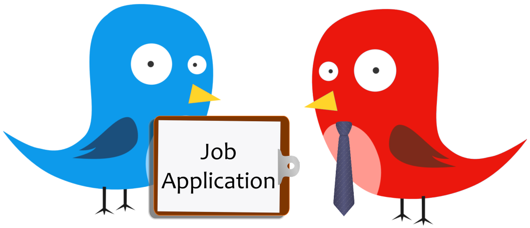

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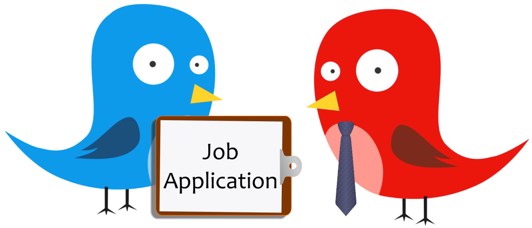

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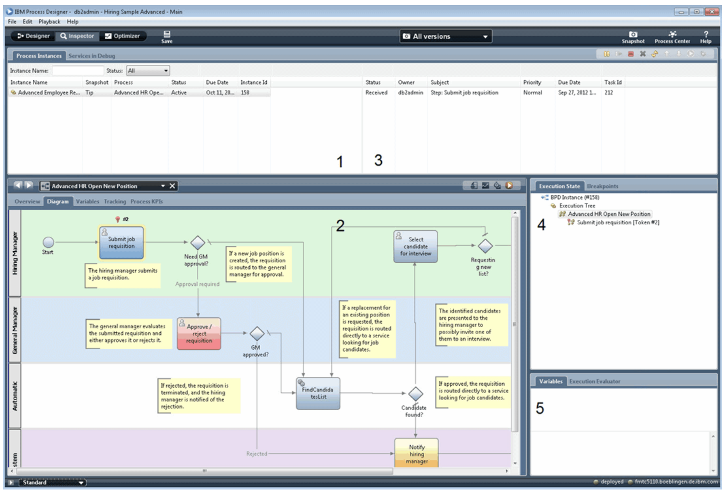

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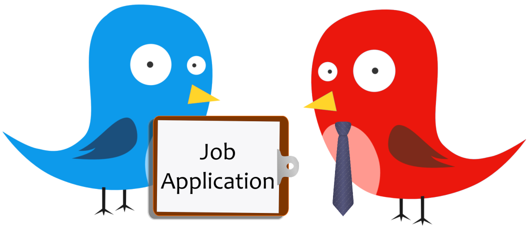
Formally modeling processes: Workflow nets



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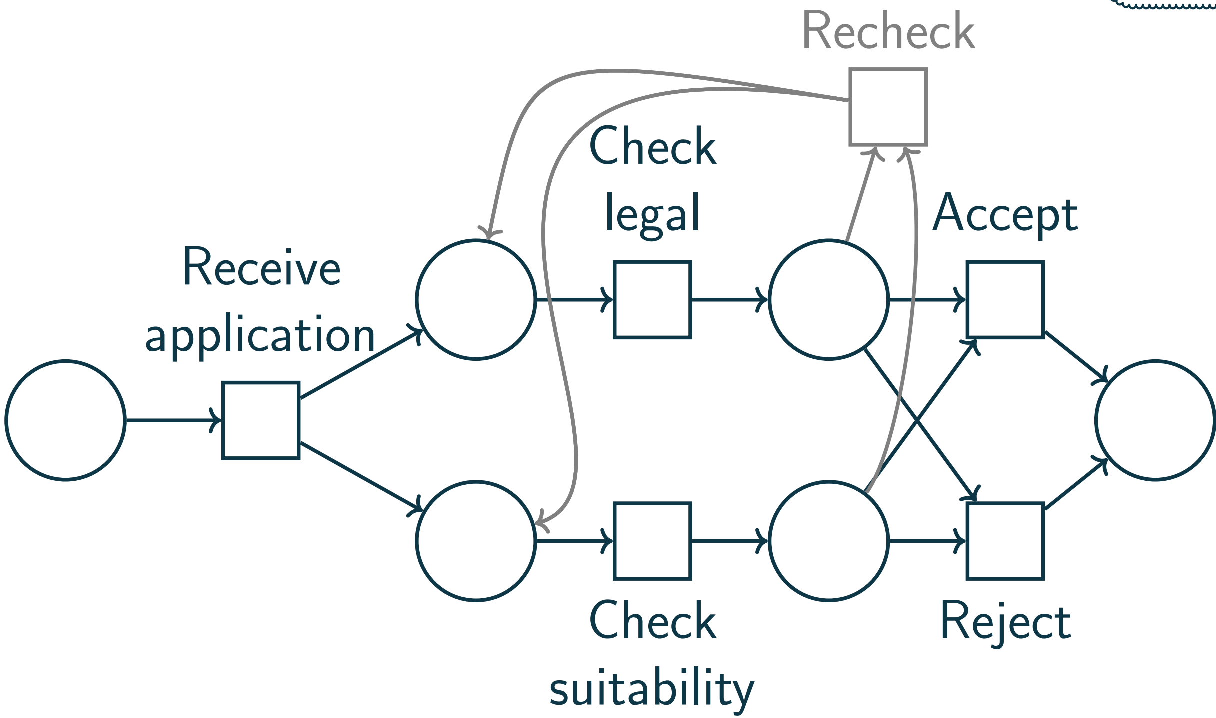

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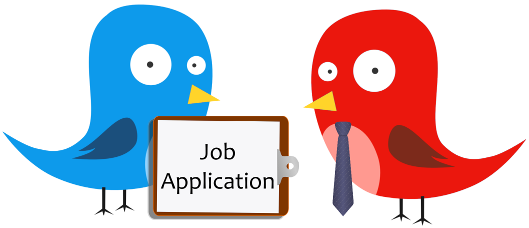

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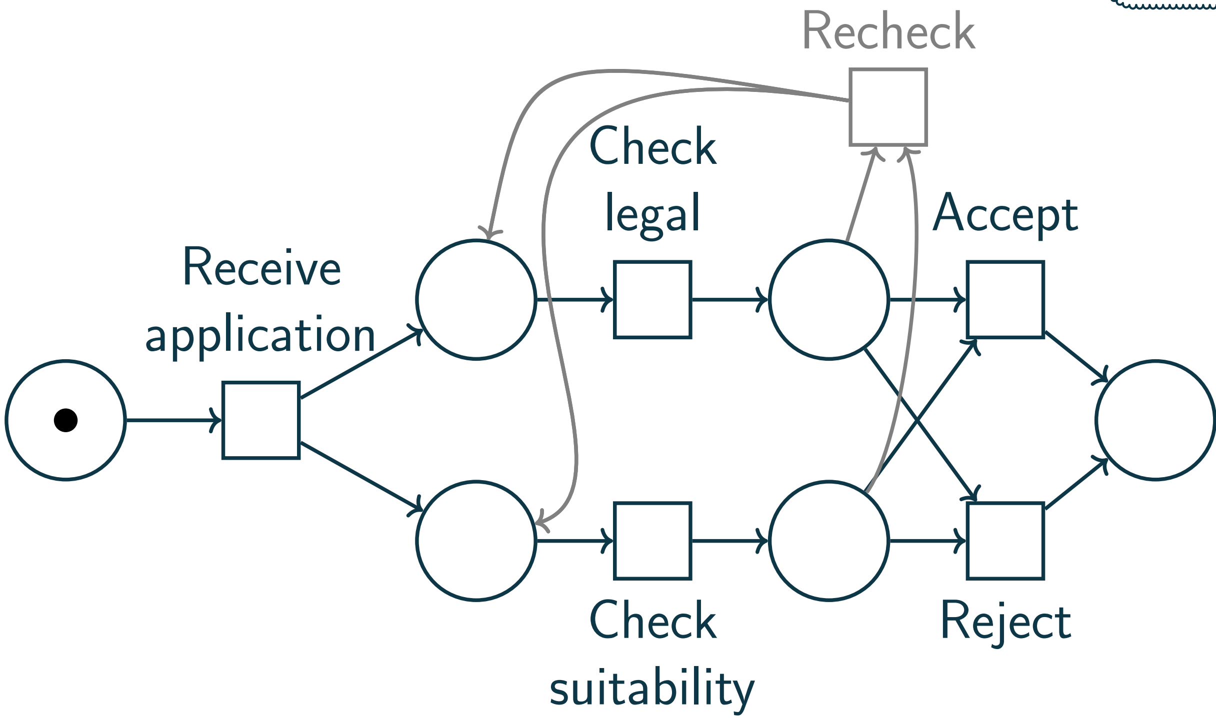

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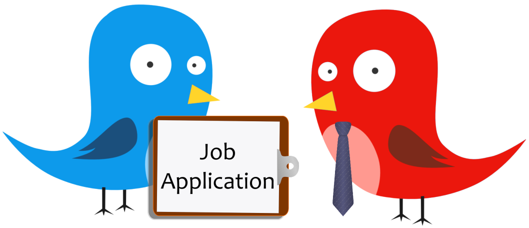

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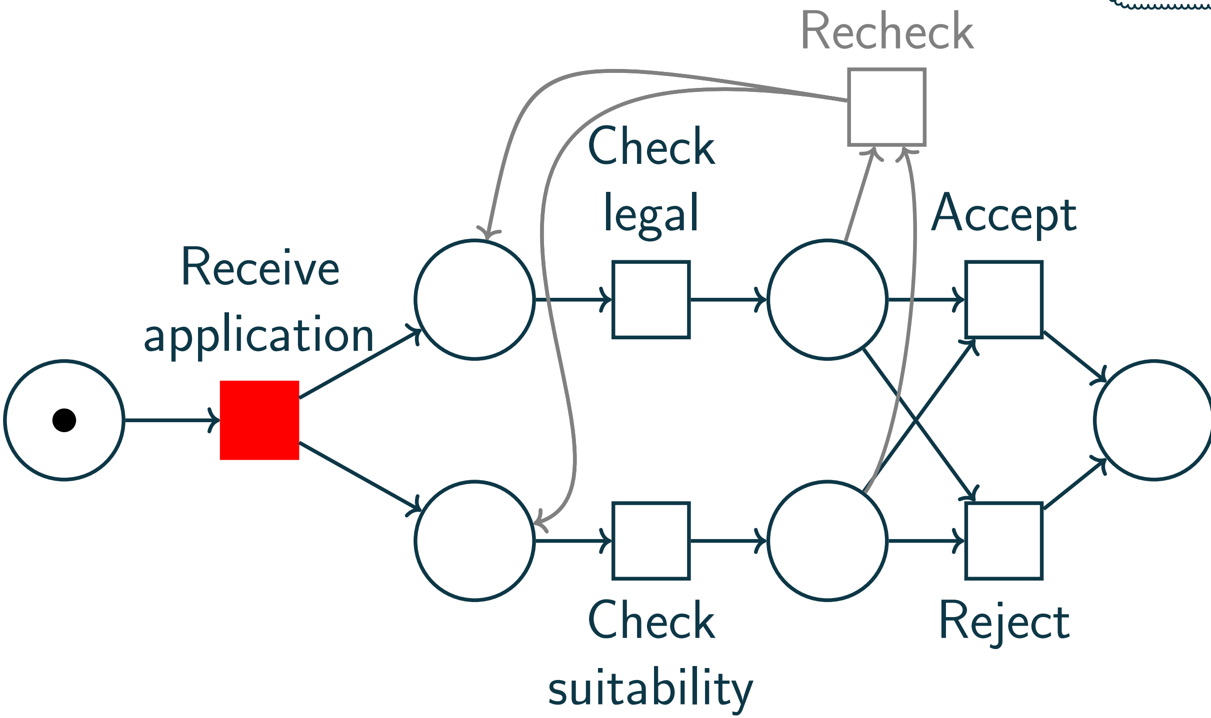

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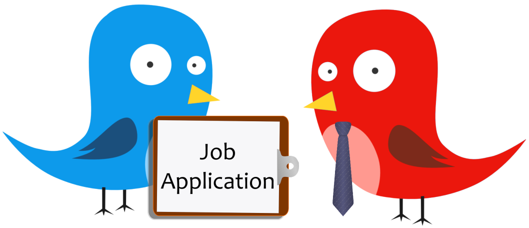

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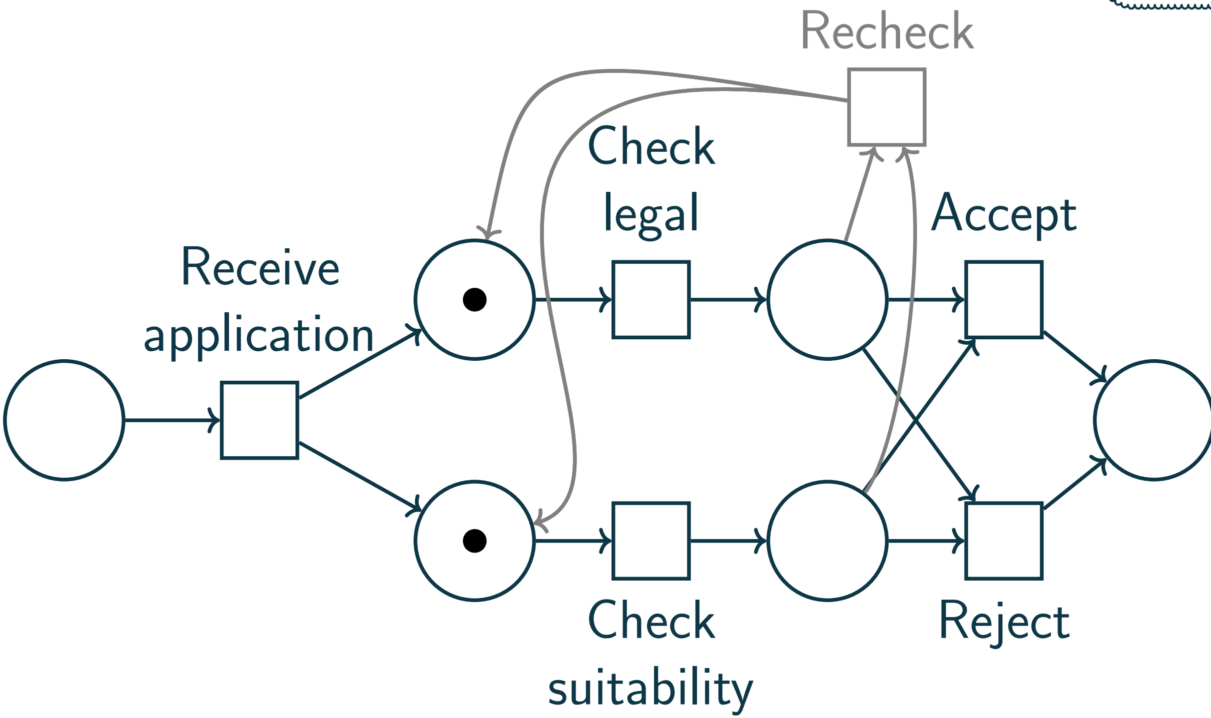

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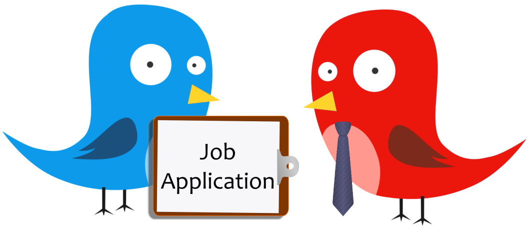

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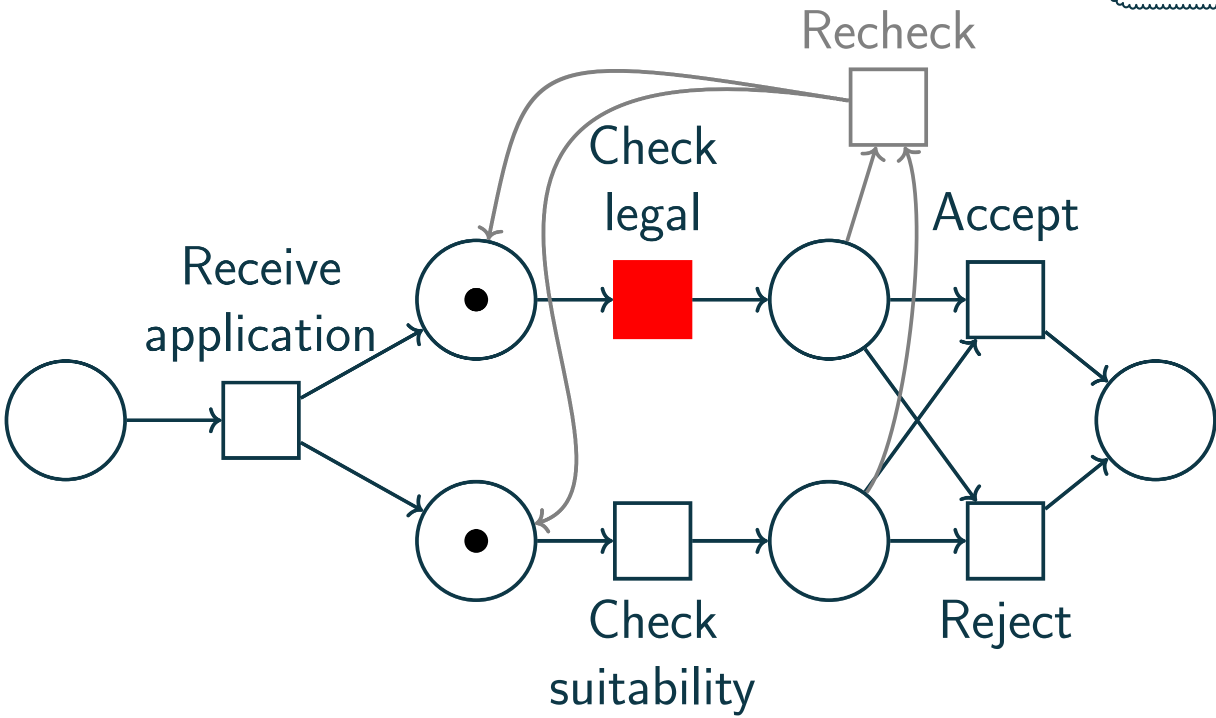

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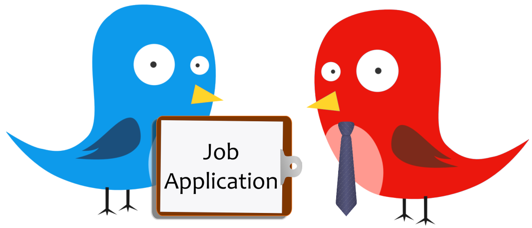

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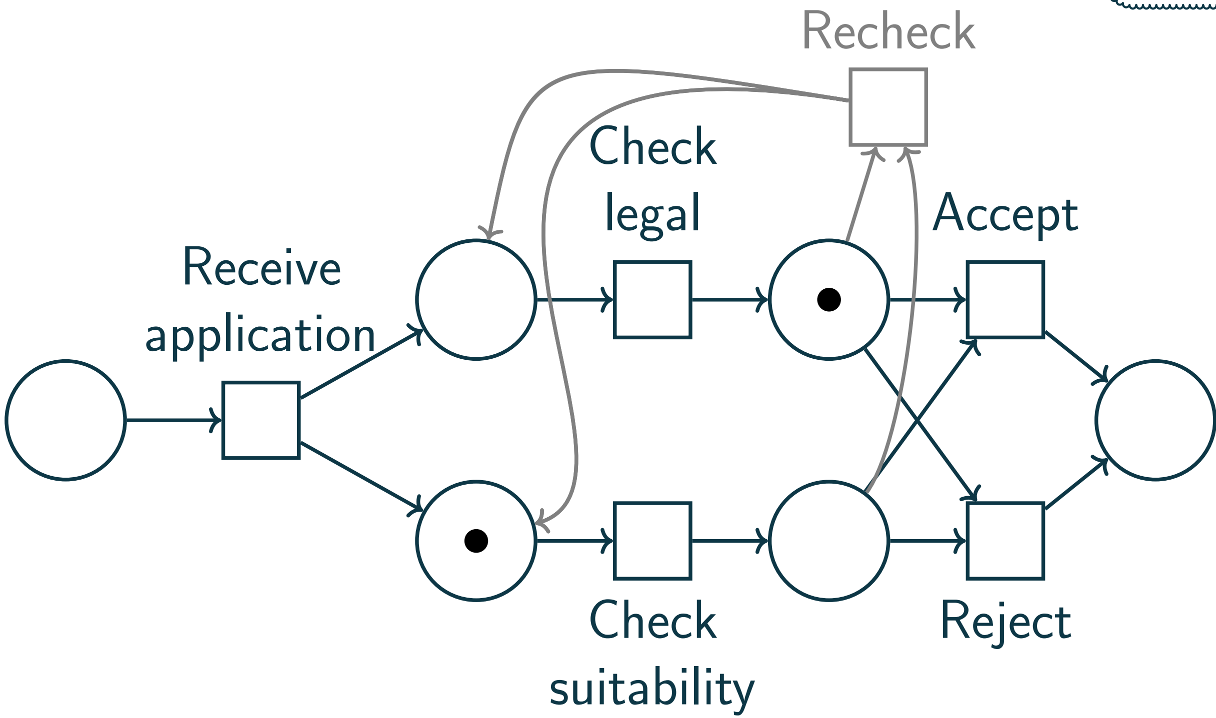

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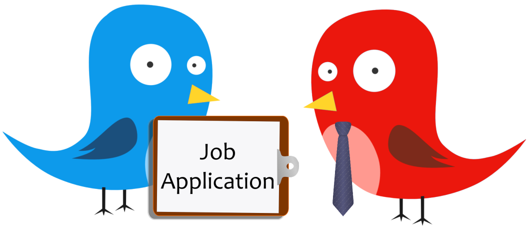

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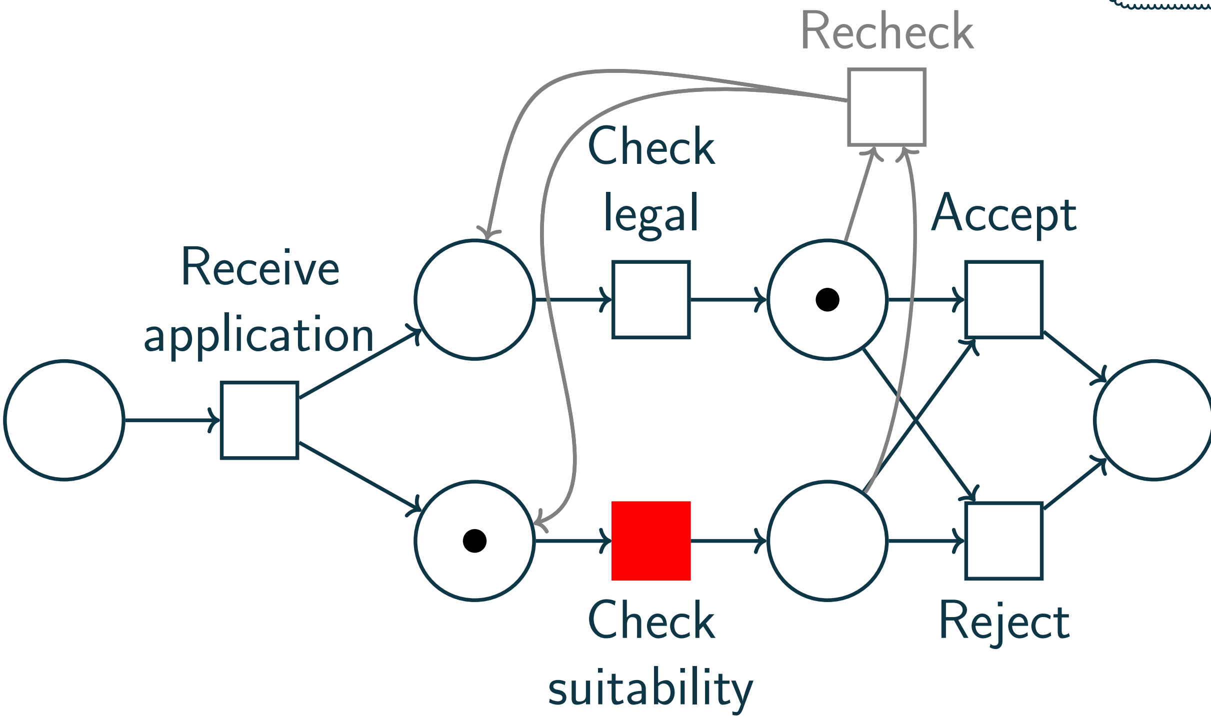

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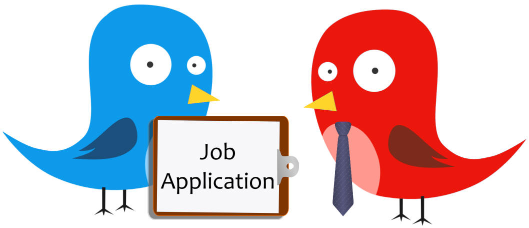

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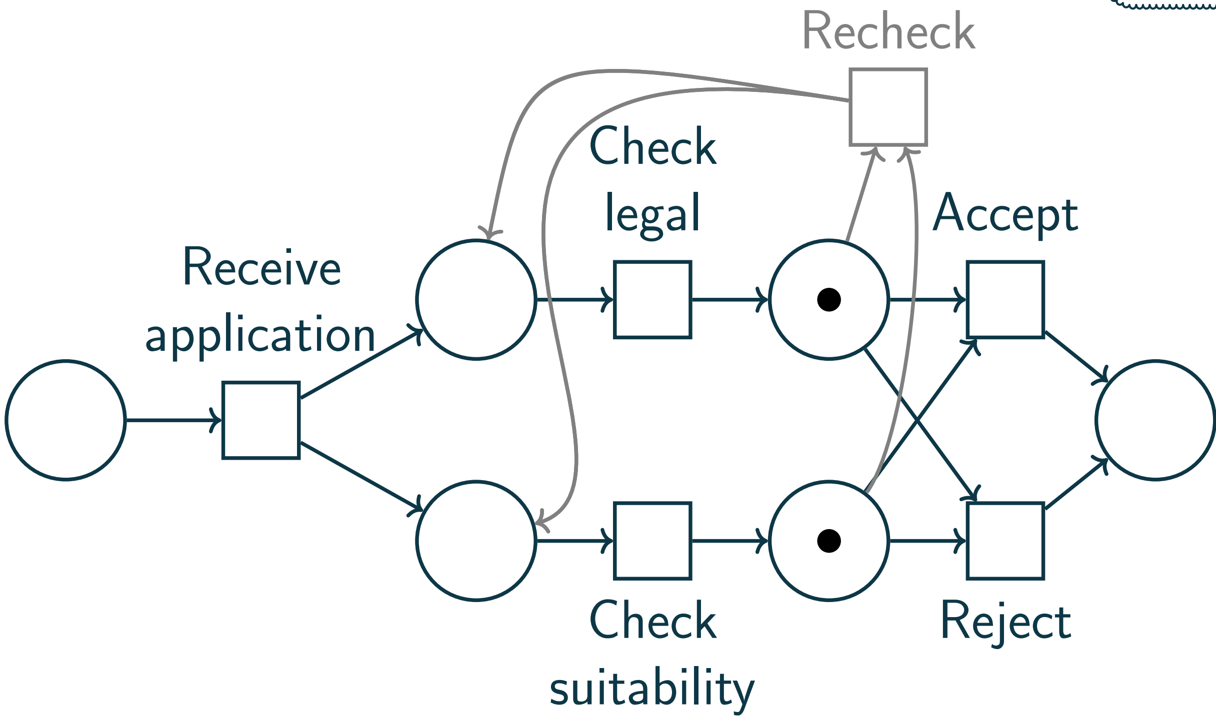

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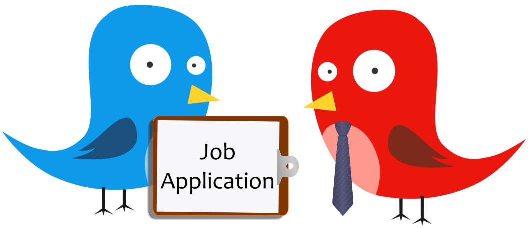

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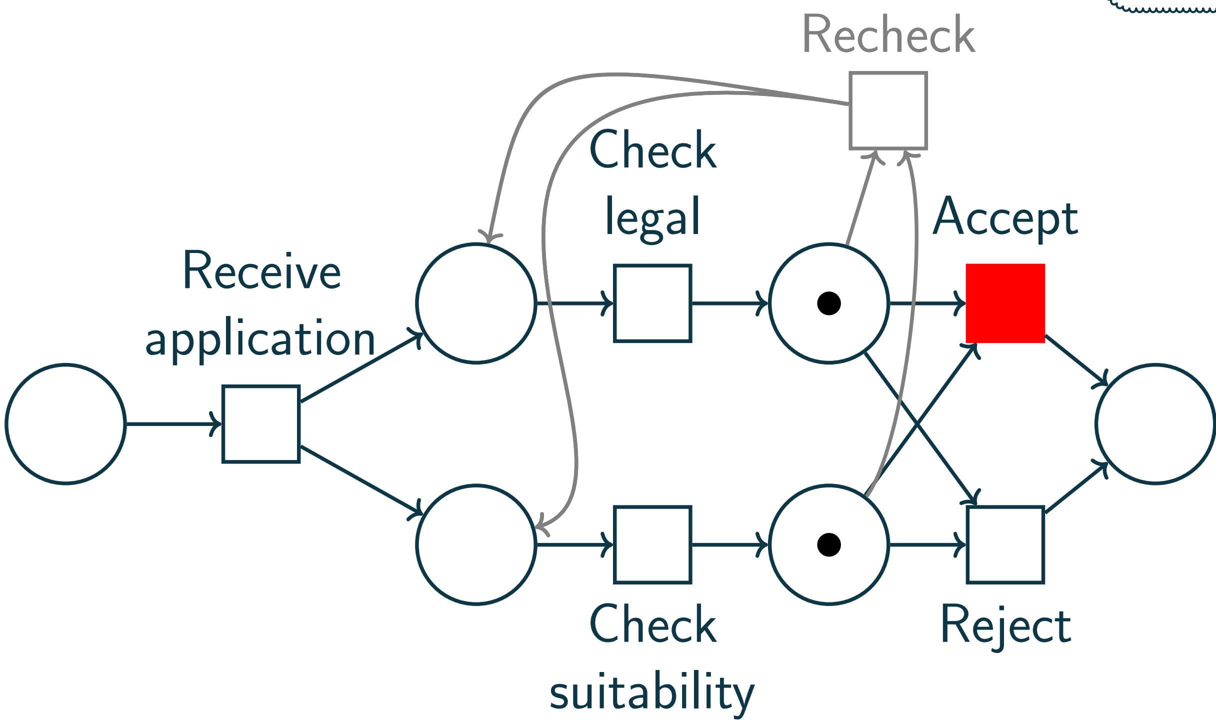

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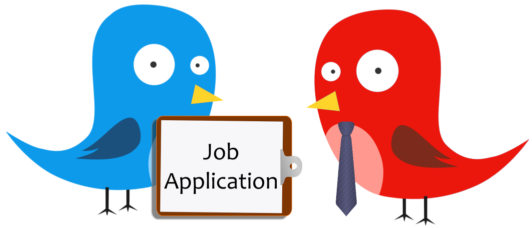

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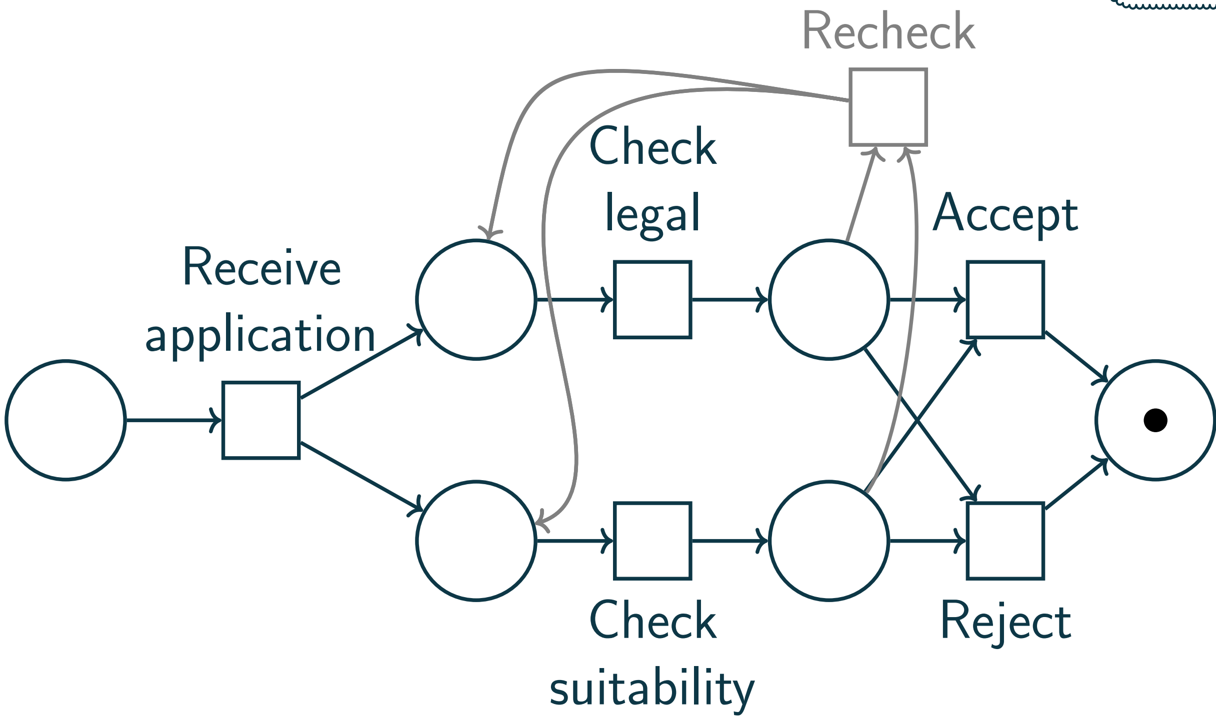
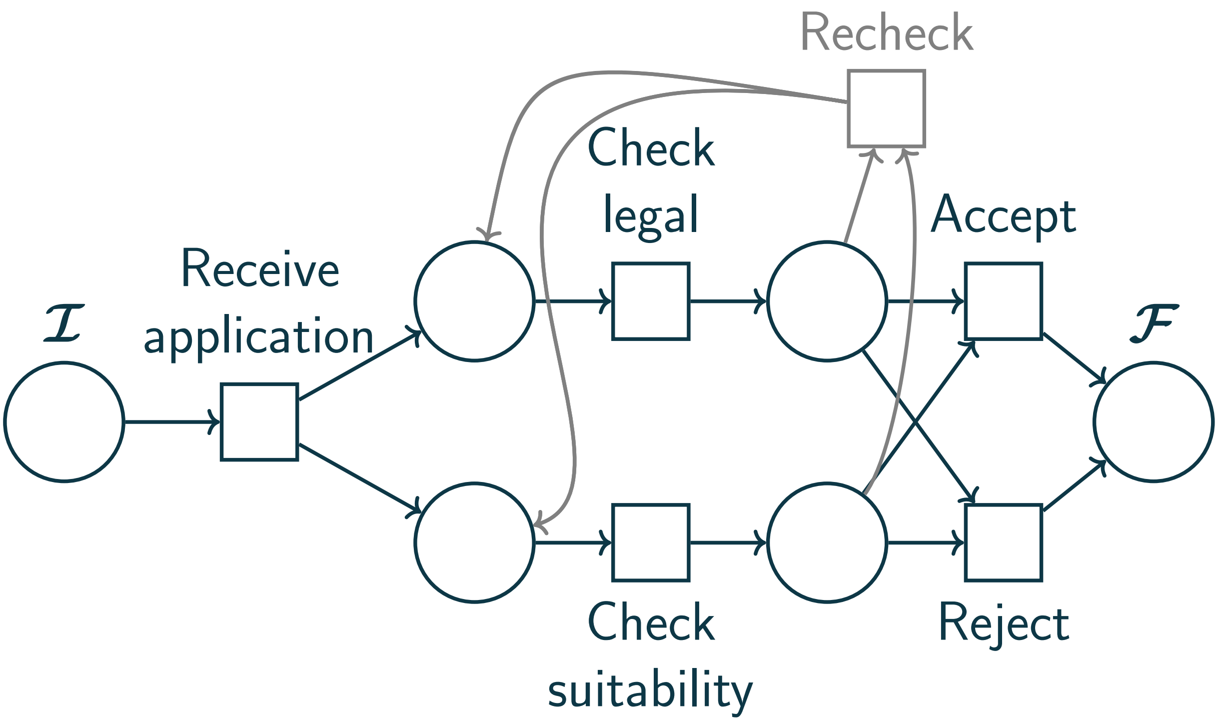
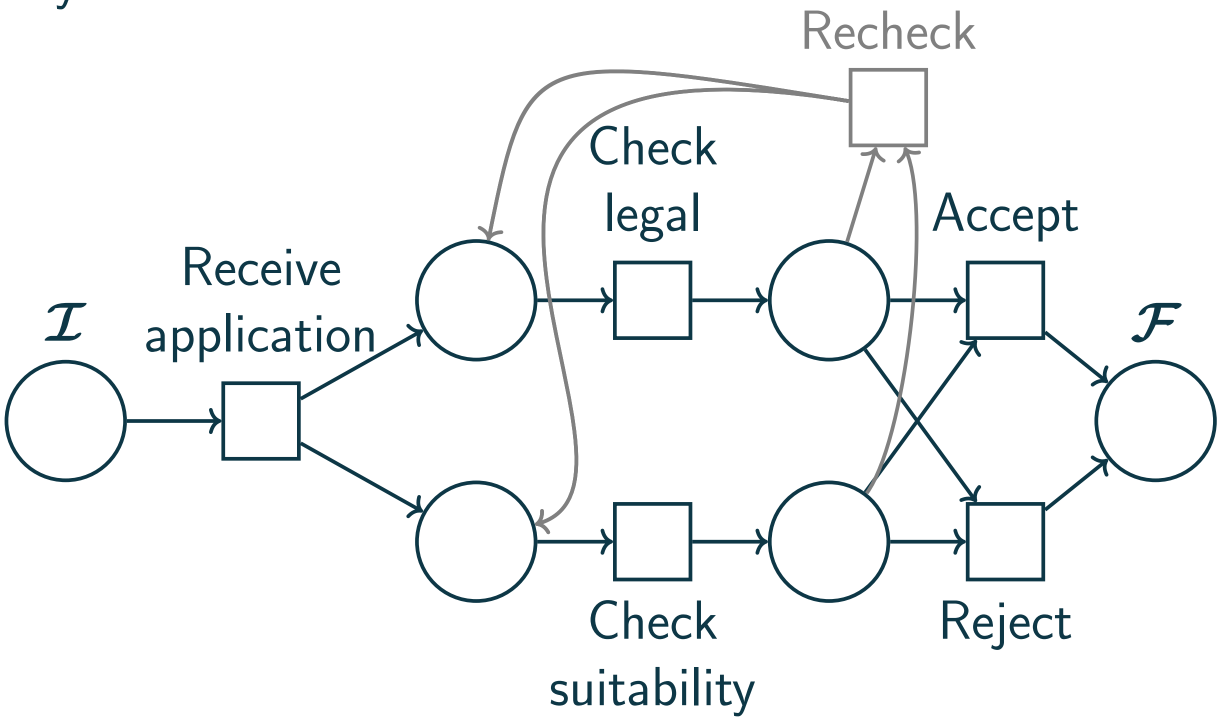


Correctness conditions for processes



Correctness conditions for processes

Option to complete:
We should be able to reach a
a marking that has tokens
only in $\mathcal{F}$



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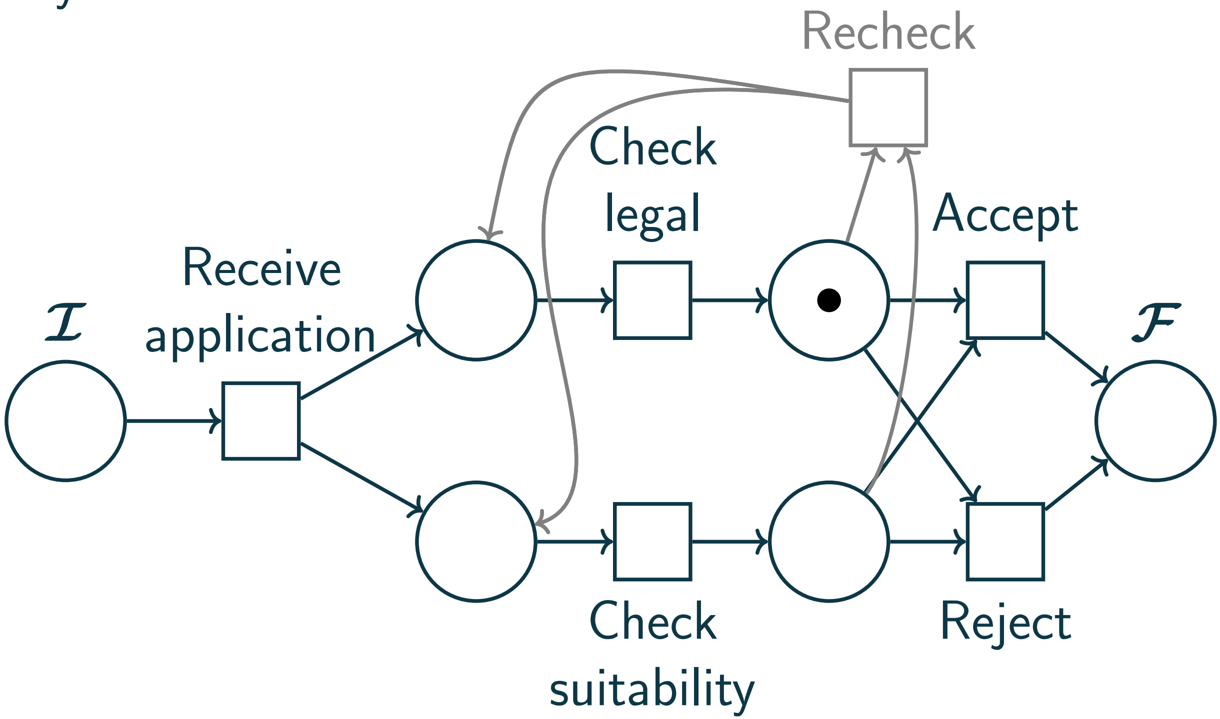

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Proper completion:
When $\mathcal{F}$ is marked
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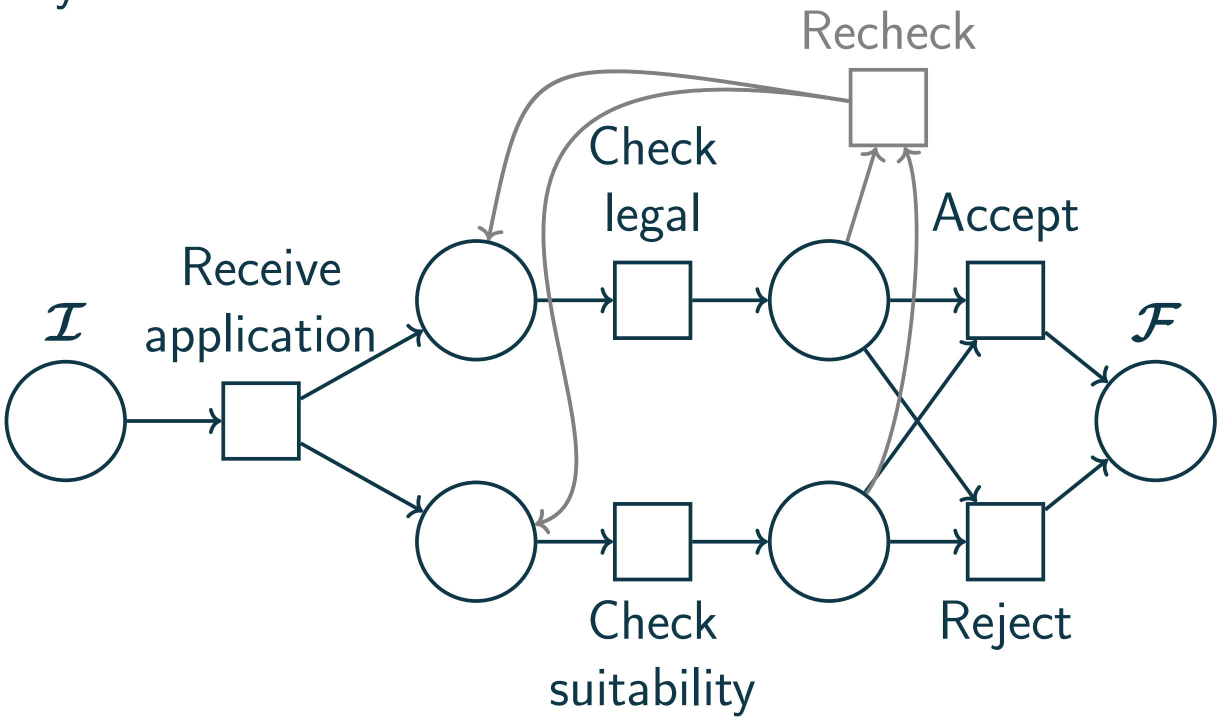

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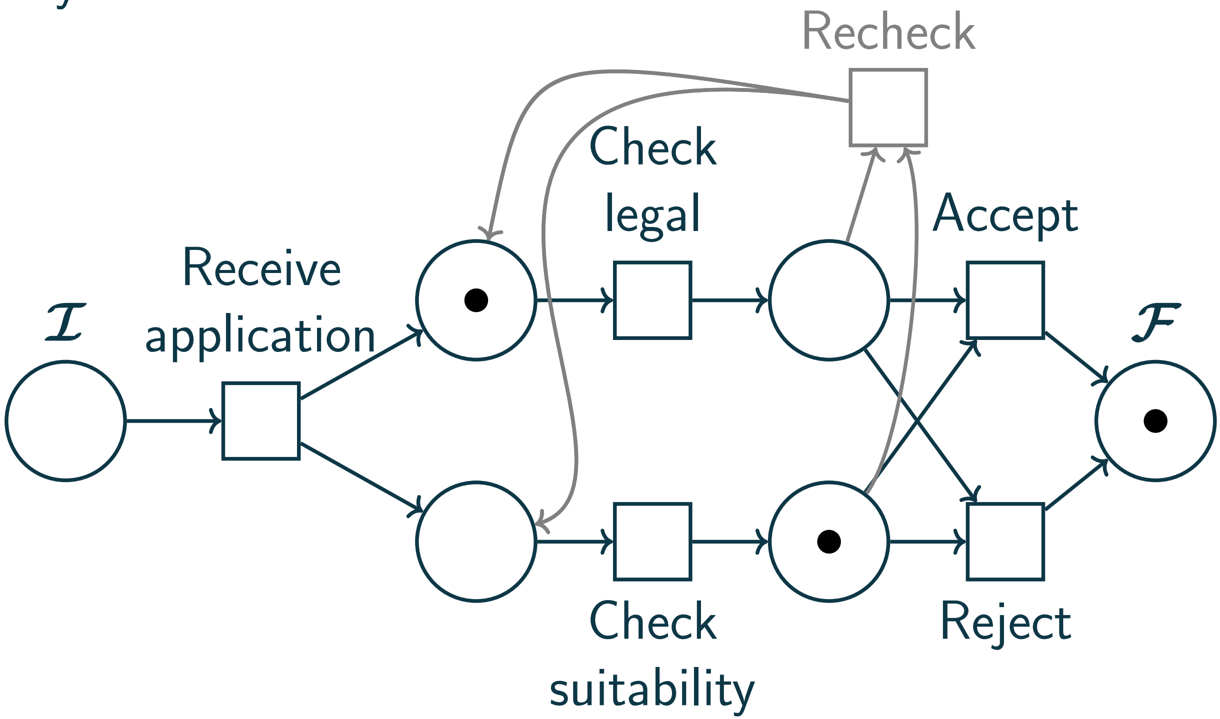

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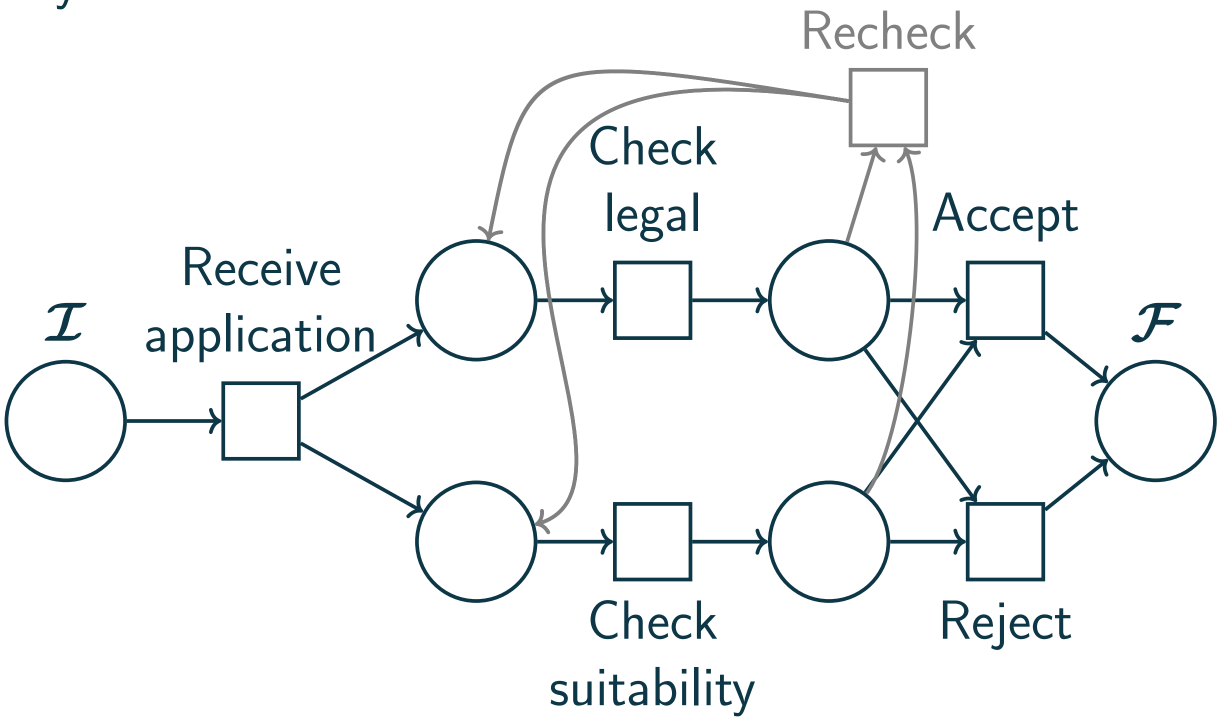
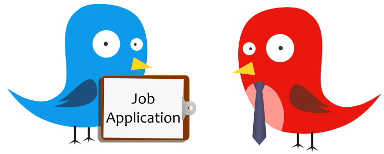


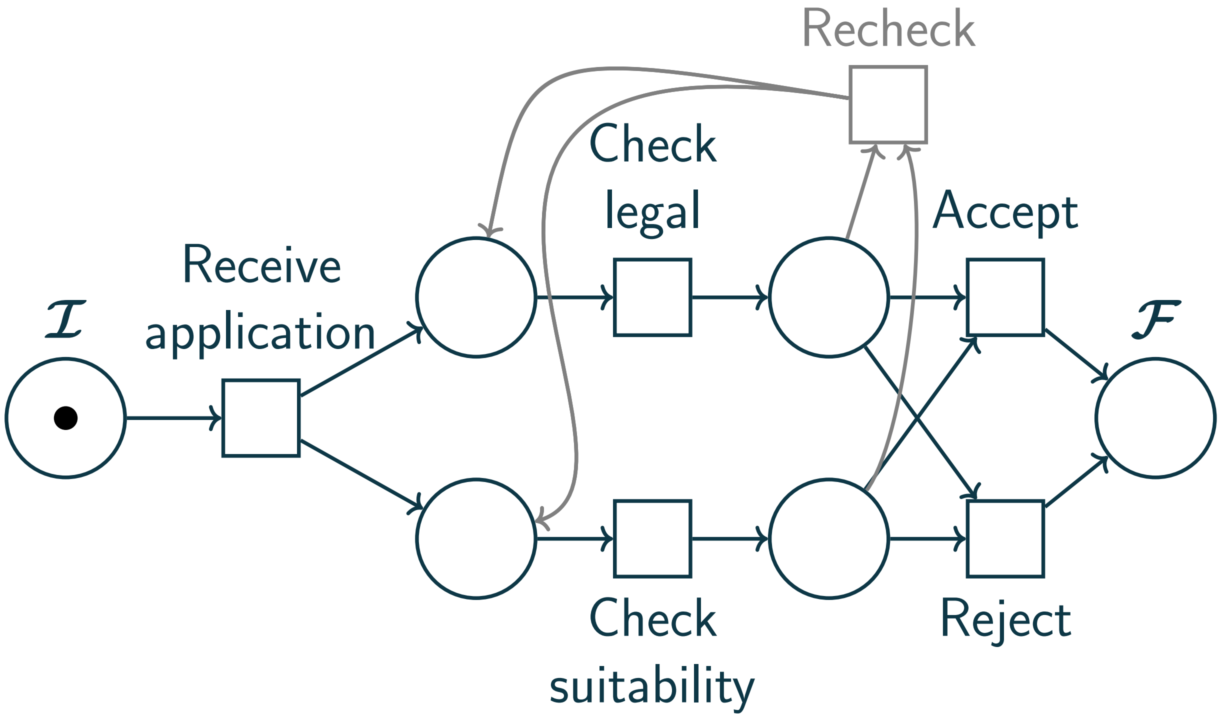
Can we condense these into a single condition?

A concise correctness condition

Soundness:
From any marking reachable from $\{\mathcal{I}\colon 1\}$, the final marking $\{\mathcal{F}\colon 1\}$ can be reached

$\forall$ runs π $\exists$ run π' : $\{\mathcal{I}\colon 1\} \xrightarrow{\pi\pi'} \{\mathcal{F}\colon 1\}$





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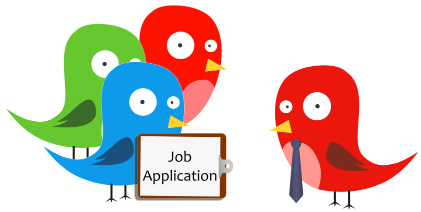

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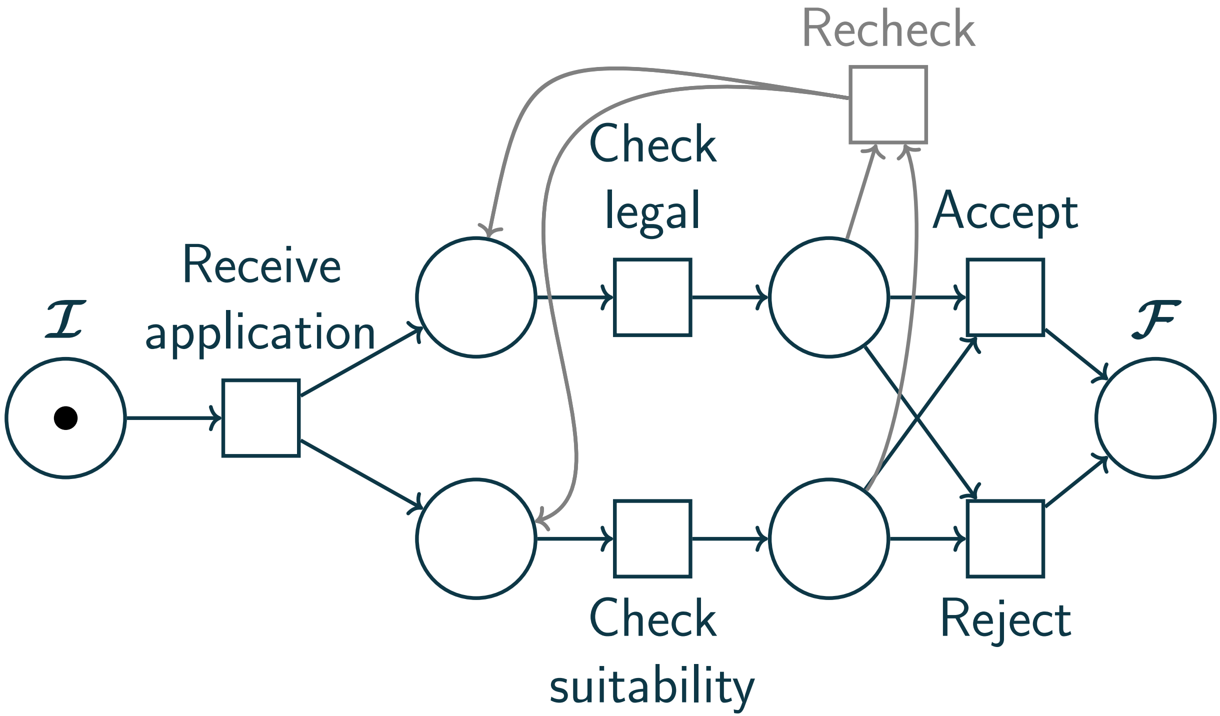

Extending soundness

***k*-soundness:**
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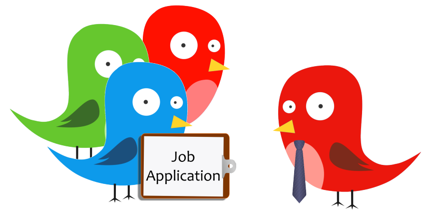

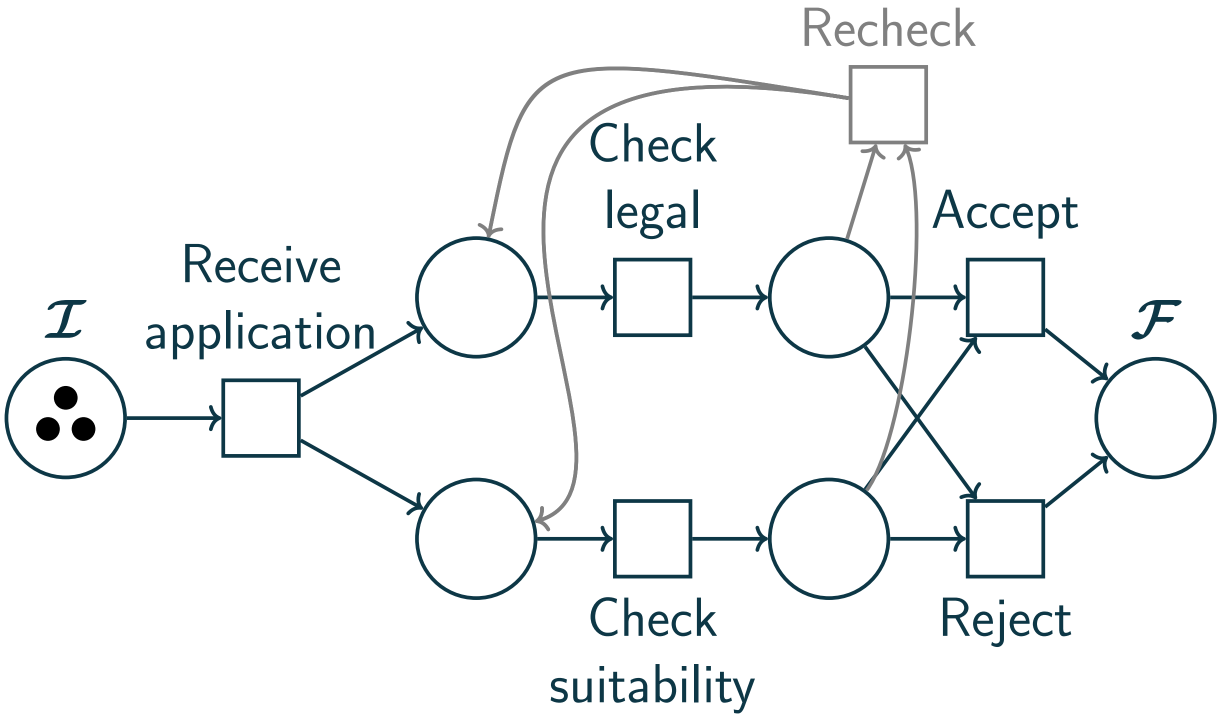

Variants of soundness

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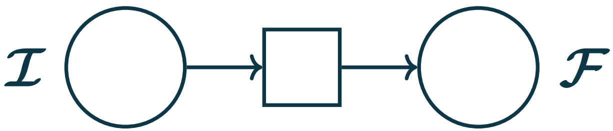

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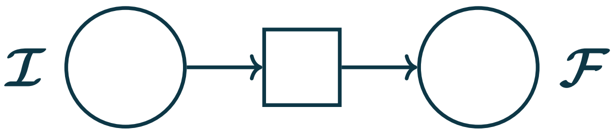

✓

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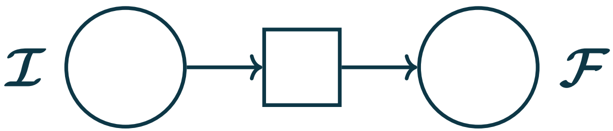	✓	✓

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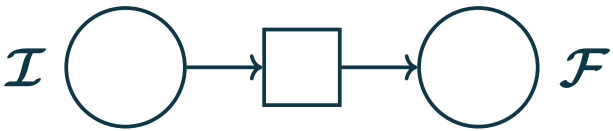
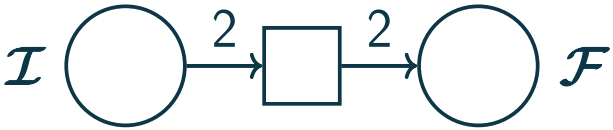
	✓	✓
		

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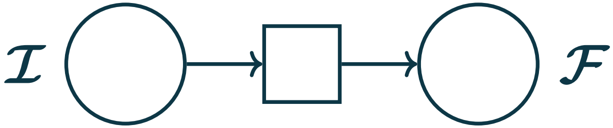
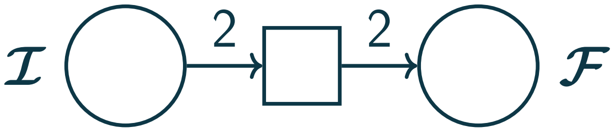
	✓	✓
	✗ Not 1-sound	

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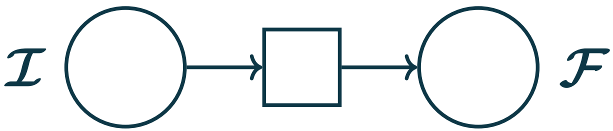
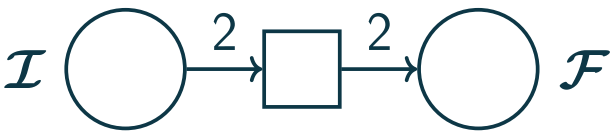
	✓	✓
	X Not 1-sound	✓ 2-sound

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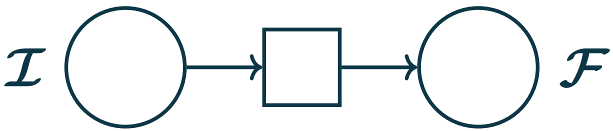
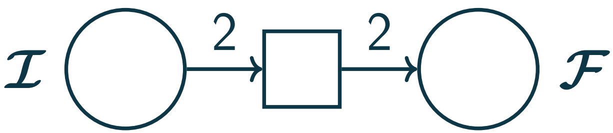
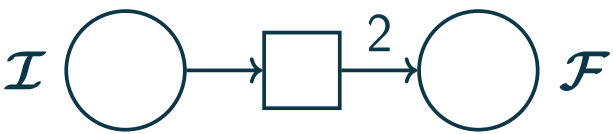
	✓	✓
	X Not 1-sound	✓ 2-sound
		

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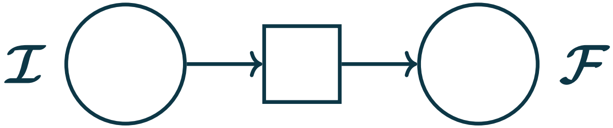
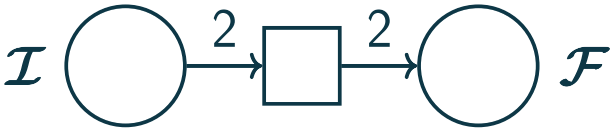
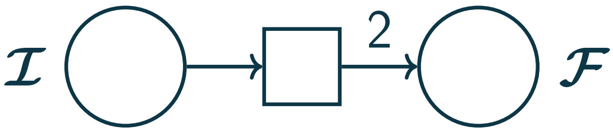
	✓	✓
	X Not 1-sound	✓ 2-sound
	X	

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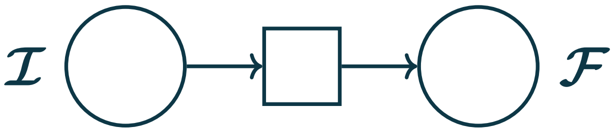
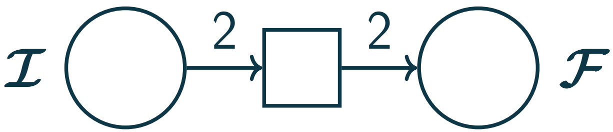
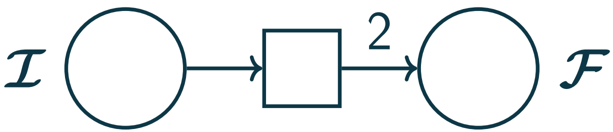
	✓	✓
	✗ Not 1-sound	✓ 2-sound
	✗	✗

Verifying soundness

Complexity

Generalised soundness	
Structural soundness	

Verifying soundness

	Complexity
Generalised soundness	PSPACE-complete
Structural soundness	

Verifying soundness

	Complexity
Generalised soundness	PSPACE-complete
Structural soundness	EXPSPACE-complete

Verifying soundness

Complexity

Generalised soundness	PSPACE-complete
Structural soundness	EXPSPACE-complete

Known exact algorithms:

Use Petri net reachability

Exhaustive exploration is slow

Verifying soundness

Complexity

Generalised soundness	PSPACE-complete
Structural soundness	EXPSPACE-complete

Known incomplete algorithms:

Reduction rules

$$\begin{tikzcd} \boxed{\text{Net}} \arrow[d, "\text{Reduce}"] \\ \boxed{\text{Reduced net}} \end{tikzcd}$$

Known exact algorithms:

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Verifying soundness

Complexity

Generalised soundness	PSPACE-complete
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Reduction rules

Net

Reduce

Reduced net

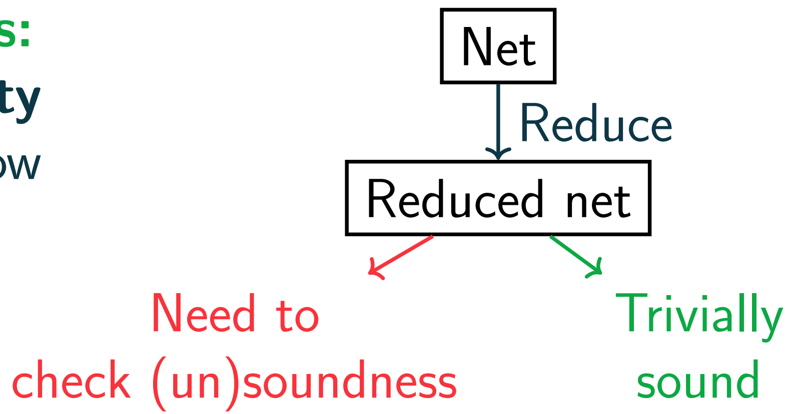
Trivially sound

Verifying soundness

	Complexity
Generalised soundness	PSPACE-complete
Structural soundness	EXPSPACE-complete

Known incomplete algorithms:

Reduction rules



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Exhaustive exploration is slow

Verifying soundness

Complexity

Generalised soundness	PSPACE-complete
Structural soundness	EXPSPACE-complete

Our work

Integer unboundedness
Continuous soundness

Structural quasi-soundness via continuous reachability

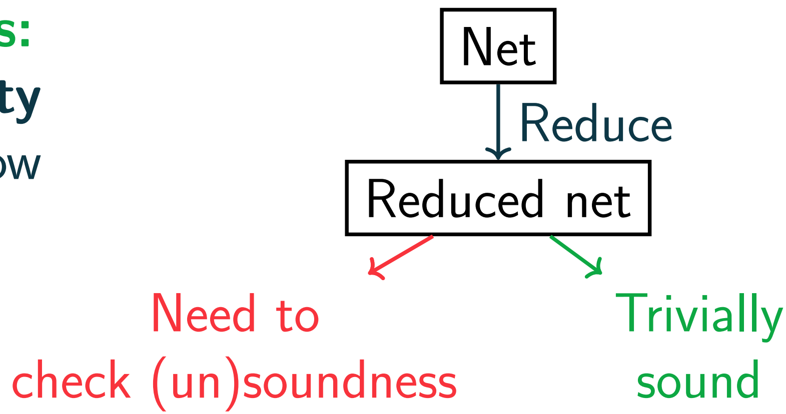
Known exact algorithms:

Use Petri net reachability

Exhaustive exploration is slow

Known incomplete algorithms:

Reduction rules



Verifying soundness

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Reduced net

Need to check (un)soundness

Trivially sound

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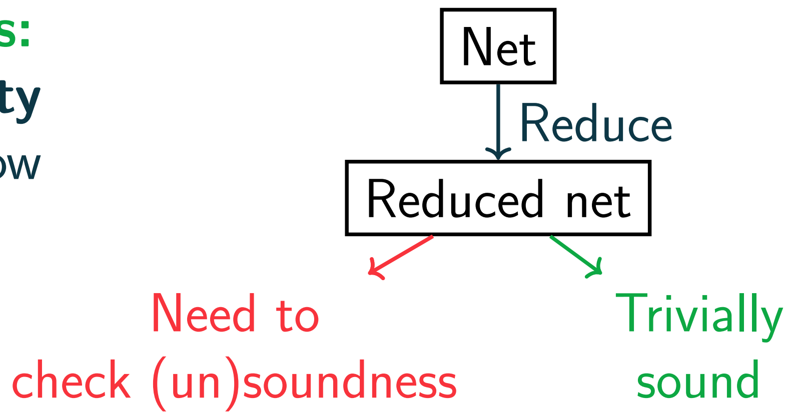
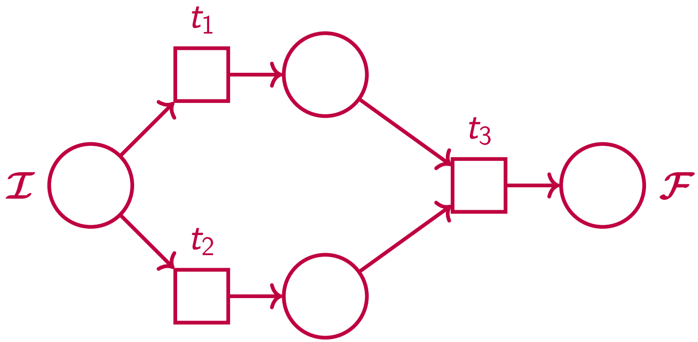
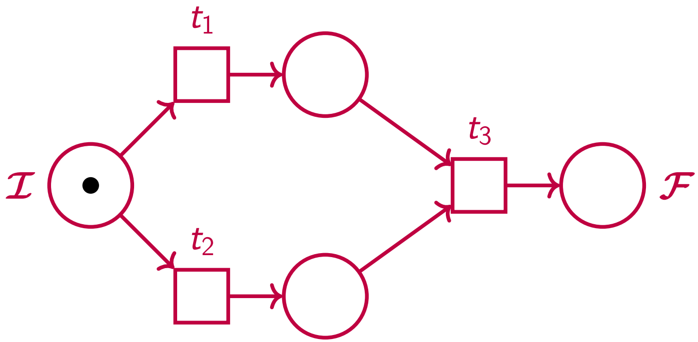


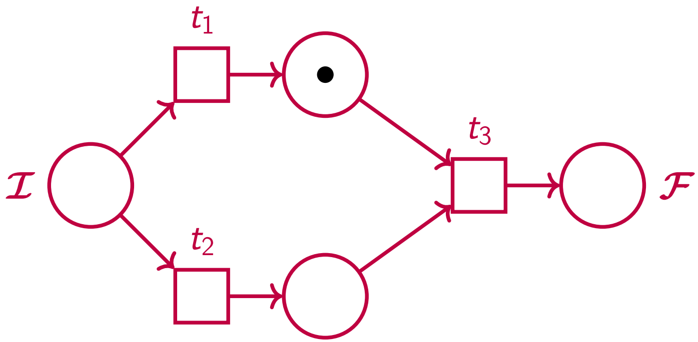
Reachability Relaxations



Reachability Relaxations

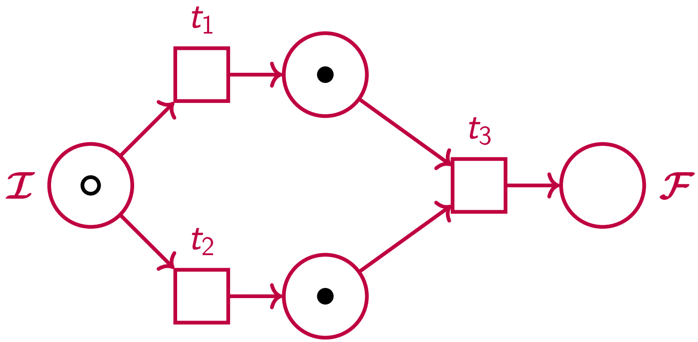


Reachability Relaxations



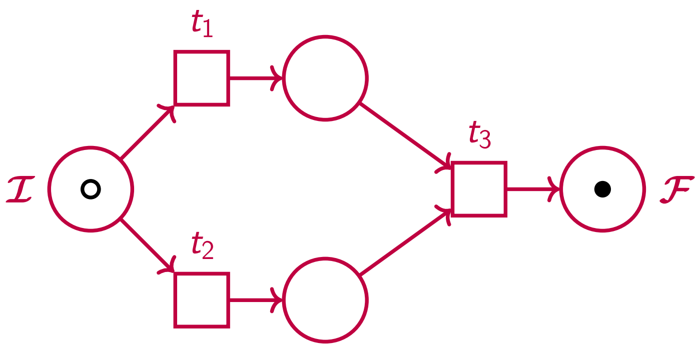
t_1

Reachability Relaxations



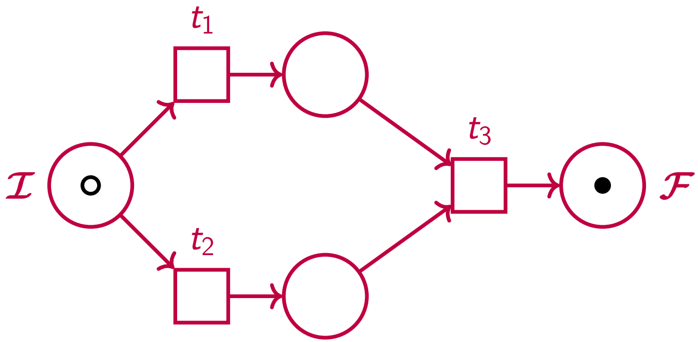
$t_1 \quad t_2$

Reachability Relaxations



$t_1 \quad t_2 \quad t_3$

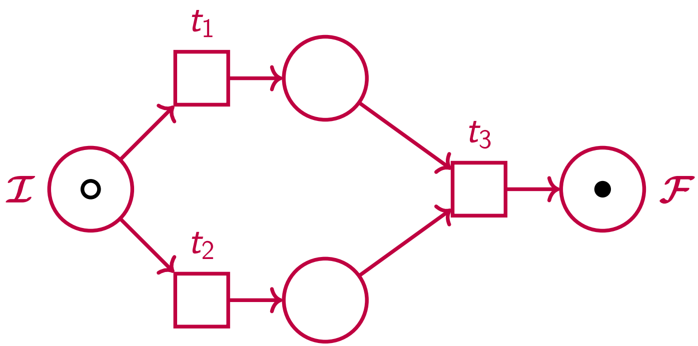
Reachability Relaxations

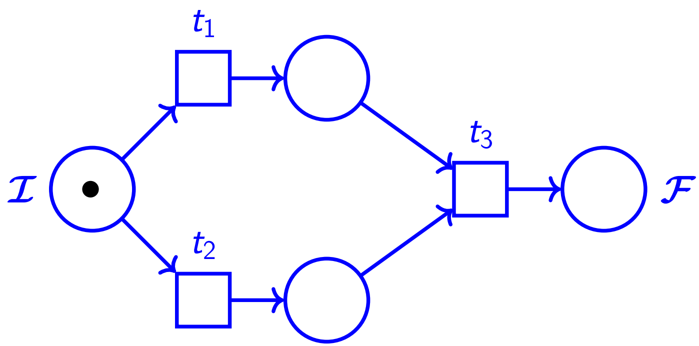


t_1 t_2 t_3

Integer semantics

Reachability Relaxations





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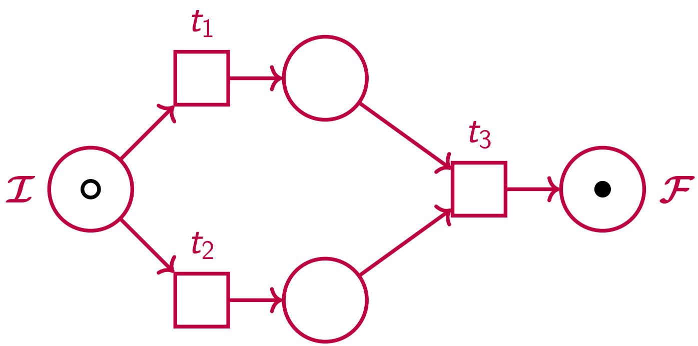
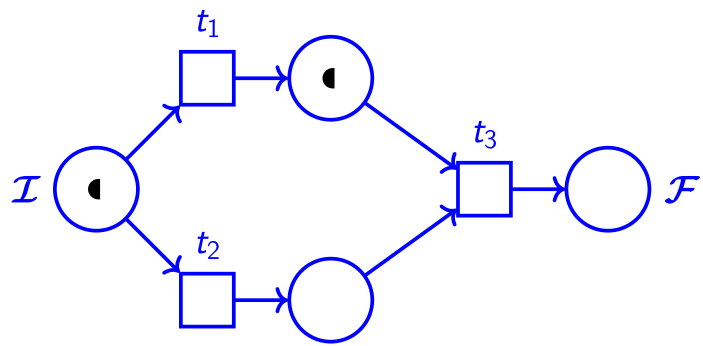
Integer semantics

Reachability Relaxations



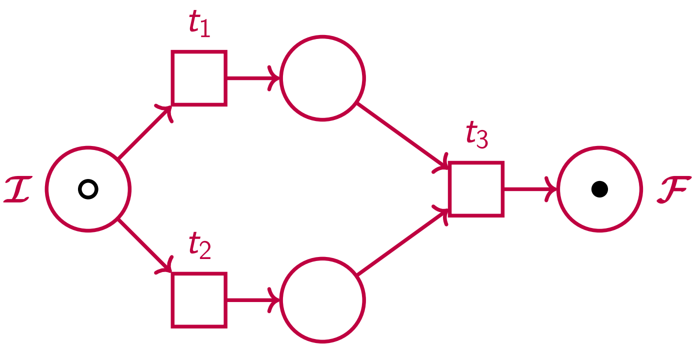
t_1 t_2 t_3

Integer semantics



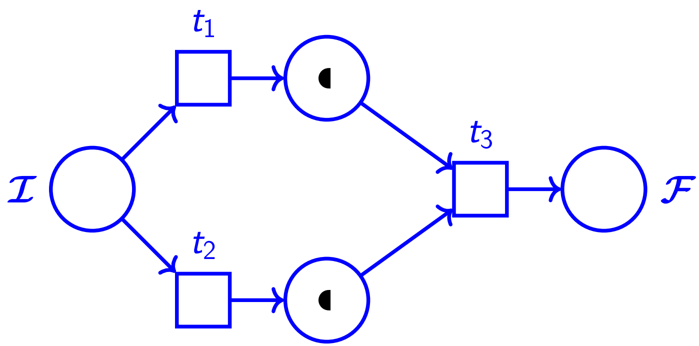
$1/2 t_1$

Reachability Relaxations



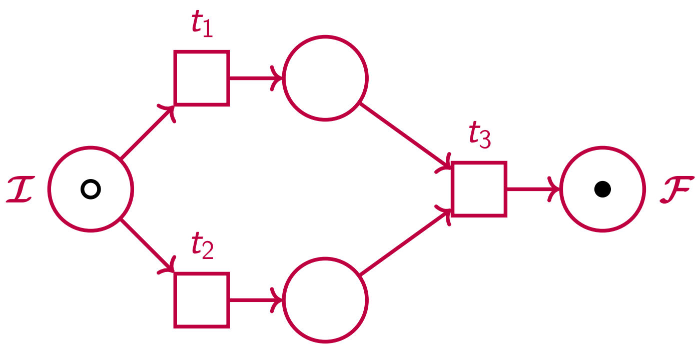
$t_1 \quad t_2 \quad t_3$

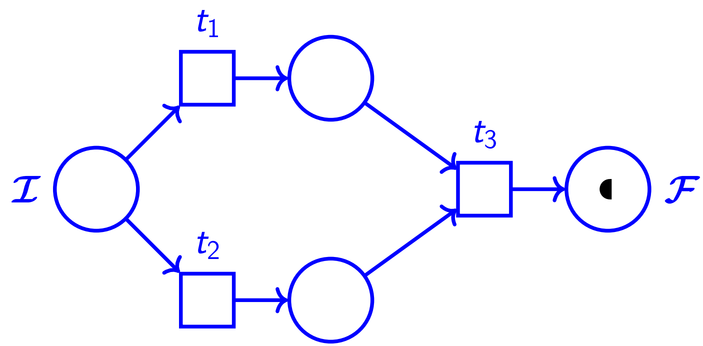
Integer semantics



$1/2 t_1 \quad 1/2 t_2$

Reachability Relaxations



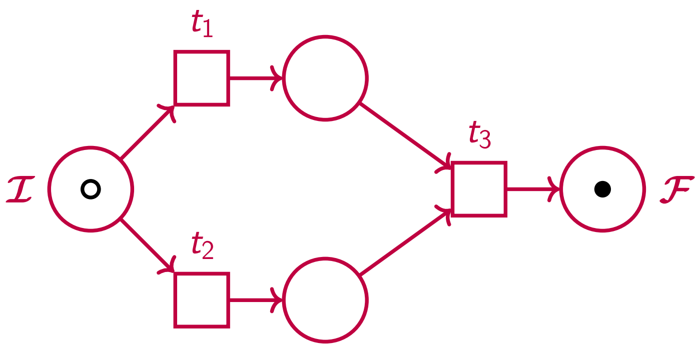


$t_1 \quad t_2 \quad t_3$

Integer semantics

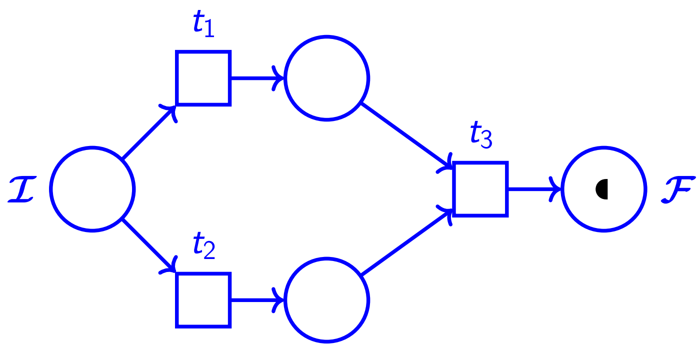
$1/2t_1 \quad 1/2t_2 \quad 1/2t_3$

Reachability Relaxations



$t_1 \quad t_2 \quad t_3$

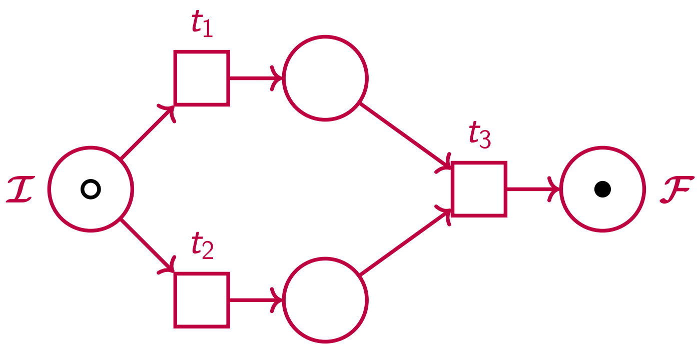
Integer semantics



$1/2t_1 \quad 1/2t_2 \quad 1/2t_3$

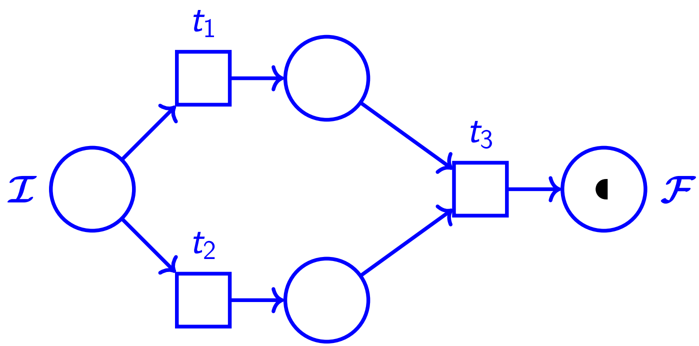
Continuous semantics

Reachability Relaxations



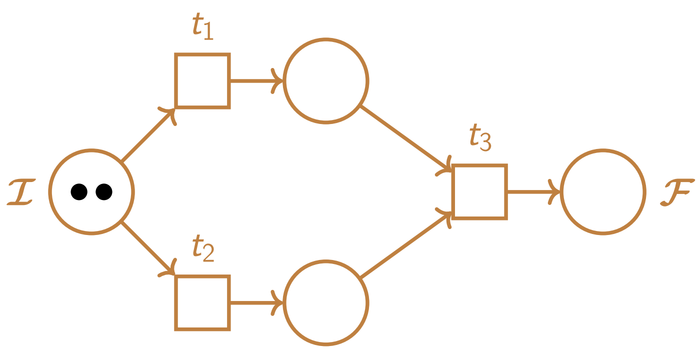
$t_1 \quad t_2 \quad t_3$

Integer semantics

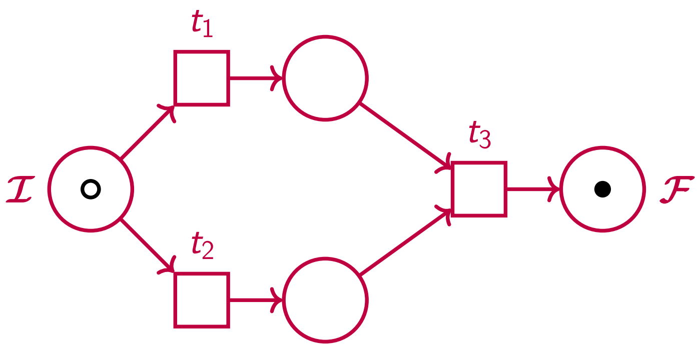


$1/2t_1 \quad 1/2t_2 \quad 1/2t_3$

Continuous semantics

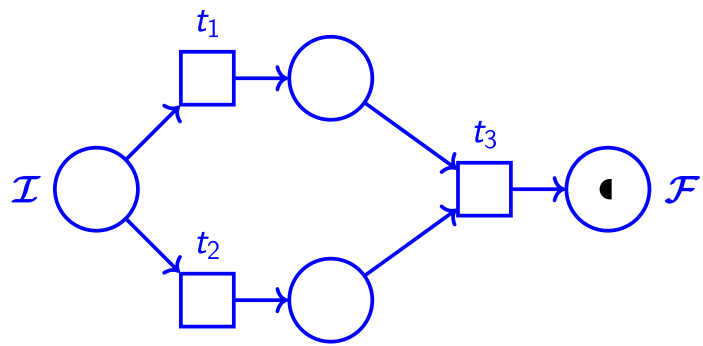


Reachability Relaxations



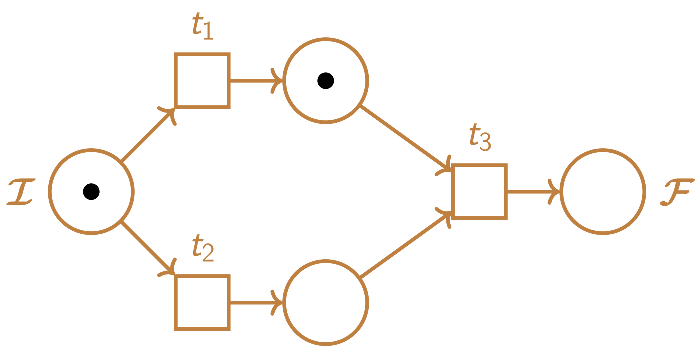
$t_1 \quad t_2 \quad t_3$

Integer semantics



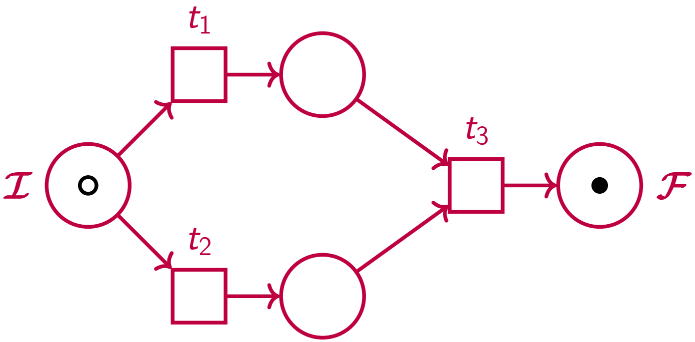
$1/2 t_1 \quad 1/2 t_2 \quad 1/2 t_3$

Continuous semantics



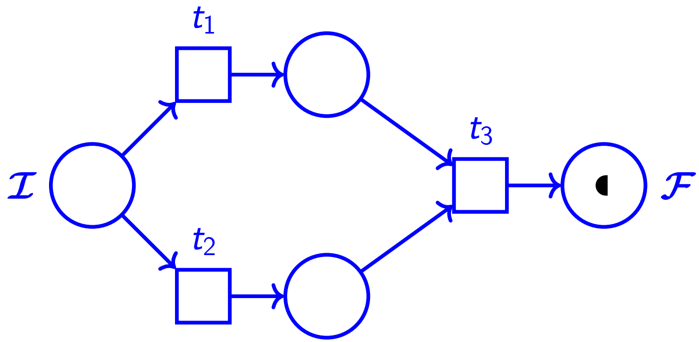
t_1

Reachability Relaxations



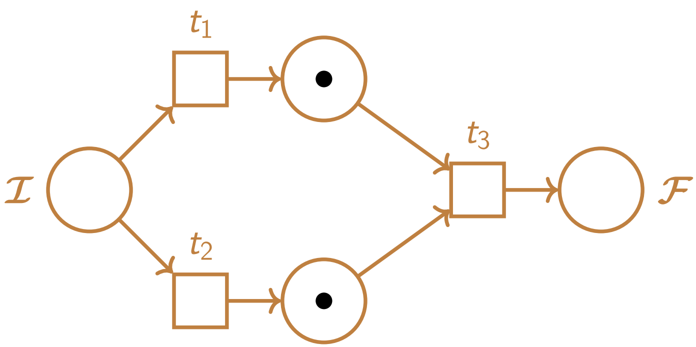
$t_1 \quad t_2 \quad t_3$

Integer semantics



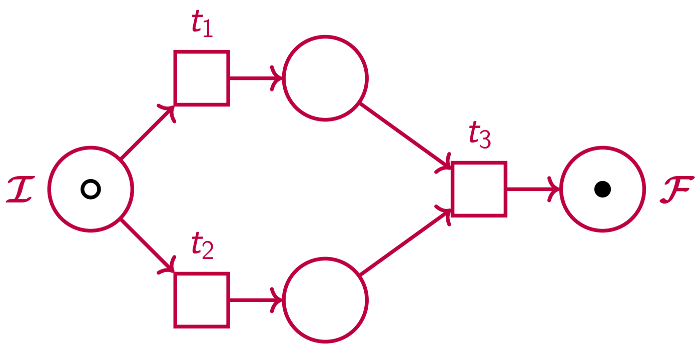
$1/2t_1 \quad 1/2t_2 \quad 1/2t_3$

Continuous semantics



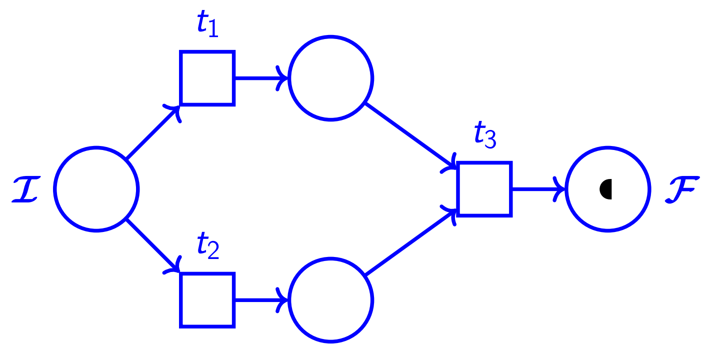
$t_1 \quad t_2$

Reachability Relaxations



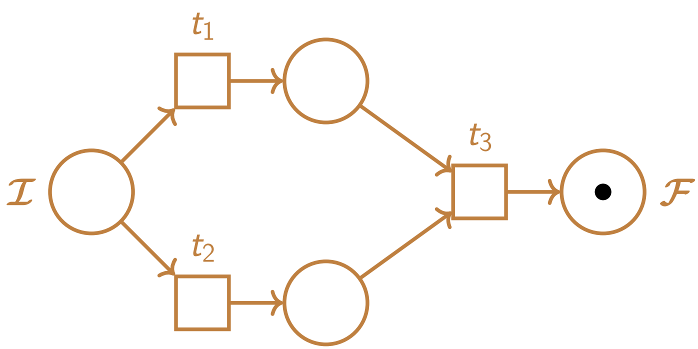
$t_1 \quad t_2 \quad t_3$

Integer semantics



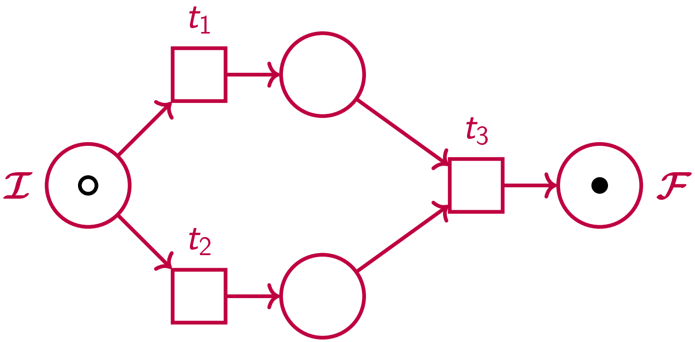
$1/2t_1 \quad 1/2t_2 \quad 1/2t_3$

Continuous semantics



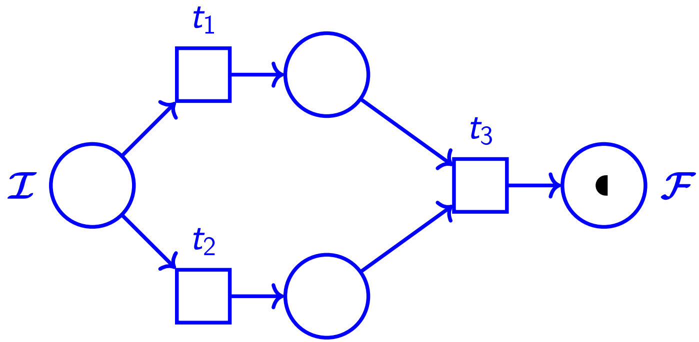
$t_1 \quad t_2 \quad t_3$

Reachability Relaxations



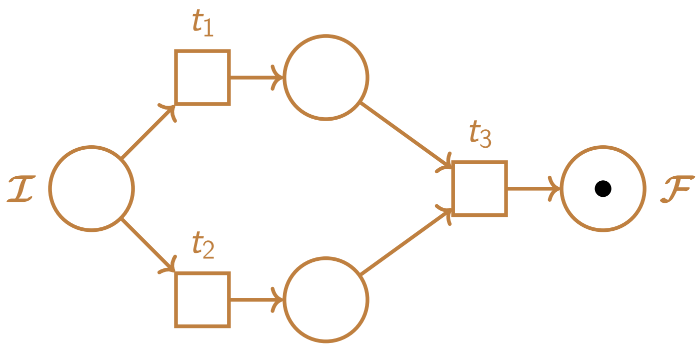
t_1 t_2 t_3

Integer semantics



$1/2t_1$ $1/2t_2$ $1/2t_3$

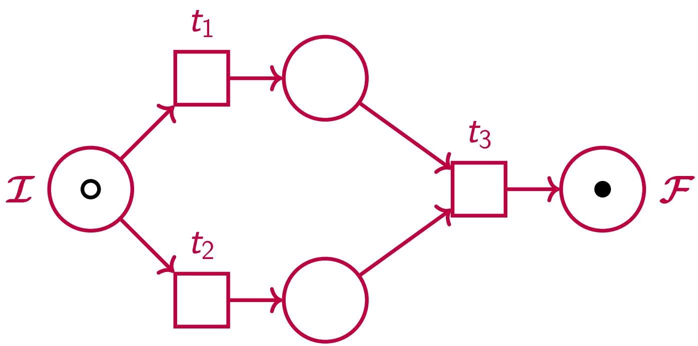
Continuous semantics



t_1 t_2 t_3

Reachability with many initial tokens

Reachability Relaxations



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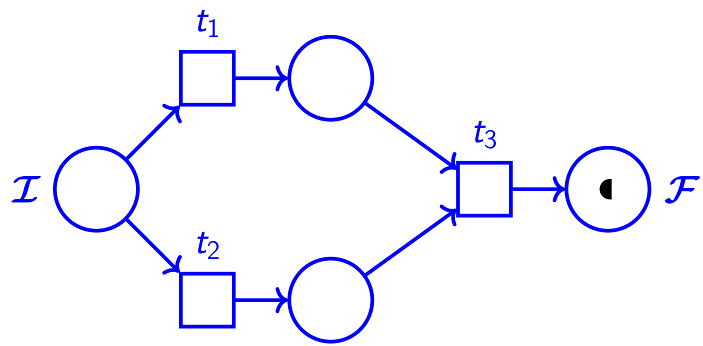
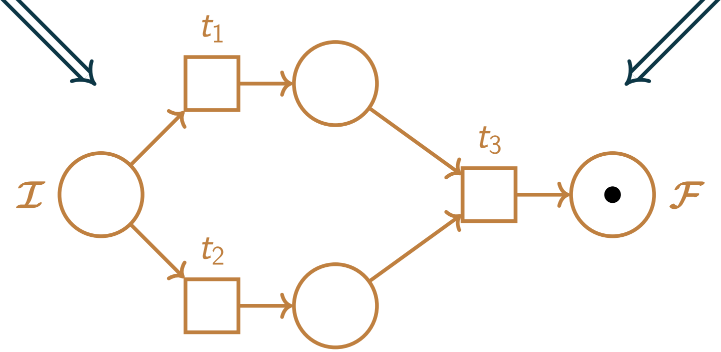
Integer semantics



$1/2 t_1 \quad 1/2 t_2 \quad 1/2 t_3$

Continuous semantics



$t_1 \quad t_2 \quad t_3$

Reachability with many initial tokens

Integer Semantics and Generalised Soundness

Integer Semantics and Generalised Soundness

Integer unboundedness:
$\{\mathcal{I}: 1\}$ reaches m reaches m' with $m' > m$
under **integer** semantics

Integer Semantics and Generalised Soundness

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$$\boxed{\text{A net } N \text{ is integer unbounded} \implies N \text{ is not generalised sound}}$$

Integer Semantics and Generalised Soundness

Integer unboundedness:
$\{\mathcal{I} : 1\}$ reaches m reaches m' with $m' > m$
under **integer** semantics

$$\boxed{\text{A net } N \text{ is integer unbounded} \implies N \text{ is not generalised sound}}$$

Checking integer unboundedness:
PTIME via Integer Linear Programming

Continuous Semantics and Generalised Soundness

Continuous Semantics and Generalised Soundness

Continuous Soundness:

$\{\mathcal{I}: 1\}$ reaches $m \implies m$ reaches $\{\mathcal{F}: 1\}$

under **continuous** semantics

Continuous Semantics and Generalised Soundness

Continuous Soundness:
$\{\mathcal{I}\colon 1\}$ reaches $m \implies m$ reaches $\{\mathcal{F}\colon 1\}$
under **continuous** semantics

$$\boxed{\text{A net } N \text{ is not continuously sound} \implies N \text{ is not generalised sound}}$$

Continuous Semantics and Generalised Soundness

Continuous Soundness:
$\{\mathcal{I}\colon 1\}$ reaches $m \implies m$ reaches $\{\mathcal{F}\colon 1\}$
under **continuous** semantics

A net N is not continuously sound $\implies$ N is not generalised sound

Checking continuous soundness:
coNP-complete

Continuous Semantics and Generalised Soundness

Continuous Soundness:
$\{\mathcal{I}\colon 1\}$ reaches $m \implies m$ reaches $\{\mathcal{F}\colon 1\}$
under **continuous** semantics

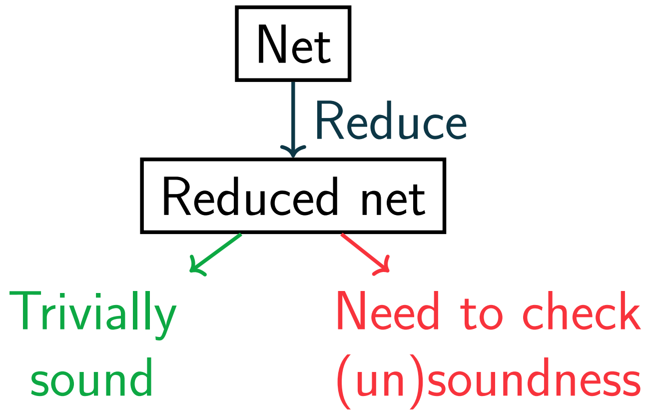
$\boxed{\text{A net } N \text{ is not continuously sound} \implies N \text{ is not generalised sound}}$

Checking continuous soundness:
coNP-complete

Bonus:
Continuous sound $\equiv$ Generalised sound $\equiv$ Structurally sound
on *Free-Choice Nets*

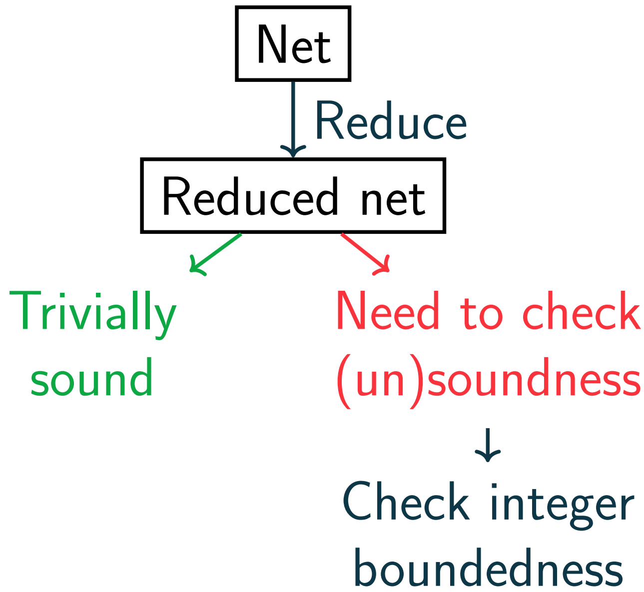
Generalised Soundness: Our approach

Reduction rules



Generalised Soundness: Our approach

Reduction rules



Generalised Soundness: Our approach

Reduction rules

Net

↓ Reduce

Reduced net

Trivially sound

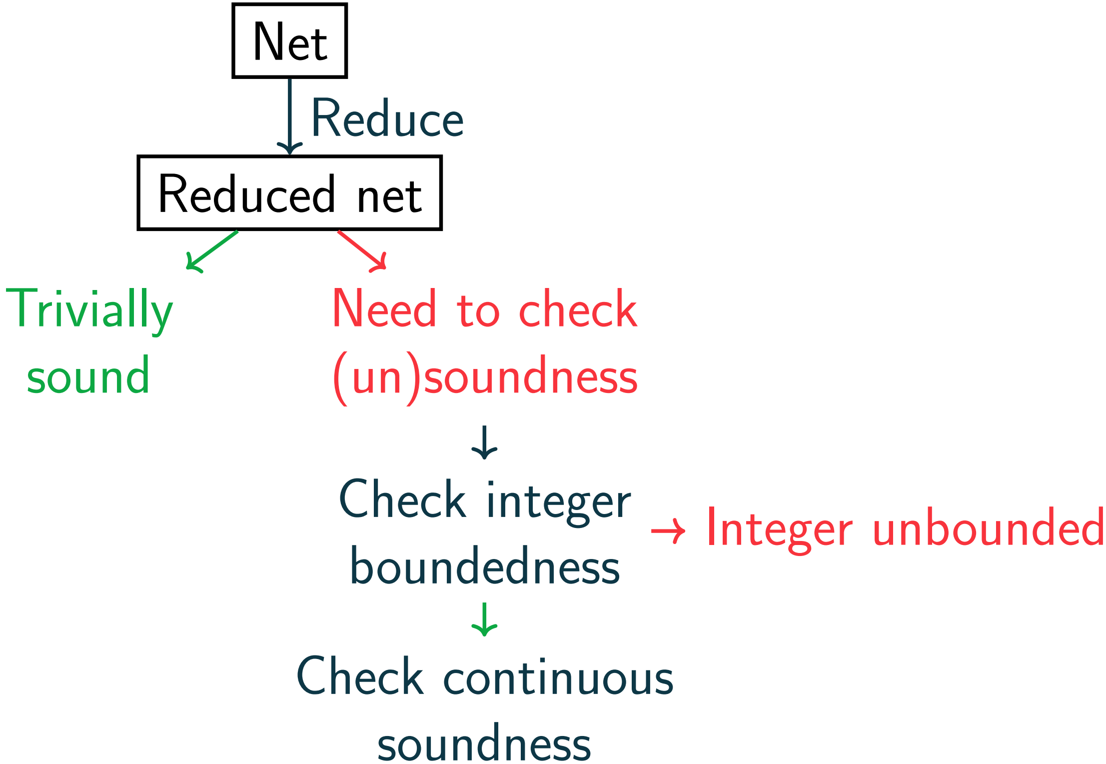
Need to check (un)soundness

↓

Check integer boundedness → Integer unbounded

Generalised Soundness: Our approach

Reduction rules



Generalised Soundness: Our approach

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Reduced net

Trivially sound

Need to check (un)soundness

Check integer boundedness → Integer unbounded

Check continuous soundness → Continuously unsound

Generalised Soundness: Our approach

Reduction rules

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Reduce

Reduced net

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Exhaustive exploration needed

Generalised Soundness: Our approach

Reduction rules

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Check continuous soundness

← Continuously sound

→ Continuously unsound

Exhaustive exploration needed

Benchmarks: 1976 industrial nets

Generalised Soundness: Our approach

Reduction rules

Net

↓ Reduce

Reduced net

642/1976 Trivially sound

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1976 industrial nets

Generalised Soundness: Our approach

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1111/1976

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Reduced net

642/1976 Trivially sound

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↓

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1111/1976

↓

Continuously sound ← Check continuous soundness → Continuously unsound

Exhaustive exploration needed

223/1976

Benchmarks:
1976 industrial nets

Verifying soundness

Complexity

Generalised soundness	PSPACE-complete
Structural soundness	EXPSPACE-complete

Integer unboundedness
Continuous soundness 1

Structural quasi-soundness via continuous reachability 2

Quasi-Soundness

k-**soundness:**

$\{\mathcal{I}\colon k\}$ reaches m
$\implies$ m reaches $\{\mathcal{F}\colon k\}$

Quasi-Soundness

k-soundness:

$\{\mathcal{I}\colon k\}$ reaches m

$\implies$ m reaches $\{\mathcal{F}\colon k\}$

k-quasi-soundness:

$\{\mathcal{I}\colon k\}$ reaches $\{\mathcal{F}\colon k\}$

Quasi-Soundness

k-**soundness:**
$\{\mathcal{I}\colon k\}$ reaches m
$\implies m$ reaches $\{\mathcal{F}\colon k\}$

$\Longrightarrow$

k-**quasi-soundness:**
$\{\mathcal{I}\colon k\}$ reaches $\{\mathcal{F}\colon k\}$

Quasi-Soundness

k-**soundness:**
$\{\mathcal{I}\colon k\}$ reaches m
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$\Longrightarrow$

k-**quasi-soundness:**
$\{\mathcal{I}\colon k\}$ reaches $\{\mathcal{F}\colon k\}$

$\mathbf{k_N}$:
min so that N
is k-quasi-sound

Quasi-Soundness

k-soundness:
$\{\mathcal{I}: k\}$ reaches m
$\implies$ m reaches $\{\mathcal{F}: k\}$

$\implies$

k-quasi-soundness:
$\{\mathcal{I}: k\}$ reaches $\{\mathcal{F}: k\}$

$\mathbf{k_N}$:
min so that N
is k-quasi-sound

N is structurally sound
$\implies$ N is k_N sound
[Tiplea & Marinescu, 2005]

Quasi-Soundness

k-soundness:
$\{\mathcal{I}: k\}$ reaches m
$\implies$ m reaches $\{\mathcal{F}: k\}$

$\Longrightarrow$

k-quasi-soundness:
$\{\mathcal{I}: k\}$ reaches $\{\mathcal{F}: k\}$

$\mathbf{k_N}$:
min so that N
is k-quasi-sound

Net
$\downarrow$ Reduce
Reduced net
$\swarrow$
Trivially sound

N is structurally sound
$\implies$ N is k_N sound
[Tiplea & Marinescu, 2005]

Quasi-Soundness

k-soundness:
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$\implies$

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$\mathbf{k_N}$:
min so that N
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Net

Reduce

Reduced net

Trivially sound

Find k_N

N is structurally sound
$\implies$ N is k_N sound
[Tiplea & Marinescu, 2005]

Quasi-Soundness

k-soundness:
$\{\mathcal{I}: k\}$ reaches m
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k-quasi-soundness:
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$\mathbf{k_N}$:
min so that N
is k-quasi-sound

N is structurally sound
$\implies$ N is k_N sound
[Tiplea & Marinescu, 2005]

Net $\xrightarrow{\text{Reduce}}$ Reduced net

Reduced net $\to$ Trivially sound

Reduced net $\to$ Find k_N $\to$ None $\implies$ not struct. sound

Quasi-Soundness

k-soundness:
$\{\mathcal{I}\colon k\}$ reaches m
$\implies$ m reaches $\{\mathcal{F}\colon k\}$

$\Longrightarrow$

k-quasi-soundness:
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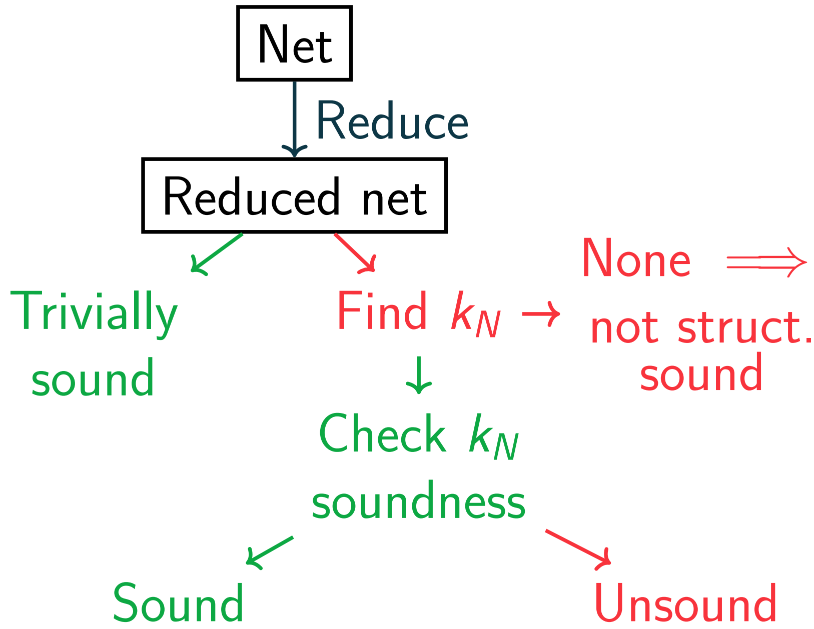

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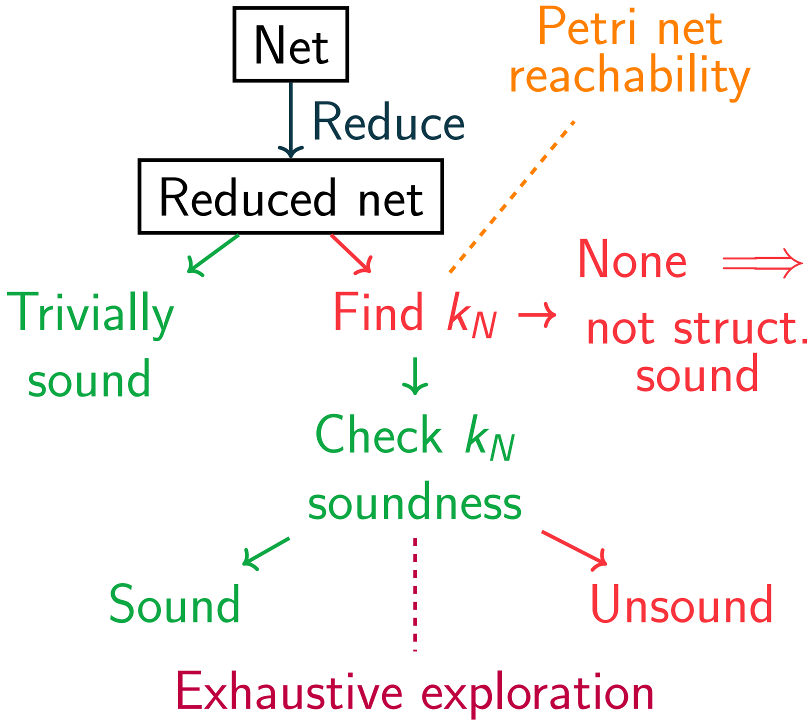

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Our approach:
Continuous reachability

Petri net
reachability

Net

Reduce

Reduced net

Trivially
sound

Find k_N $\to$

None $\implies$
not struct.
sound

Check k_N
soundness

Sound

Unsound

Exhaustive exploration

Quasi-Soundness via Continuous Reachability

k_N exists $\equiv$ $\{\mathcal{I}\colon k\}$ reaches $\{\mathcal{F}\colon k\}$ under the **continuous semantics**

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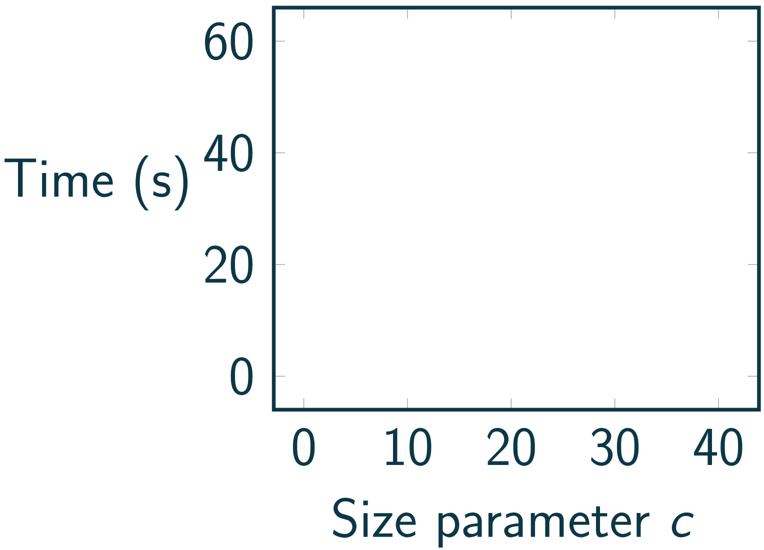

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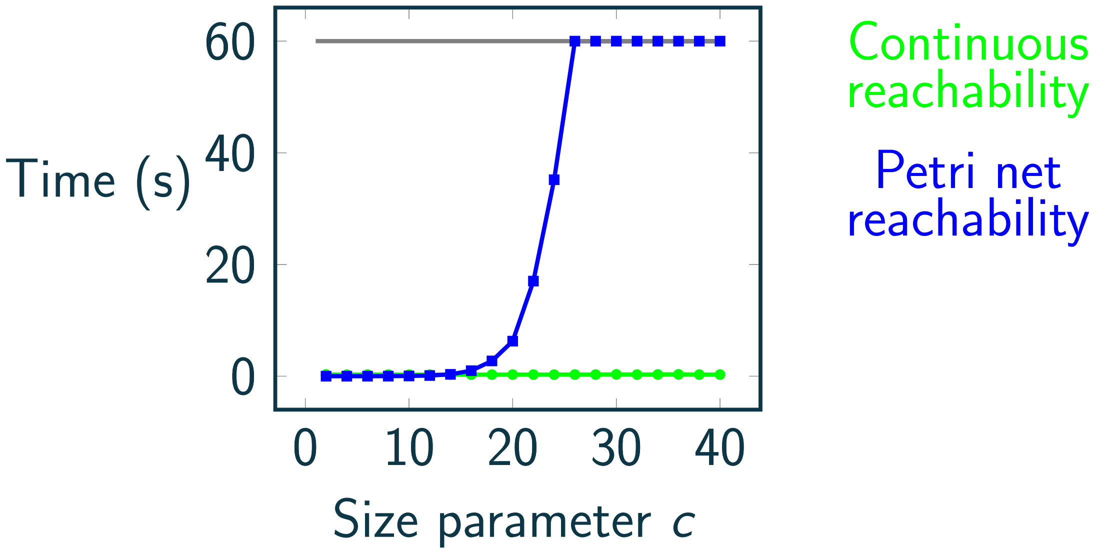

Conclusion

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Generalised and **structural** soundness are challenging to verify

Approximations can provide helpful heuristics

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`https://doi.org/10.6084/m9.figshare.19721674.v2`

CAV Artifact Evaluation Available

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Thanks!