Introduction to Process Mining

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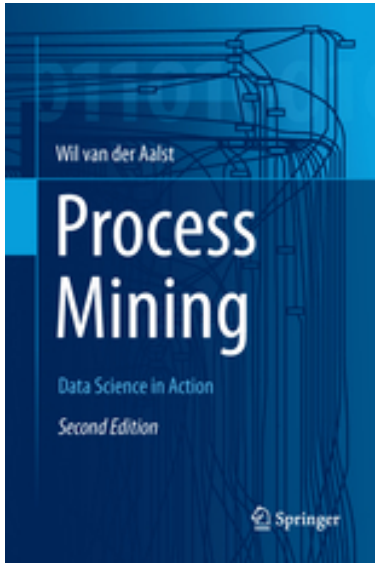
Syllabus

- 9/05 (TODAY): Process mining intro, Process Discovery [T]
- 13/05: DISCO + Inductive Miner [L]
- 15/05: Conformance Checking [T]
- 20/05: Process Mining in Python [L]

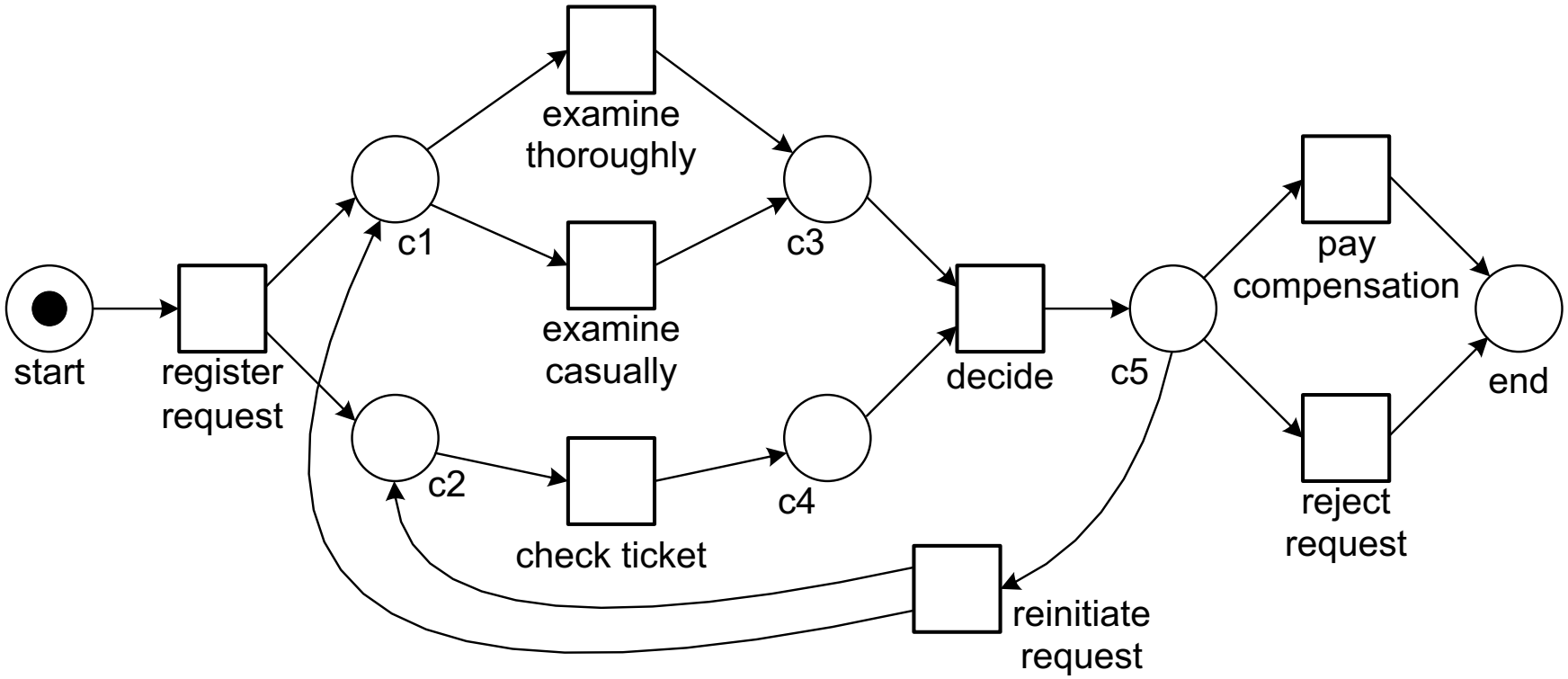
Disclaimer



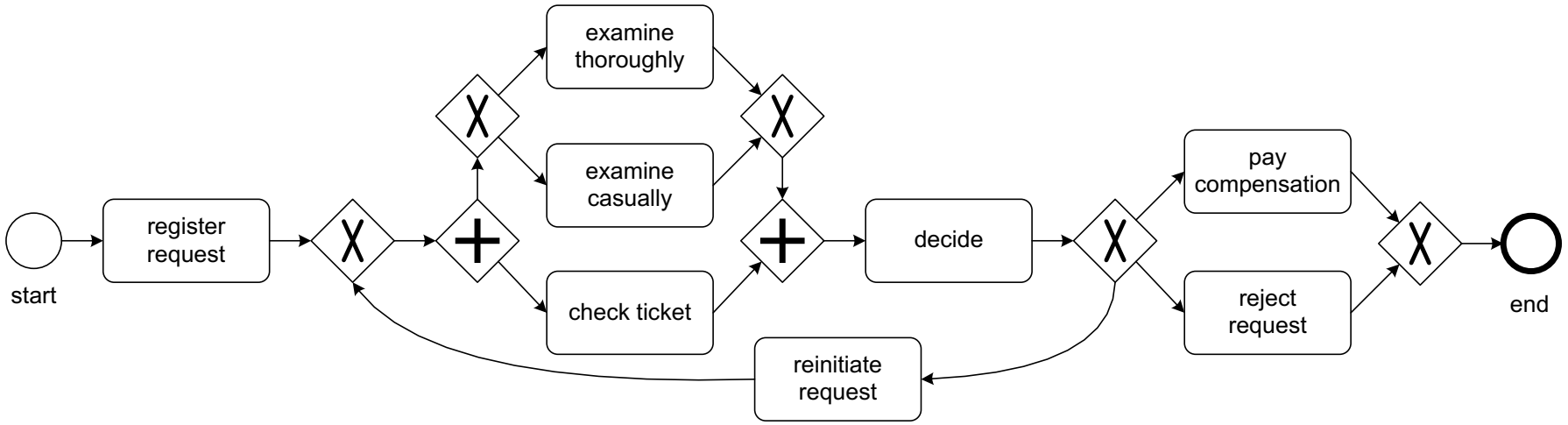
Part of this presentation is taken from the slides of the book from Prof. Wil van der Aalst:

*"***Process Mining - Discovery, Conformance and Enhancement of Business Processes.** Springer 2016, ISBN 978-3-662-49850-7"

Example process model



Same process in terms of BPMN rather than Petri nets



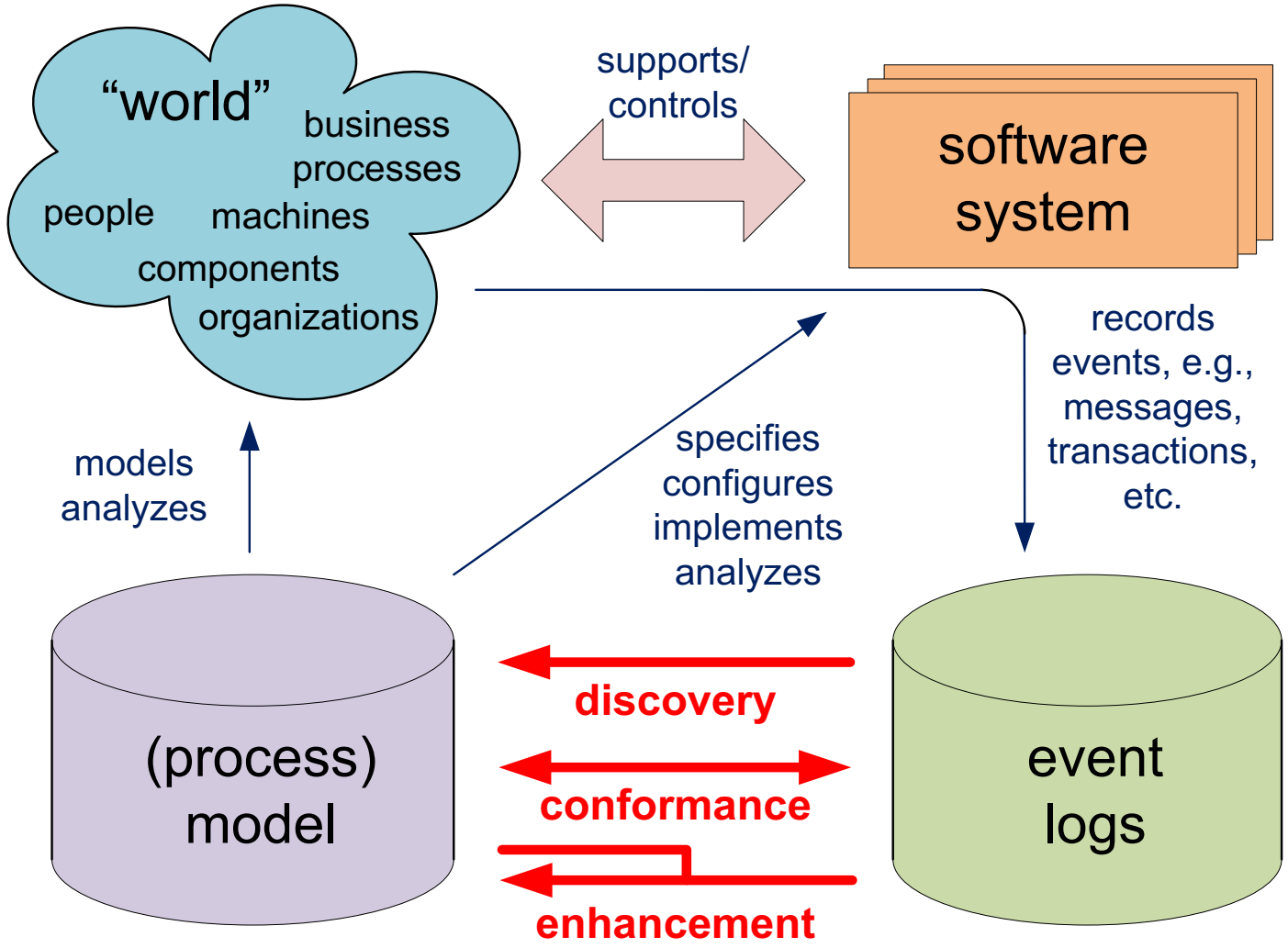
What are process models used for?

- **insight**: while making a model, the modeler is triggered to view the process from various angles;
- **discussion**: the stakeholders use models to structure discussions;
- **documentation**: processes are documented for instructing people or certification purposes (cf. ISO 9000 quality management);
- **verification**: process models are analyzed to find errors in systems or procedures (e.g., potential deadlocks);
- **performance analysis**: techniques like simulation can be used to understand the factors influencing response times, service levels, etc.;
- **animation**: models enable end users to “play out” different scenarios and thus provide feedback to the designer;
- **specification**: models can be used to describe a PAIS before it is implemented and can hence serve as a “contract” between the developer and the end user/management; and
- **configuration**: models can be used to configure a system.

Limitations

- Executable models may be used to force people to work in a particular manner.
- However, most models are not well-aligned with reality.
- Most hand-made models are disconnected from reality and provide only an idealized view on the processes at hand: “paper tigers”.
- Given (a) the interest in process models, (b) the abundance of event data, and (c) the limited quality of hand-made models, it seems worthwhile to relate event data to process models: process mining!

The three main types of process mining: discovery, conformance, and enhancement



Orthogonal: Perspectives

- The control-flow perspective focuses on the control-flow, i.e., the ordering of activities.
- The organizational perspective focuses on information about resources hidden in the log, i.e., which actors (e.g., people, systems, roles, and departments) are involved and how are they related.
- The case perspective focuses on properties of cases, e.g., cases can also be characterized by the values of the corresponding data elements.
- The time perspective is concerned with the timing and frequency of events.

Starting point: event log

case id	event id	properties				
		timestamp	activity	resource	cost	...
1	35654423	30-12-2010:11.02	register request	Pete	50	...
	35654424	31-12-2010:10.06	examine thoroughly	Sue	400	...
	35654425	05-01-2011:15.12	check ticket	Mike	100	...
	35654426	06-01-2011:11.18	decide	Sara	200	...
	35654427	07-01-2011:14.24	reject request	Pete	200	...
2	35654483	30-12-2010:11.32	register request	Mike	50	...
	35654485	30-12-2010:12.12	check ticket	Mike	100	...
	35654487	30-12-2010:14.16	examine casually	Pete	400	...
	35654488	05-01-2011:11.22	decide	Sara	200	...
	35654489	08-01-2011:12.05	pay compensation	Ellen	200	...
3	35654521	30-12-2010:14.32	register request			
	35654522	30-12-2010:15.06	examine casually			
	35654524	30-12-2010:16.34	check ticket			
	35654525	06-01-2011:09.18	decide			
	35654526	06-01-2011:12.18	reinitiate request			
	35654527	06-01-2011:13.06	examine thoroughly			
	35654530	08-01-2011:11.43	check ticket			
	35654531	09-01-2011:09.55	decide			
	35654533	15-01-2011:10.45	pay compensation			
4	35654641	06-01-2011:15.02	register request			
	35654643	07-01-2011:12.06	check ticket			
	35654644	08-01-2011:14.43	examine thoroughly			
	35654645	09-01-2011:12.02	decide			
	35654647	12-01-2011:15.44	reject request			
5	35654711	06-01-2011:09.02	register request			
	35654712	07-01-2011:10.16	examine casually			
	35654714	08-01-2011:11.22	check ticket			
	35654715	10-01-2011:13.28	decide			
	35654716	11-01-2011:16.18	reinitiate request			
	35654718	14-01-2011:14.33	check ticket			
	35654719	16-01-2011:15.50	examine casually			
	35654720	19-01-2011:11.18	decide	Sara	200	...
	35654721	20-01-2011:12.48	reinitiate request	Sara	200	...
	35654722	21-01-2011:09.06	examine casually	Sue	400	...
	35654724	21-01-2011:11.34	check ticket	Pete	100	...
	35654725	23-01-2011:13.12	decide	Sara	200	...
	35654726	24-01-2011:14.56	reject request	Mike	200	...
6	35654871	06-01-2011:15.02	register request	Mike	50	...
	35654873	06-01-2011:16.06	examine casually	Ellen	400	...
	35654874	07-01-2011:16.22	check ticket	Mike	100	...
	35654875	07-01-2011:16.52	decide	Sara	200	...
	35654877	16-01-2011:11.47	pay compensation	Mike	200	...
...	...	...	...	...	...	...

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		timestamp	activity	resource	cost	...
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	35654426	06-01-2011:11.18	decide	Sara	200	...
	35654427	07-01-2011:14.24	reject request	Pete	200	...
2	35654483	30-12-2010:11.32	register request	Mike	50	...
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	35654487	30-12-2010:14.16	examine casually	Pete	400	...
	35654488	05-01-2011:11.22	decide	Sara	200	...
	35654489	08-01-2011:12.05	pay compensation	Ellen	200	...

XES, MXML, SA-MXML, CSV, etc.

Simplified event log

case id	event id	properties				
		timestamp	activity	resource		
1	35654423	30-12-2010:11.02	register request	Pete		
	35654424	31-12-2010:10.06	examine thoroughly	Sue		
	35654425	05-01-2011:15.12	check ticket	Mike		
	35654426	06-01-2011:11.18	decide	Sara		
	35654427	07-01-2011:14.24	reject request	Pete		
2	35654483	30-12-2010:11.32	register request	Mike		
	35654485	30-12-2010:12.12	check ticket	Mike		
	35654487	30-12-2010:14.16	examine casually	Pete		
	35654488	05-01-2011:11.22	decide	Sara		
	35654489	08-01-2011:12.05	pay compensation	Ellen		
3	35654521	30-12-2010:14.32	register request	Pete		
	35654522	30-12-2010:15.06	examine casually	Mike		
	35654524	30-12-2010:16.34	check ticket	Ellen		
	35654525	06-01-2011:09.18	decide	Sara		
	35654526	06-01-2011:12.18	reinitiate request	Sara		
	35654527	06-01-2011:13.06	examine thoroughly	Sean		
	35654530	08-01-2011:11.43	check ticket	Pete		
	35654531	09-01-2011:09.55	decide	Sara		
	35654533	15-01-2011:10.45	pay compensation	Ellen		
4	35654641	06-01-2011:15.02	register request	Pete	50	...
	35654643	07-01-2011:12.06	check ticket	Mike	100	...
	35654644	08-01-2011:14.43	examine thoroughly	Sean	400	...
	35654645	09-01-2011:12.02	decide	Sara	200	...
	35654647	12-01-2011:15.44	reject request	Ellen	200	...
5	35654711	06-01-2011:09.02	register request	Ellen	50	...
	35654712	07-01-2011:10.16	examine casually	Mike	400	...
	35654714	08-01-2011:11.22	check ticket	Pete	100	...
	35654715	10-01-2011:13.28	decide	Sara	200	...
	35654716	11-01-2011:16.18	reinitiate request	Sara	200	...
	35654718	14-01-2011:14.33	check ticket	Ellen	100	...
	35654719	16-01-2011:15.50	examine casually	Mike	400	...
	35654720	19-01-2011:11.18	decide	Sara	200	...
	35654721	20-01-2011:12.48	reinitiate request	Sara	200	...
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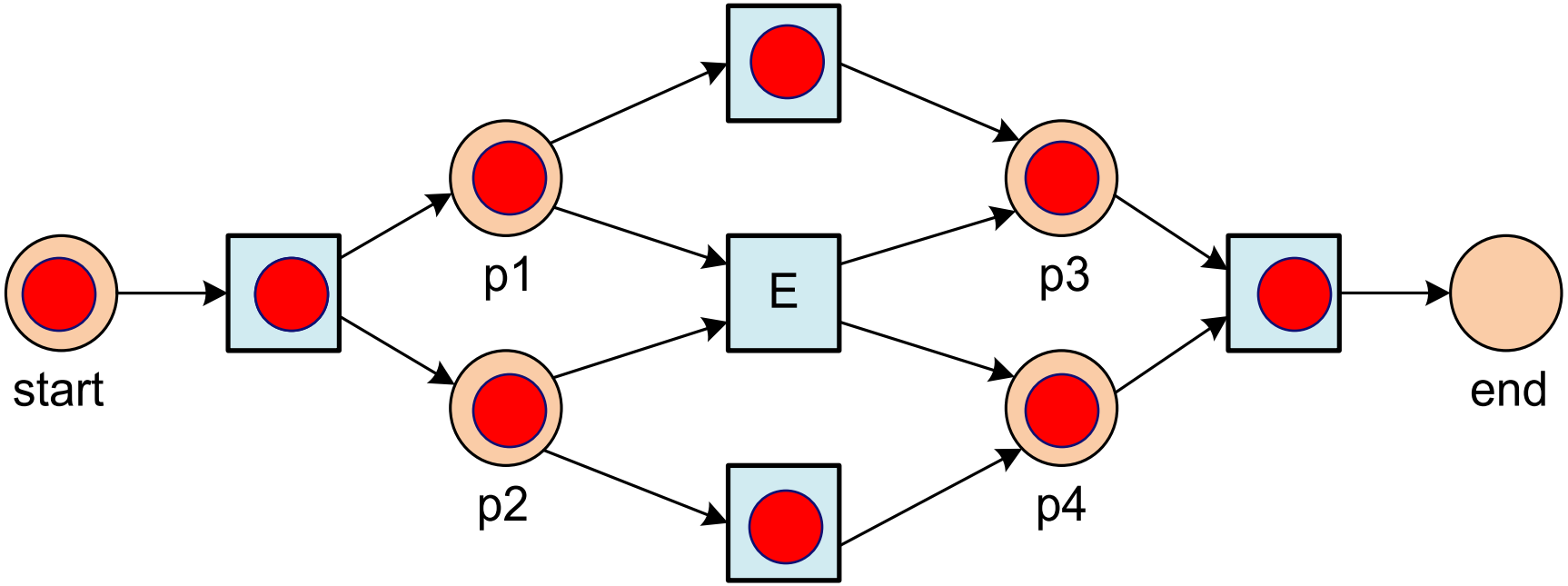
	35654874	07-01-2011:16.22	check ticket	Mike	100	...
	35654875	07-01-2011:16.52	decide	Sara	200	...
	35654877	16-01-2011:11.47	pay compensation	Mike	200	...
...	...	...	...	...	...	...

case id	trace
1	$\langle a, b, d, e, h \rangle$
2	$\langle a, d, c, e, g \rangle$
3	$\langle a, c, d, e, f, b, d, e, g \rangle$
4	$\langle a, d, b, e, h \rangle$
5	$\langle a, c, d, e, f, d, c, e, f, c, d, e, h \rangle$
6	$\langle a, c, d, e, g \rangle$
...	...

a = register request,
b = examine thoroughly,
c = examine casually,
d = check ticket,
e = decide,
f = reinitiate request,
g = pay compensation,
and h = reject request

Petri net semantics



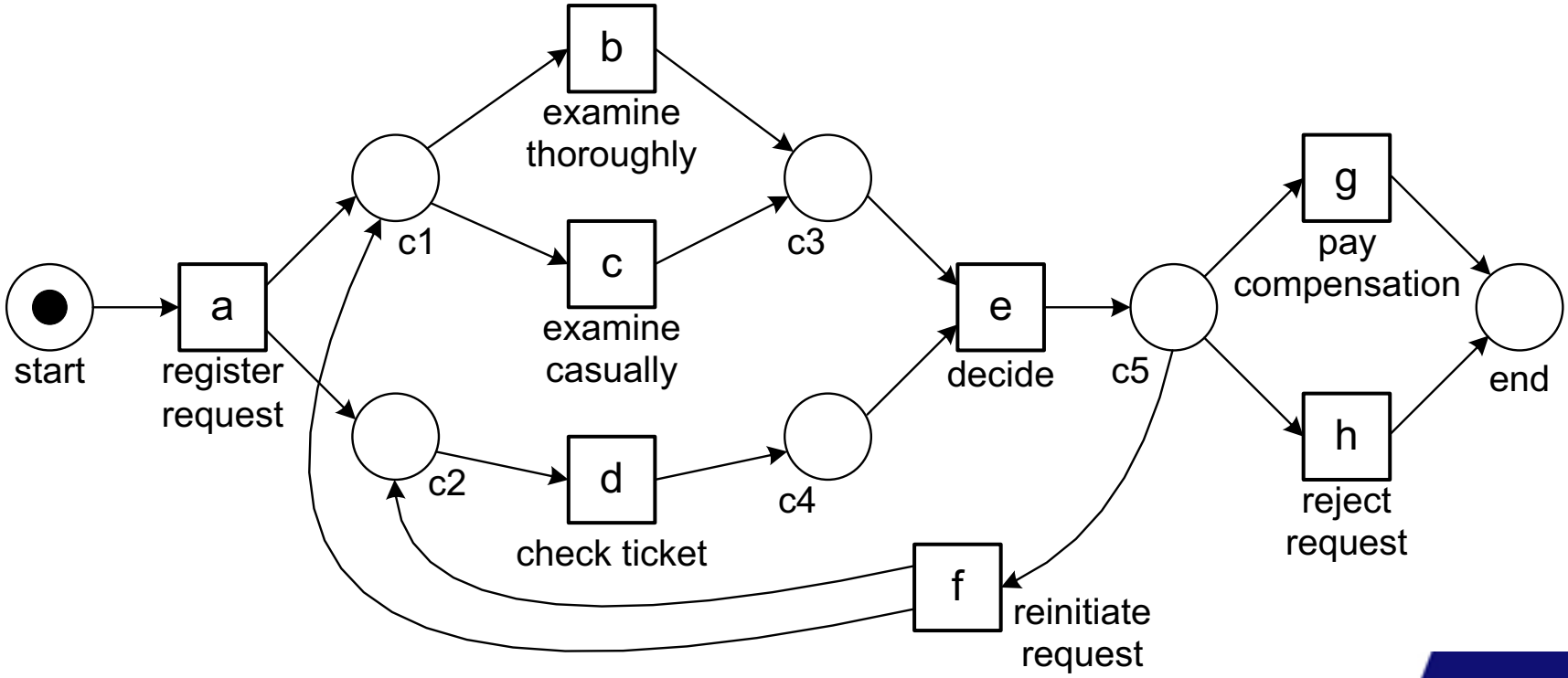
A B C D A E D A E D

A B C D A C B D

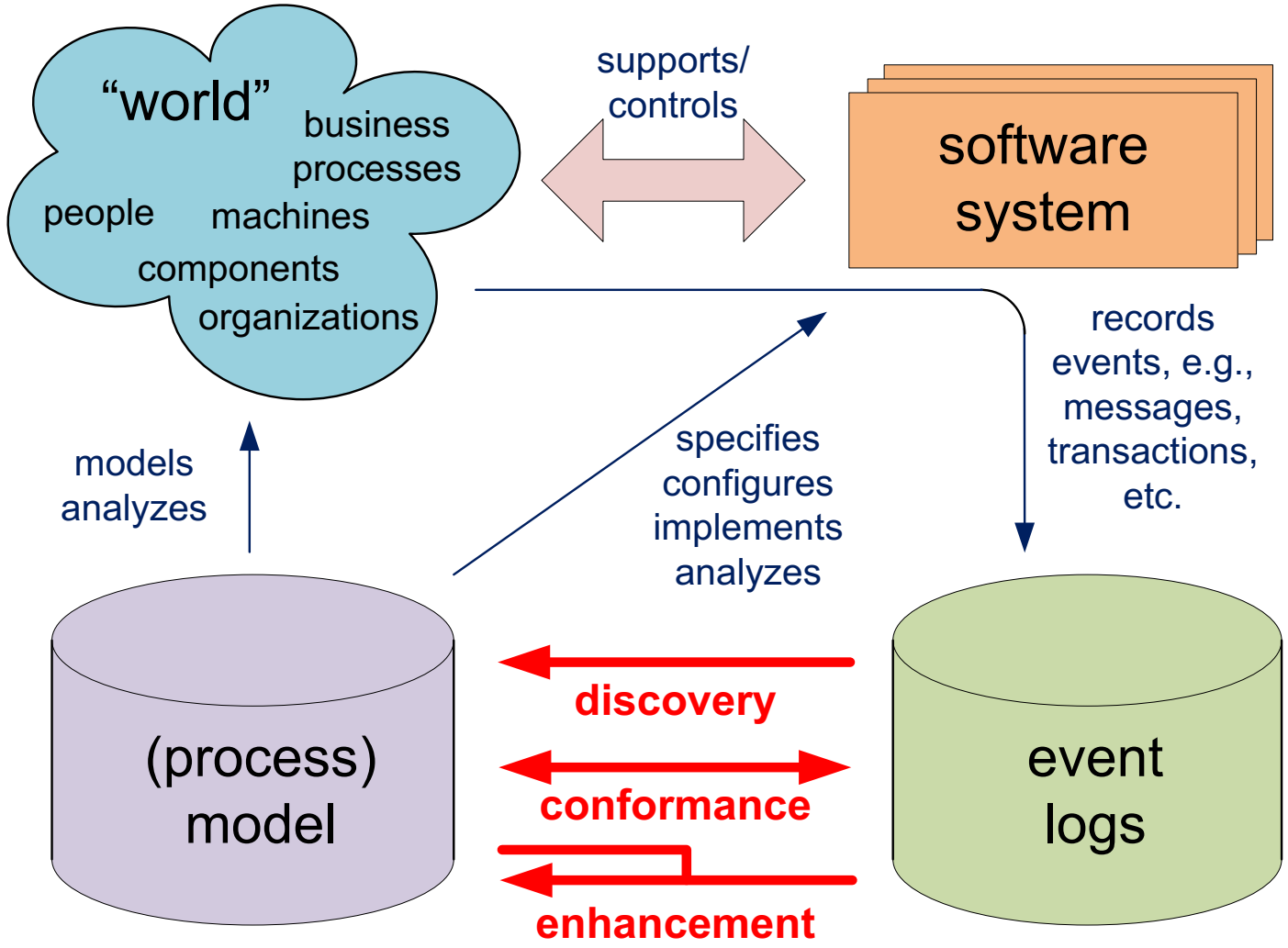
A C B D A E D A C B D

Process discovery

case id	trace
1	$\langle a, b, d, e, h \rangle$
2	$\langle a, d, c, e, g \rangle$
3	$\langle a, c, d, e, f, b, d, e, g \rangle$
4	$\langle a, d, b, e, h \rangle$
5	$\langle a, c, d, e, f, d, c, e, f, c, d, e, h \rangle$
6	$\langle a, c, d, e, g \rangle$
...	...

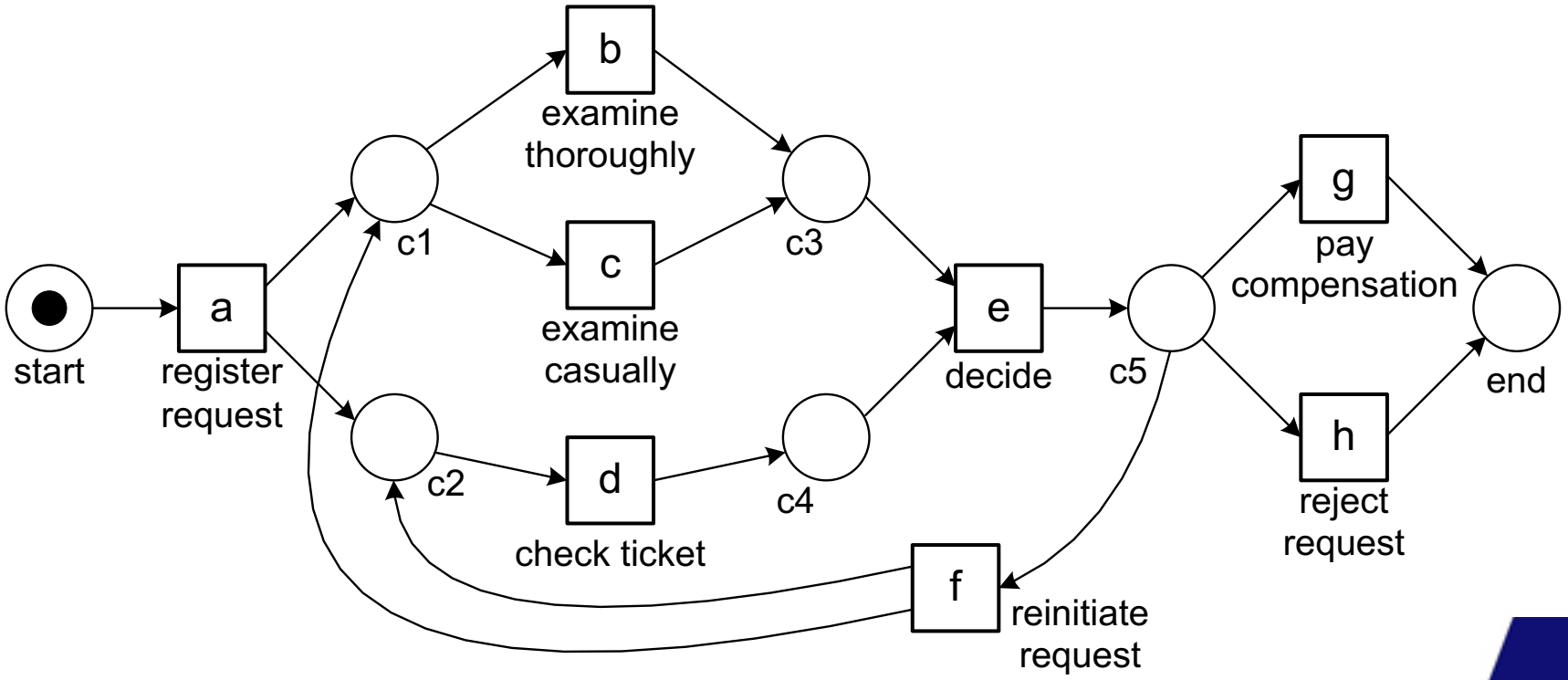


Beyond discovery: conformance and enhancement

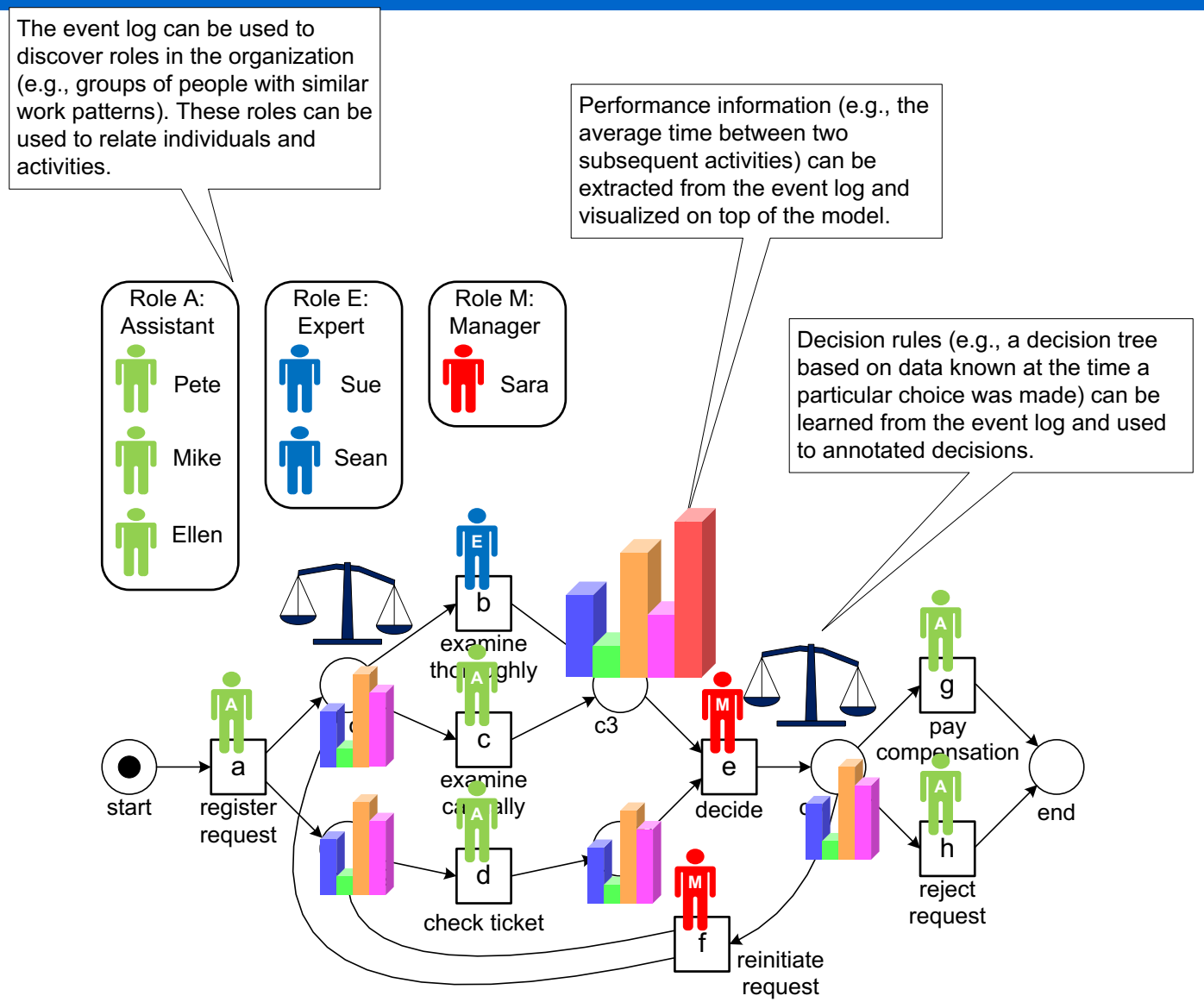


Another event log

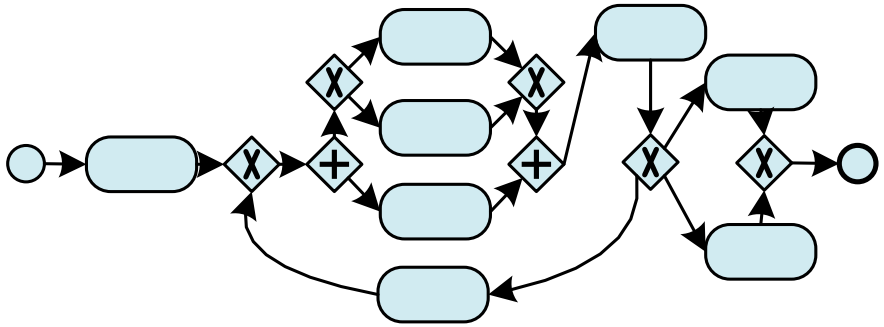
case id	trace
1	$\langle a,b,d,e,h \rangle$
2	$\langle a,d,c,e,g \rangle$
3	$\langle a,c,d,e,f,b,d,e,g \rangle$
4	$\langle a,d,b,e,h \rangle$
5	$\langle a,c,d,e,f,d,c,e,f,c,d,e,h \rangle$
6	$\langle a,c,d,e,g \rangle$
7	$\langle \mathbf{a},\mathbf{b},\mathbf{e},\mathbf{g} \rangle$
8	$\langle \mathbf{a},\mathbf{b},\mathbf{d},\mathbf{e} \rangle$
9	$\langle a,d,c,e,f,d,c,e,f,b,d,e,h \rangle$
10	$\langle \mathbf{a},\mathbf{c},\mathbf{d},\mathbf{e},\mathbf{f},\mathbf{b},\mathbf{d},\mathbf{g} \rangle$



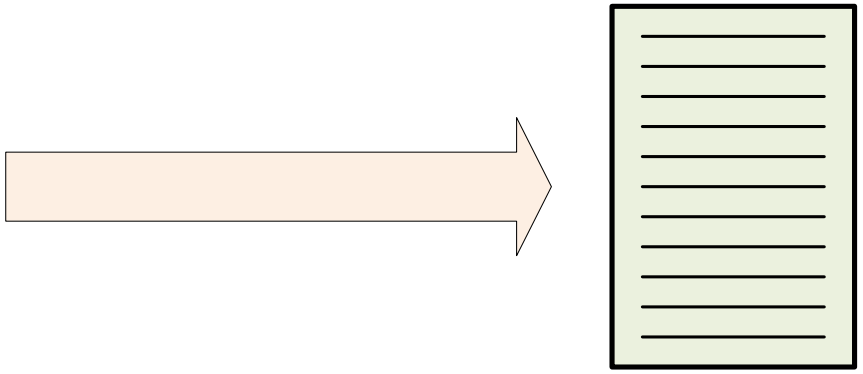
Extension


The event log can be used to discover roles in the organization (e.g., groups of people with similar work patterns). These roles can be used to relate individuals and activities.
Performance information (e.g., the average time between two subsequent activities) can be extracted from the event log and visualized on top of the model.
Decision rules (e.g., a decision tree based on data known at the time a particular choice was made) can be learned from the event log and used to annotated decisions.
Role A: Assistant
Pete
Mike
Ellen
Role E: Expert
Sue
Sean
Role M: Manager
Sara
start
a
register request
b
examine thoroughly
c
examine casually
d
check ticket
c3
e
decide
f
reinitiate request
g
pay compensation
h
reject request
end

Play-Out

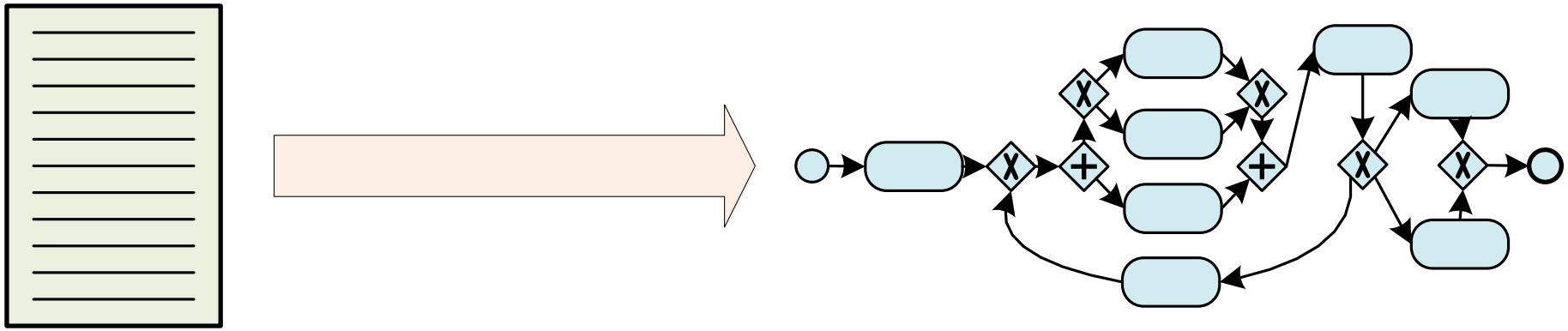


process model



event log

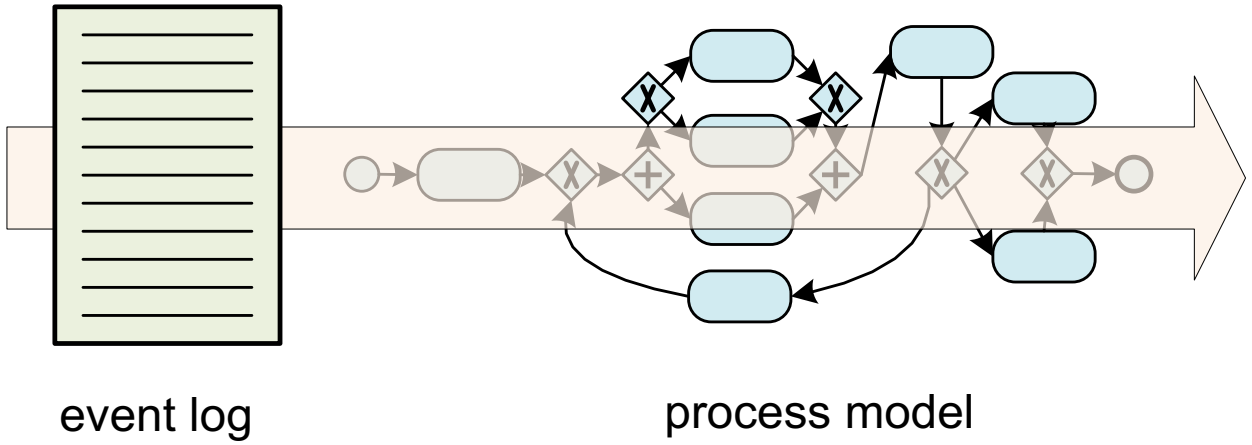
Play-In



event log

process model

Replay



event log

process model

- extended model showing times, frequencies, etc.
- diagnostics
- predictions
- recommendations

Replay

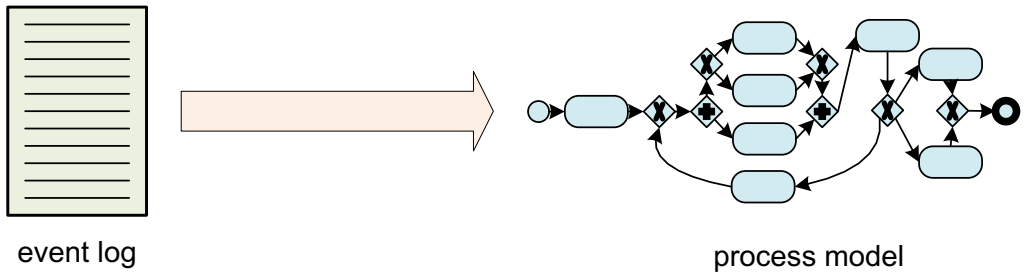
- Connecting models to real events is crucial!
- Possible uses:
  - Conformance checking
  - Repairing models
  - Extending the model with frequencies and temporal information
  - Constructing predictive models
  - Operational support (prediction, recommendation, etc.)

Relation between data mining and process mining

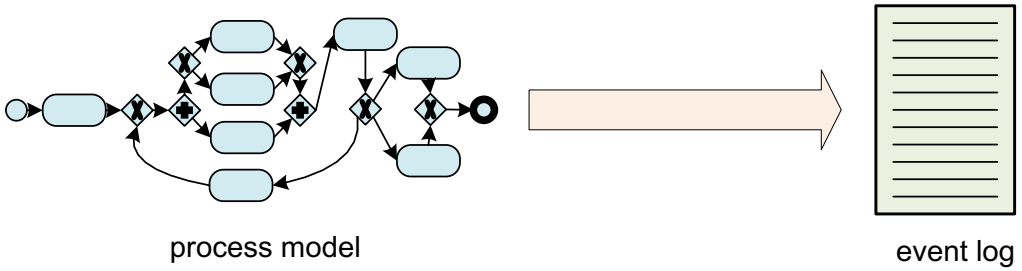
- Process mining: about end-to-end processes.
- Data mining: data-centric and not process-centric.
- Judging the quality of data mining and process mining: many similarities, but also some differences.
- Clearly, process mining techniques can benefit from experiences in the data mining field.

Process discovery = Play-In

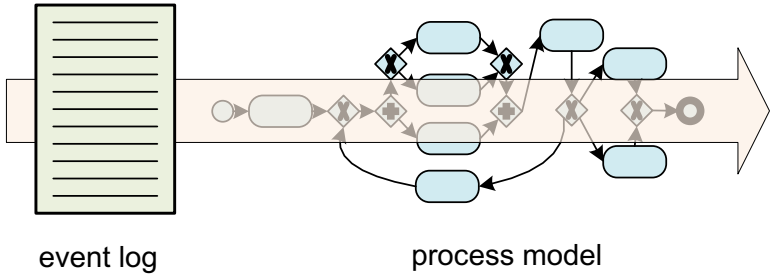
Play-In



Play-Out

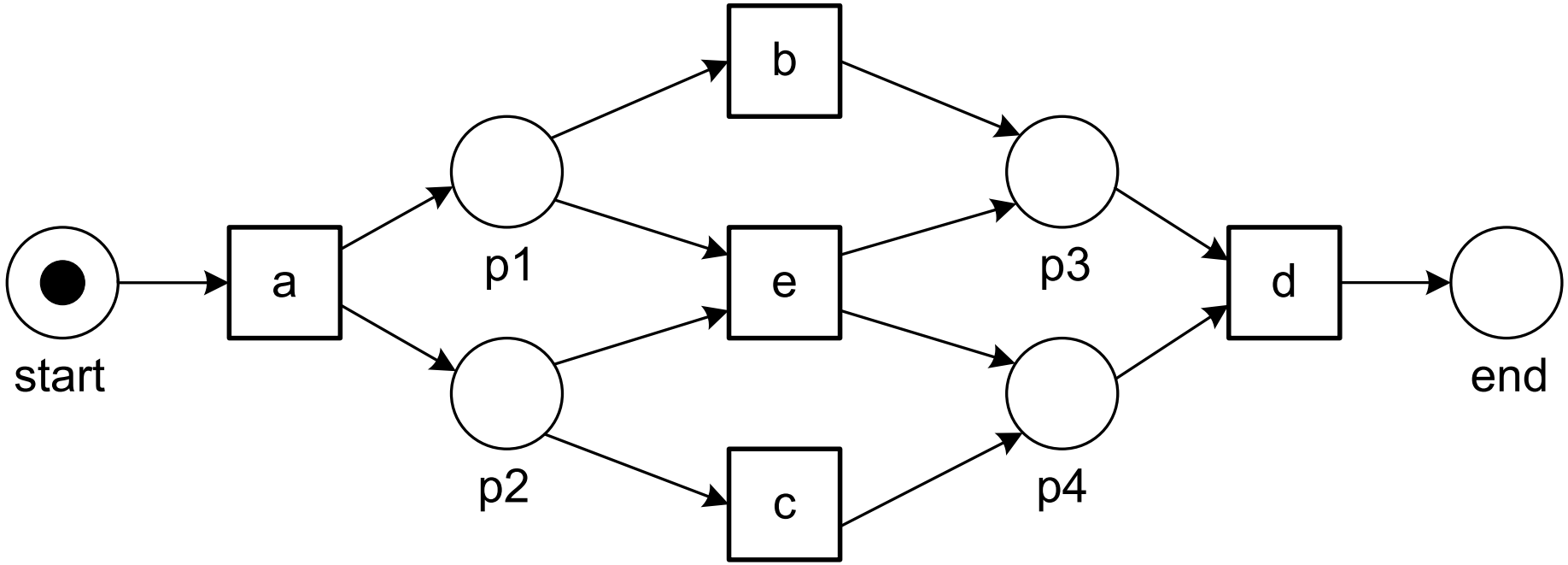


Replay



- extended model showing times, frequencies, etc.
- diagnostics
- predictions
- recommendations

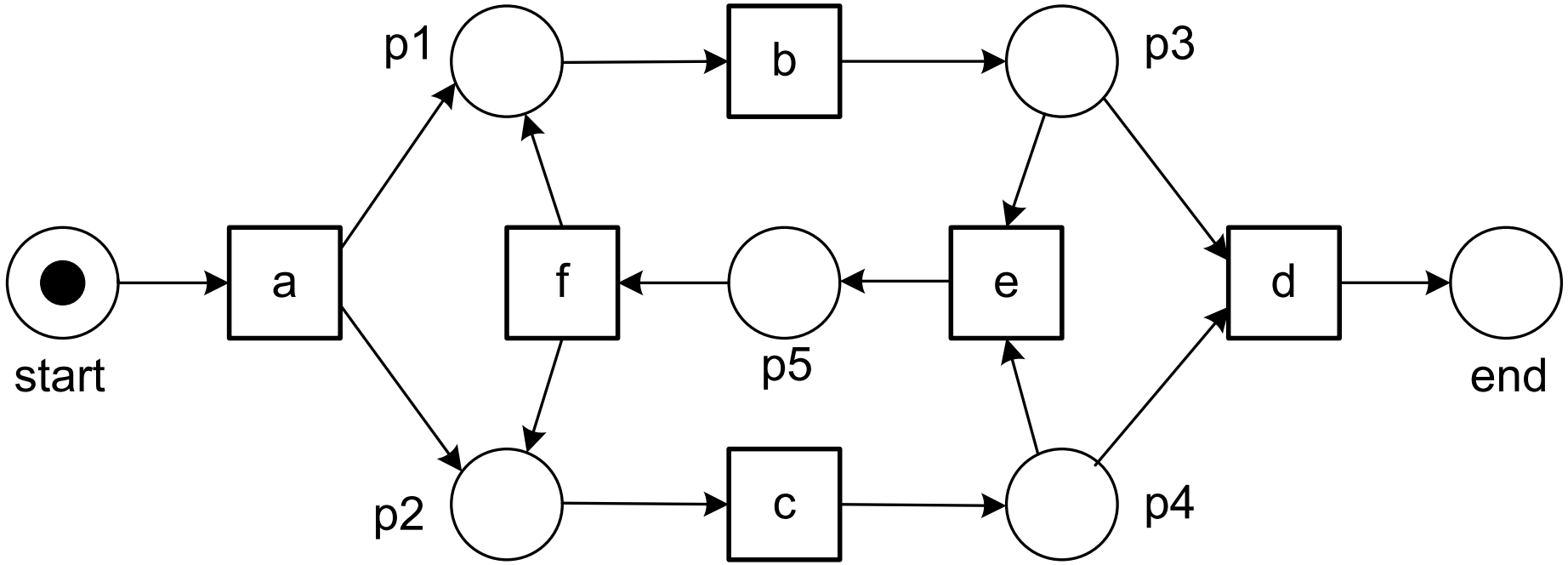
Example



$$L_1 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^2, \langle a,e,d\rangle]$$

Event log contains all possible traces of model and vice versa.

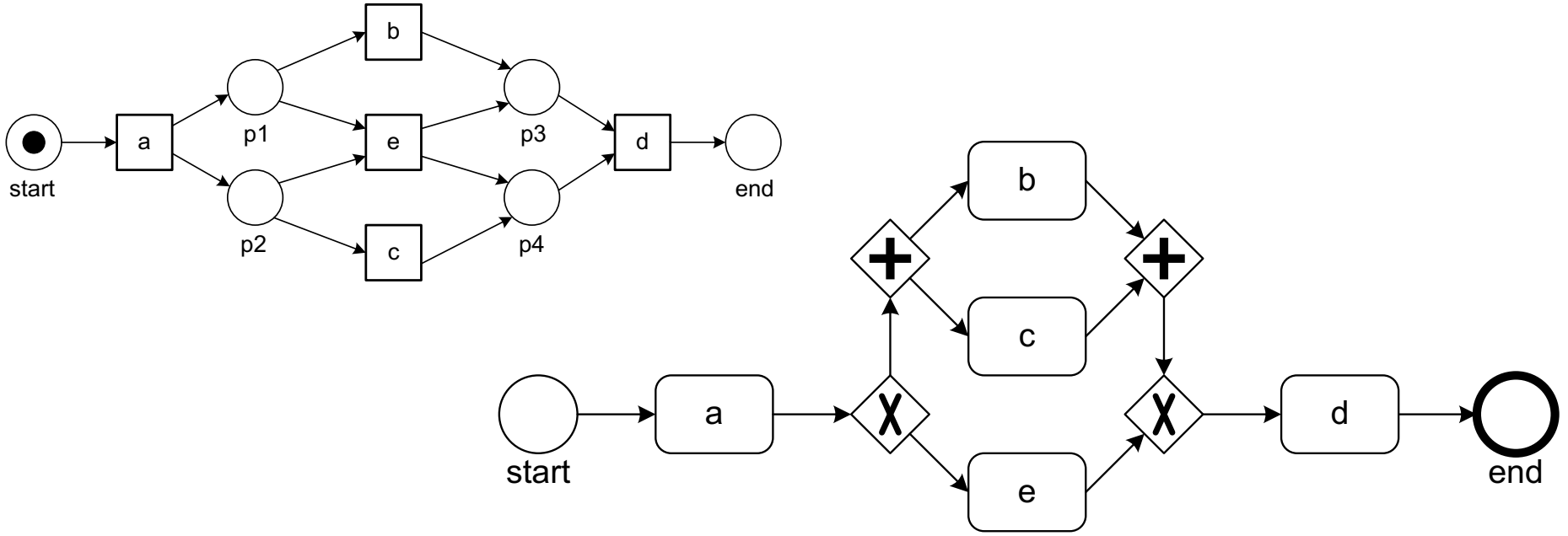
Another example



$$L_2 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^4, \langle a,b,c,e,f,b,c,d\rangle^2, \langle a,b,c,e,f,c,b,d\rangle,$$
$$\langle a,c,b,e,f,b,c,d\rangle^2, \langle a,c,b,e,f,b,c,e,f,c,b,d\rangle]$$

Generalization: event log contains only subset of all possible traces of model.

Notation is less relevant (e.g. BPMN)



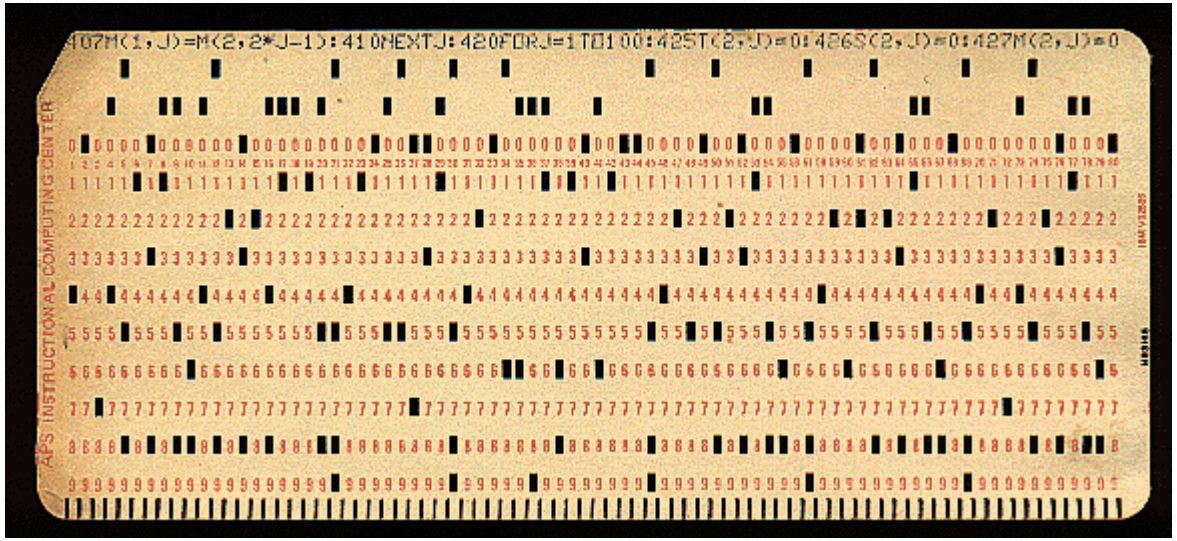
$$L_1 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^2, \langle a,e,d\rangle]$$

Challenge

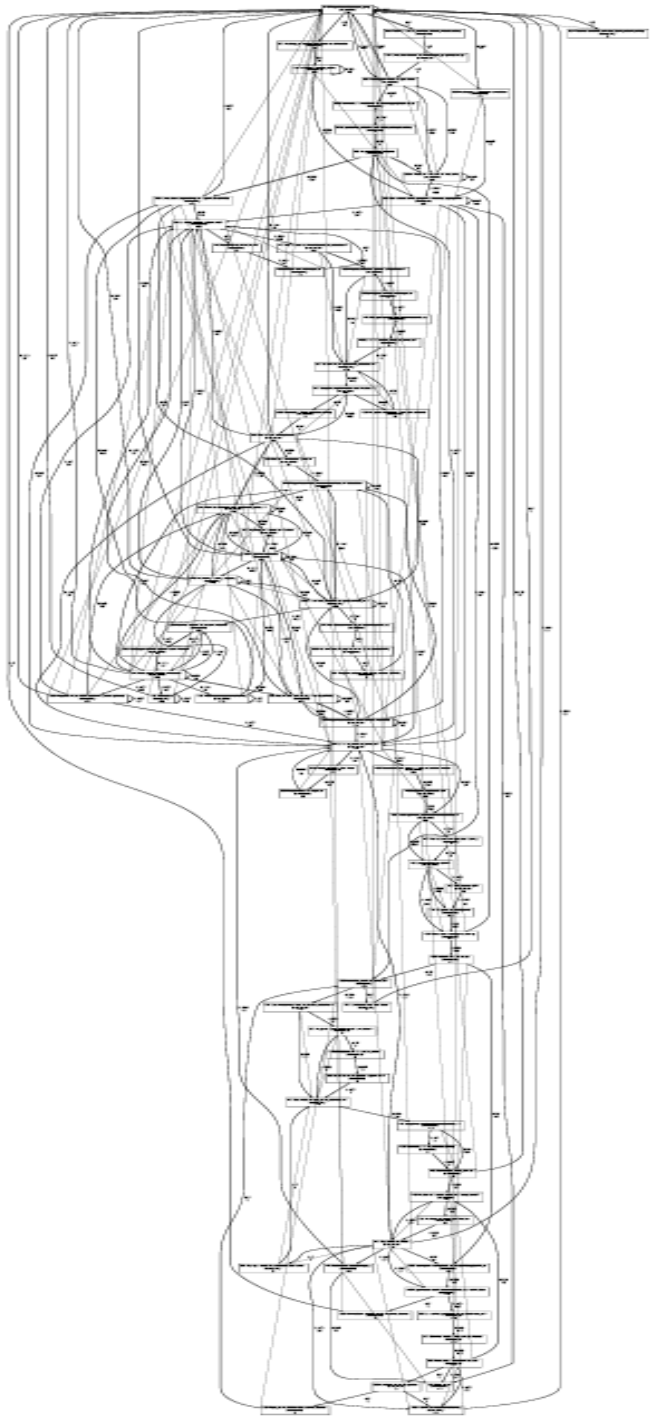
- In general, there is a trade-off between the following four quality criteria:

1. **Fitness**: the discovered model should allow for the behavior seen in the event log.
2. **Precision (avoid underfitting)**: the discovered model should not allow for behavior completely unrelated to what was seen in the event log.
3. **Generalization (avoid overfitting)**: the discovered model should generalize the example behavior seen in the event log.
4. **Simplicity**: the discovered model should be as simple as possible.

Process Discovery: example of algorithm



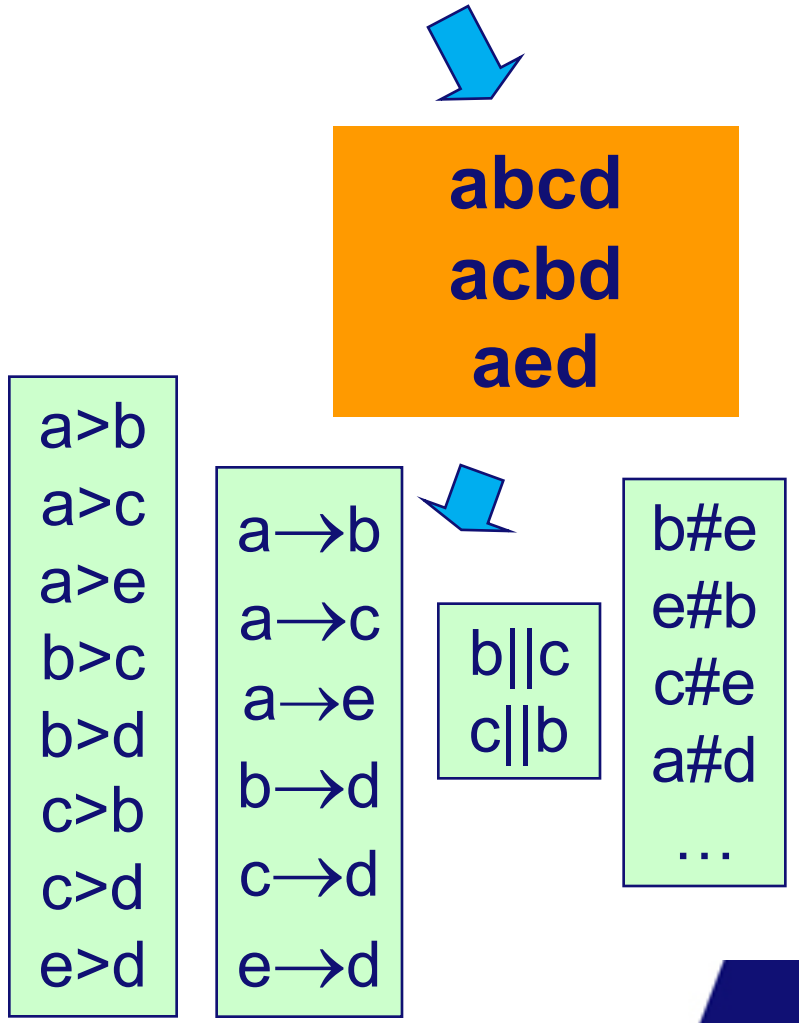
α



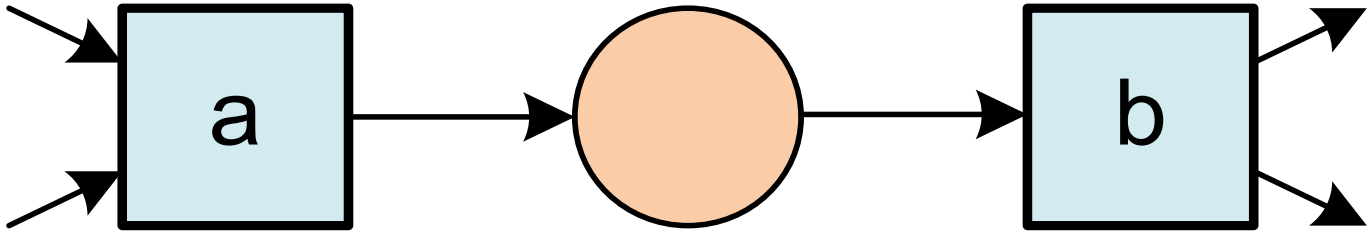
>,→,||,# relations

$$L_1 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^2, \langle a,e,d\rangle]$$

- Direct succession: **x>y iff for some case x is directly followed by y.**
- Causality: **x→y iff x>y and not y>x.**
- Parallel: **x||y iff x>y and y>x**
- Choice: **x#y iff not x>y and not y>x.**

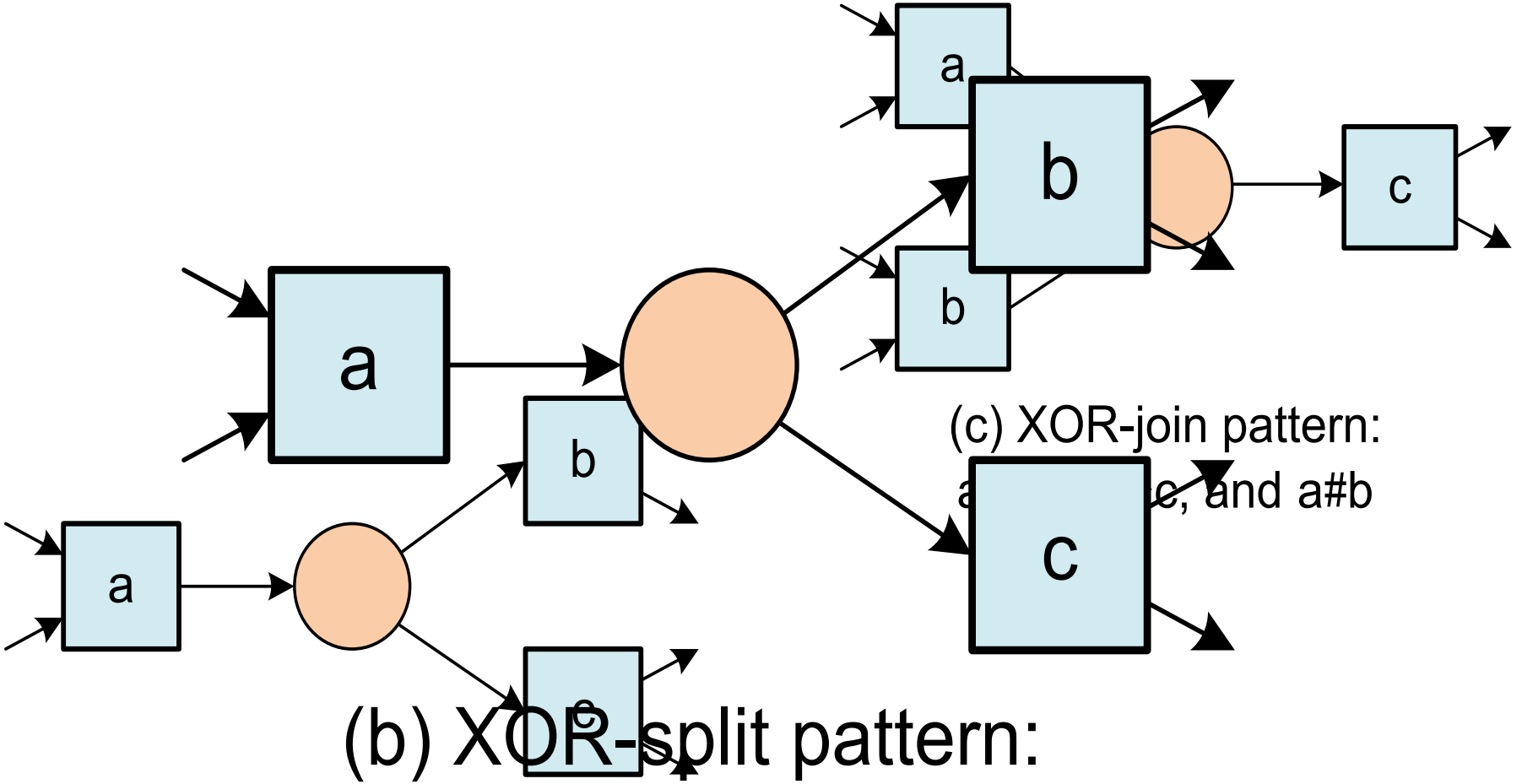


Basic Idea Used by α Algorithm (1)



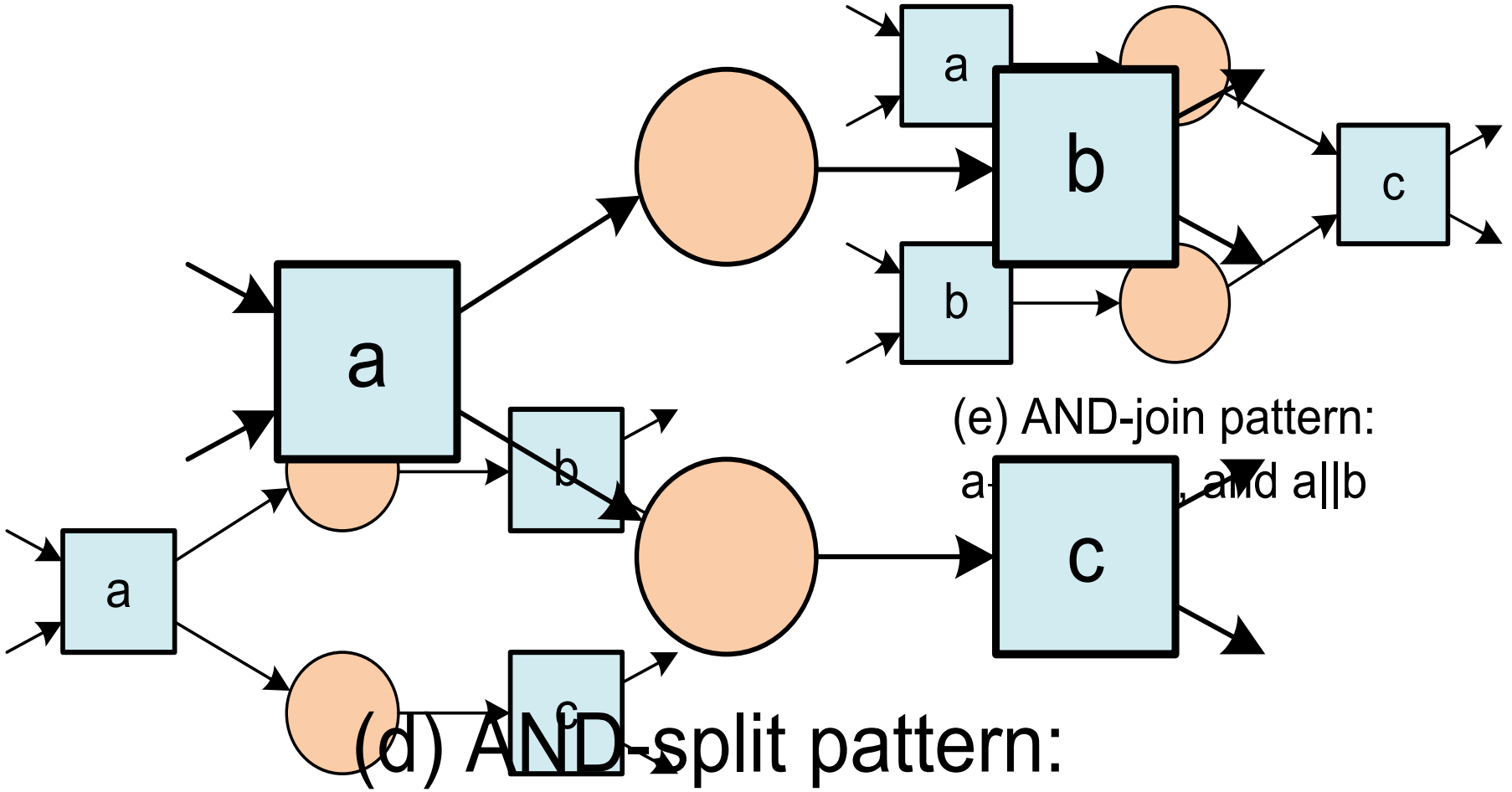
(a) sequence pattern: a→b

Basic Idea Used by α Algorithm (2)



(b) XOR-split pattern:
a→b, a→c, and b#c

Basic Idea Used by α Algorithm (3)



(e) AND-join pattern:
a→c, and a||b

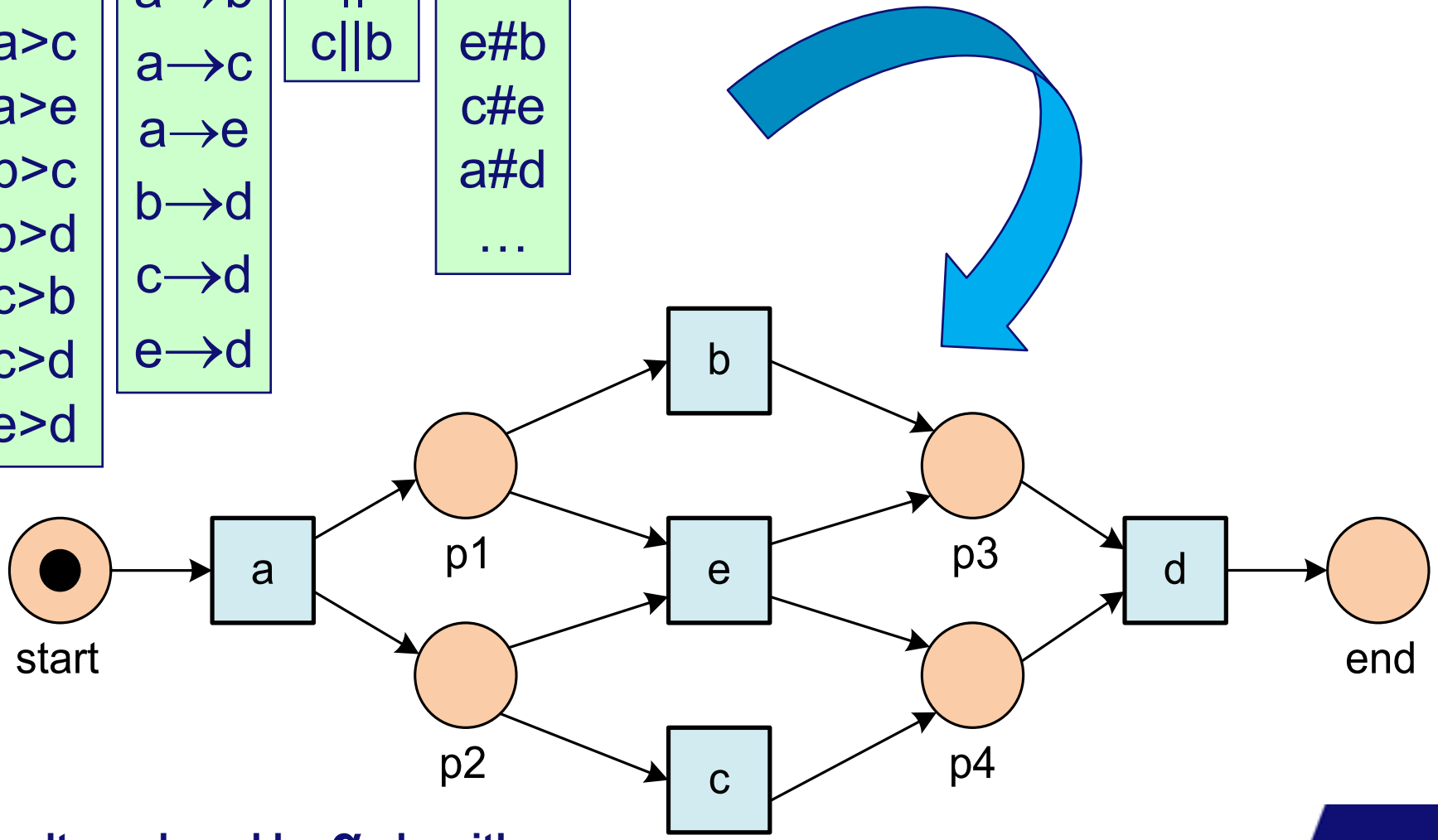
(d) AND-split pattern:
a→b, a→c, and b||c

(d) AND-split pattern:
a→b, a→c, and b||c

Example Revisited

$$L_1 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^2, \langle a,e,d\rangle]$$

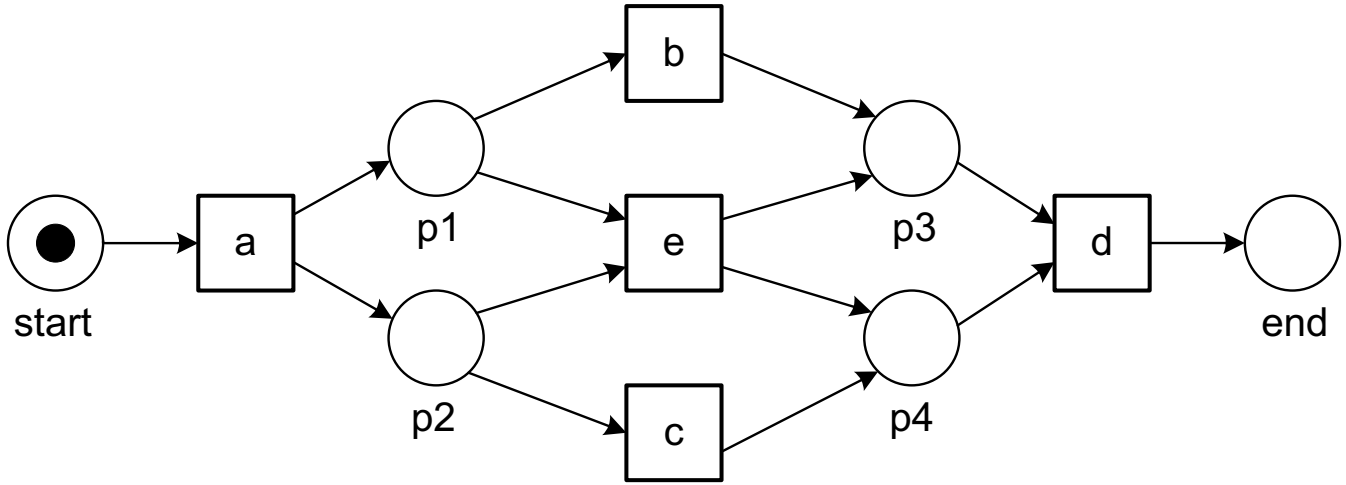
a>b	a→b	b||c	b#e
a>c	a→c	c||b	e#b
a>e	a→e		c#e
b>c	b→d		a#d
b>d	c→d		…
c>b	e→d		
c>d			
e>d			



Result produced by α algorithm

Footprint of L_1

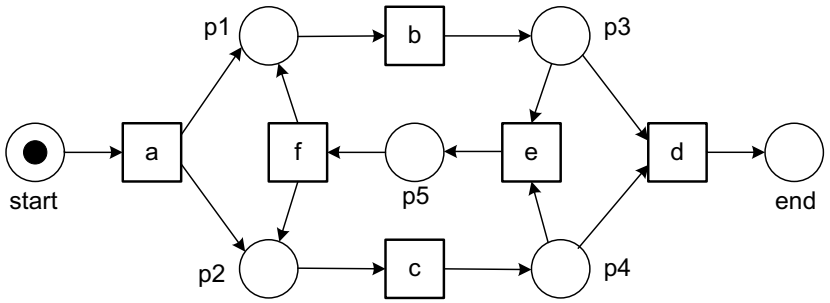
$$L_1 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^2, \langle a,e,d\rangle]$$



	a	b	c	d	e
a	$\#_{L_1}$	$\rightarrow_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$	$\rightarrow_{L_1}$
b	$\leftarrow_{L_1}$	$\#_{L_1}$	$\|\|_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$
c	$\leftarrow_{L_1}$	$\|\|_{L_1}$	$\#_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$
d	$\#_{L_1}$	$\leftarrow_{L_1}$	$\leftarrow_{L_1}$	$\#_{L_1}$	$\leftarrow_{L_1}$
e	$\leftarrow_{L_1}$	$\#_{L_1}$	$\#_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$

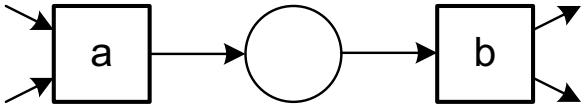
Footprint of L_2

$$L_2 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^4, \langle a,b,c,e,f,b,c,d\rangle^2, \langle a,b,c,e,f,c,b,d\rangle,$$
$$\langle a,c,b,e,f,b,c,d\rangle^2, \langle a,c,b,e,f,b,c,e,f,c,b,d\rangle]$$

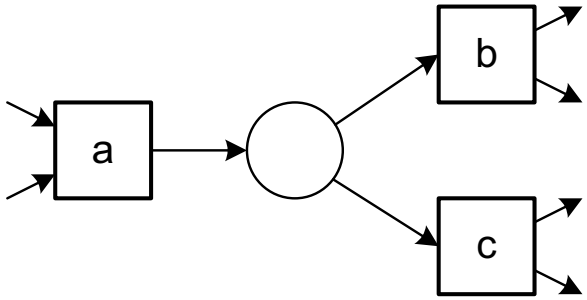


	a	b	c	d	e	f
a	#	$\rightarrow$	$\rightarrow$	#	#	#
b	$\leftarrow$	#	$\parallel$	$\rightarrow$	$\rightarrow$	$\leftarrow$
c	$\leftarrow$	$\parallel$	#	$\rightarrow$	$\rightarrow$	$\leftarrow$
d	#	$\leftarrow$	$\leftarrow$	#	#	#
e	#	$\leftarrow$	$\leftarrow$	#	#	$\rightarrow$
f	#	$\rightarrow$	$\rightarrow$	#	$\leftarrow$	#

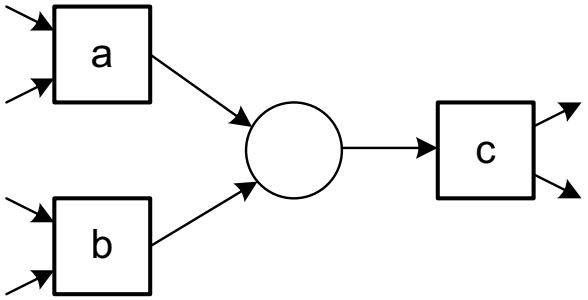
Simple patterns



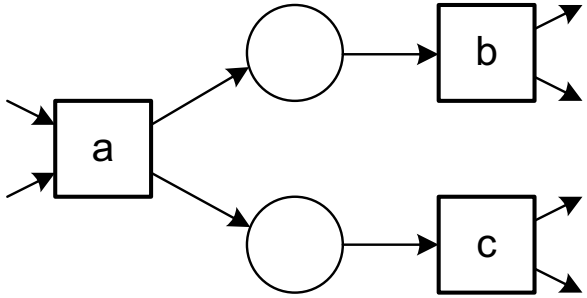
(a) sequence pattern: a→b



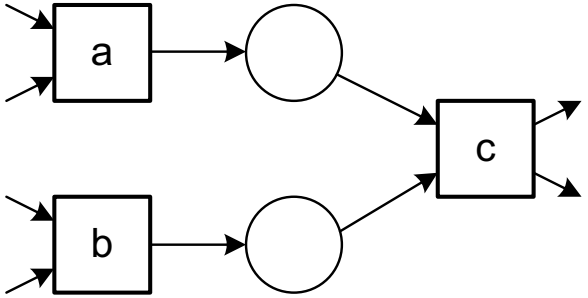
(b) XOR-split pattern:
a→b, a→c, and b#c



(c) XOR-join pattern:
a→c, b→c, and a#b



(d) AND-split pattern:
a→b, a→c, and b||c



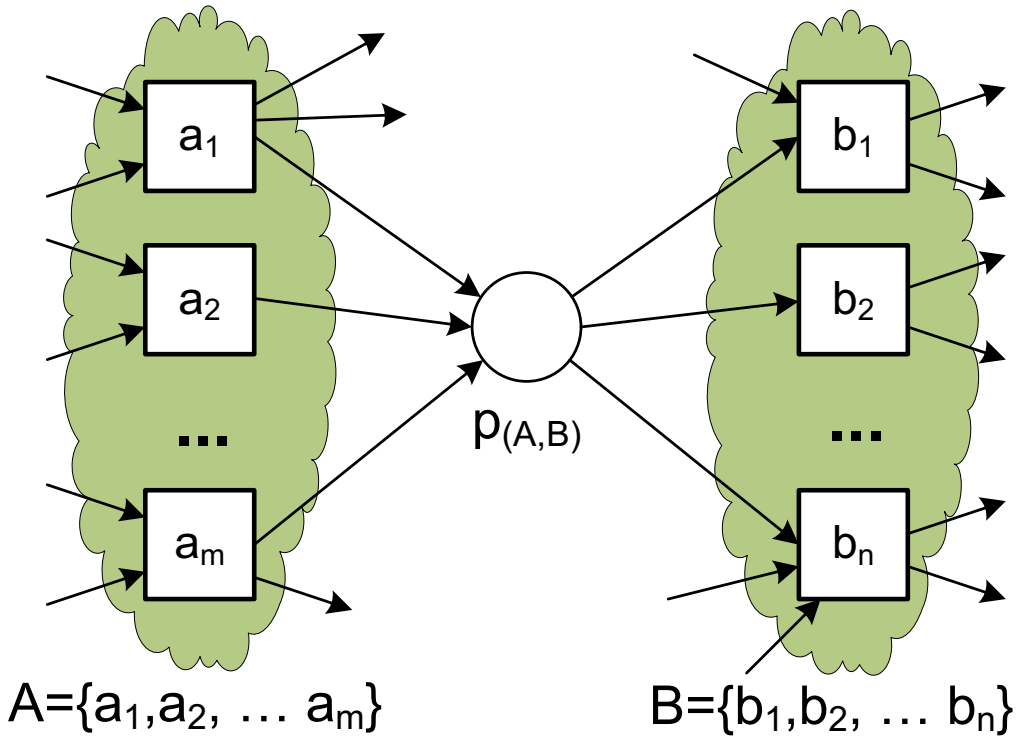
(e) AND-join pattern:
a→c, b→c, and a||b

Algorithm

Let L be an event log over T. $\alpha(L)$ is defined as follows.

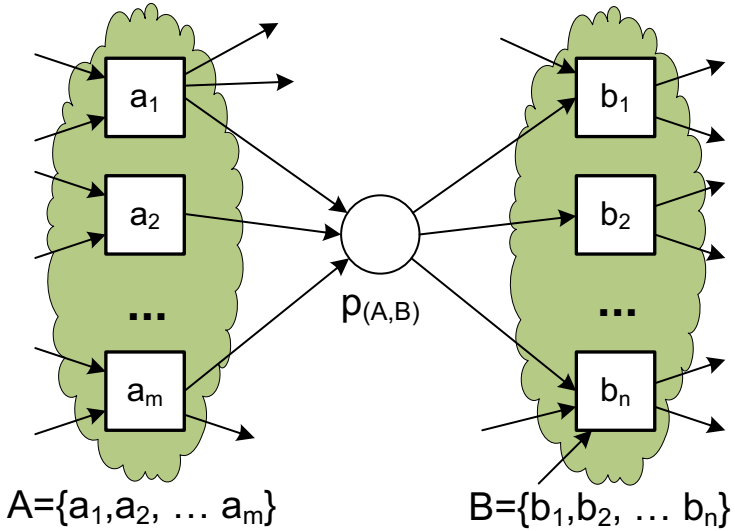
1. $T_L = \{ t \in T \mid \exists_{\sigma \in L}\, t \in \sigma \}$,
2. $T_I = \{ t \in T \mid \exists_{\sigma \in L}\, t = \mathit{first}(\sigma) \}$,
3. $T_O = \{ t \in T \mid \exists_{\sigma \in L}\, t = \mathit{last}(\sigma) \}$,
4. $X_L = \{ (A,B) \mid A \subseteq T_L \wedge A \neq \emptyset \wedge B \subseteq T_L \wedge B \neq \emptyset \wedge \forall_{a \in A} \forall_{b \in B}\, a \rightarrow_L b \wedge \forall_{a1,a2 \in A}\, a_1 \#_L a_2 \wedge \forall_{b1,b2 \in B}\, b_1 \#_L b_2 \}$,
5. $Y_L = \{ (A,B) \in X_L \mid \forall_{(A',B') \in X_L}\, A \subseteq A' \wedge B \subseteq B' \Rightarrow (A,B) = (A',B') \}$,
6. $P_L = \{ p_{(A,B)} \mid (A,B) \in Y_L \} \cup \{i_L, o_L\}$,
7. $F_L = \{ (a, p_{(A,B)}) \mid (A,B) \in Y_L \wedge a \in A \} \cup \{ (p_{(A,B)}, b) \mid (A,B) \in Y_L \wedge b \in B \} \cup \{ (i_L, t) \mid t \in T_I \} \cup \{ (t, o_L) \mid t \in T_O \}$, and
8. $\alpha(L) = (P_L, T_L, F_L)$.

Key idea: find places



4. $X_L = \{ (A,B) \mid A \subseteq T_L \wedge A \neq \emptyset \wedge B \subseteq T_L \wedge B \neq \emptyset \wedge \forall_{a \in A} \forall_{b \in B} a \rightarrow_L b \wedge \forall_{a1,a2 \in A} a_1 \#_L a_2 \wedge \forall_{b1,b2 \in B} b_1 \#_L b_2 \}$,
5. $Y_L = \{ (A,B) \in X_L \mid \forall_{(A',B') \in X_L} A \subseteq A' \wedge B \subseteq B' \Rightarrow (A,B) = (A',B') \}$,

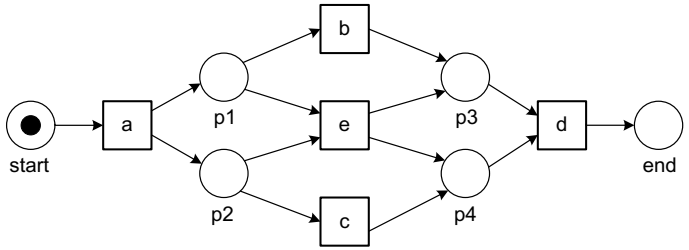
Places as footprints



	a_1	a_2	...	a_m	b_1	b_2	...	b_n
a_1	#	#	...	#	$\rightarrow$	$\rightarrow$	...	$\rightarrow$
a_2	#	#	...	#	$\rightarrow$	$\rightarrow$	...	$\rightarrow$
...	...	...	...	...	...	...	...	...
a_m	#	#	...	#	$\rightarrow$	$\rightarrow$	...	$\rightarrow$
b_1	$\leftarrow$	$\leftarrow$	...	$\leftarrow$	#	#	...	#
b_2	$\leftarrow$	$\leftarrow$	...	$\leftarrow$	#	#	...	#
...	...	...	...	...	...	...	...	...
b_n	$\leftarrow$	$\leftarrow$	...	$\leftarrow$	#	#	...	#

$$L_1 = [\langle a,b,c,d\rangle^3, \langle a,c,b,d\rangle^2, \langle a,e,d\rangle]$$

	a	b	c	d	e
a	$\#_{L_1}$	$\rightarrow_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$	$\rightarrow_{L_1}$
b	$\leftarrow_{L_1}$	$\#_{L_1}$	$\|\|_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$
c	$\leftarrow_{L_1}$	$\|\|_{L_1}$	$\#_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$
d	$\#_{L_1}$	$\leftarrow_{L_1}$	$\leftarrow_{L_1}$	$\#_{L_1}$	$\leftarrow_{L_1}$
e	$\leftarrow_{L_1}$	$\#_{L_1}$	$\#_{L_1}$	$\rightarrow_{L_1}$	$\#_{L_1}$



$$X_{L_1} = \{(\{a\},\{b\}),(\{a\},\{c\}),(\{a\},\{e\}),(\{a\},\{b,e\}),(\{a\},\{c,e\}),$$
$$(\{b\},\{d\}),(\{c\},\{d\}),(\{e\},\{d\}),(\{b,e\},\{d\}),(\{c,e\},\{d\})\}$$

$$Y_{L_1} = \{(\{a\},\{b,e\}),(\{a\},\{c,e\}),(\{b,e\},\{d\}),(\{c,e\},\{d\})\}$$

Another event log L_3

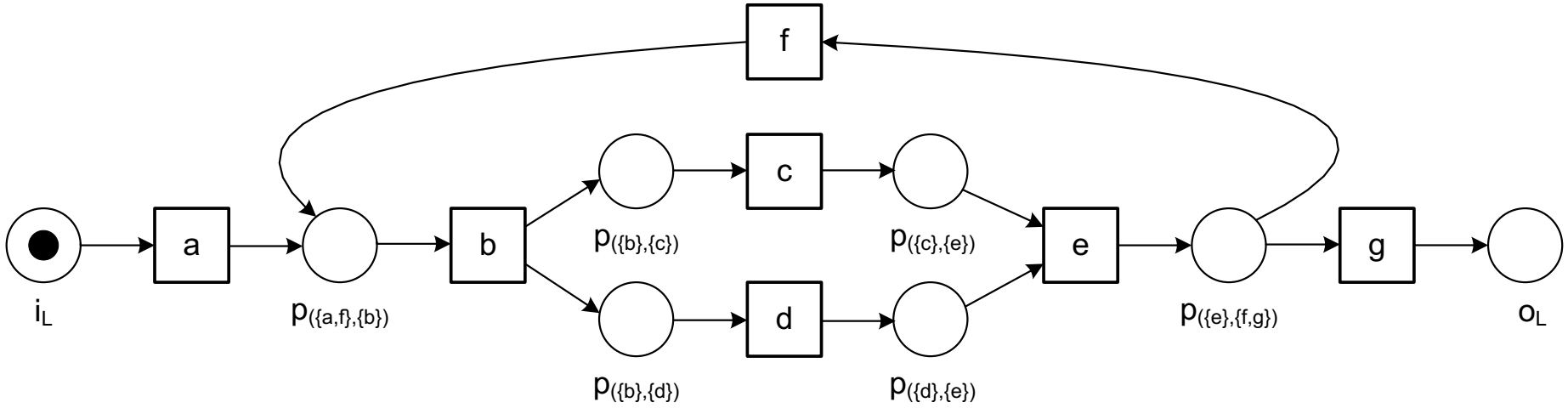
$$L_3 = [\langle a,b,c,d,e,f,b,d,c,e,g\rangle, \langle a,b,d,c,e,g\rangle^2, \langle a,b,c,d,e,f,b,c,d,e,f,b,d,c,e,g\rangle]$$

	a	b	c	d	e	f	g
a	#	$\rightarrow$	#	#	#	#	#
b	$\leftarrow$	#	$\rightarrow$	$\rightarrow$	#	$\leftarrow$	#
c	#	$\leftarrow$	#	$\|\|$	$\rightarrow$	#	#
d	#	$\leftarrow$	$\|\|$	#	$\rightarrow$	#	#
e	#	#	$\leftarrow$	$\leftarrow$	#	$\rightarrow$	$\rightarrow$
f	#	$\rightarrow$	#	#	$\leftarrow$	#	#
g	#	#	#	#	$\leftarrow$	#	#

Model for L_3

	a	b	c	d	e	f	g
a	#	$\rightarrow$	#	#	#	#	#
b	$\leftarrow$	#	$\rightarrow$	$\rightarrow$	#	$\leftarrow$	#
c	#	$\leftarrow$	#	$\parallel$	$\rightarrow$	#	#
d	#	$\leftarrow$	$\parallel$	#	$\rightarrow$	#	#
e	#	#	$\leftarrow$	$\leftarrow$	#	$\rightarrow$	$\rightarrow$
f	#	$\rightarrow$	#	#	$\leftarrow$	#	#
g	#	#	#	#	$\leftarrow$	#	#

$$L_3 = [\langle a,b,c,d,e,f,b,d,c,e,g\rangle, \langle a,b,d,c,e,g\rangle^2, \langle a,b,c,d,e,f,b,c,d,e,f,b,d,c,e,g\rangle]$$



Event log L_5

$$L_5 = [\langle a,b,e,f\rangle^2, \langle a,b,e,c,d,b,f\rangle^3, \langle a,b,c,e,d,b,f\rangle^2, \langle a,b,c,d,e,b,f\rangle^4, \langle a,e,b,c,d,b,f\rangle^3]$$

	a	b	c	d	e	f
a	#	$\rightarrow$	#	#	$\rightarrow$	#
b	$\leftarrow$	#	$\rightarrow$	$\leftarrow$	$\|\|$	$\rightarrow$
c	#	$\leftarrow$	#	$\rightarrow$	$\|\|$	#
d	#	$\rightarrow$	$\leftarrow$	#	$\|\|$	#
e	$\leftarrow$	$\|\|$	$\|\|$	$\|\|$	#	$\rightarrow$
f	#	$\leftarrow$	#	#	$\leftarrow$	#

$$T_L = \{a, b, c, d, e, f\}$$

$$T_I = \{a\}$$

$$T_I = \{f\}$$

$$X_L = \{(\{a\},\{b\}),(\{a\},\{e\}),(\{b\},\{c\}),(\{b\},\{f\}),(\{c\},\{d\}),$$
$$(\{d\},\{b\}),(\{e\},\{f\}),(\{a,d\},\{b\}),(\{b\},\{c,f\})\}$$

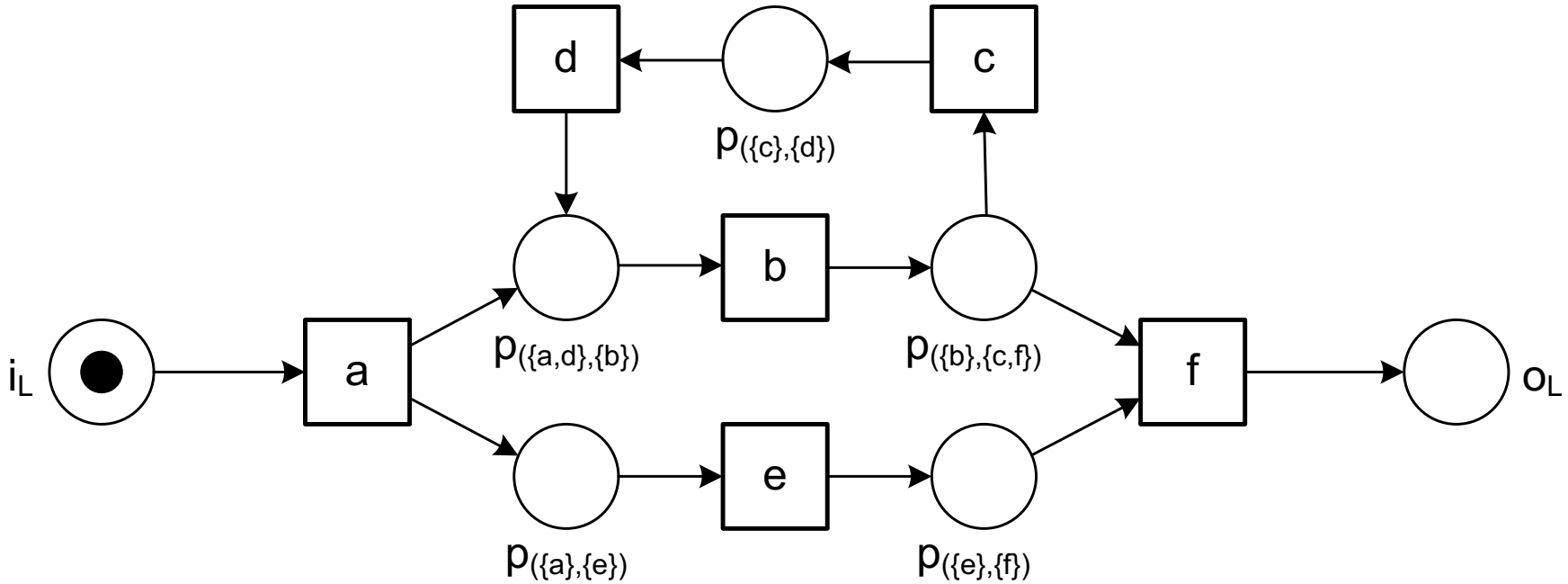
$$Y_L = \{(\{a\},\{e\}),(\{c\},\{d\}),(\{e\},\{f\}),(\{a,d\},\{b\}),(\{b\},\{c,f\})\}$$

$$P_L = \{p_{(\{a\},\{e\})}, p_{(\{c\},\{d\})}, p_{(\{e\},\{f\})}, p_{(\{a,d\},\{b\})}, p_{(\{b\},\{c,f\})}, i_L, o_L\}$$

$$F_L = \{(a, p_{(\{a\},\{e\})}), (p_{(\{a\},\{e\})}, e), (c, p_{(\{c\},\{d\})}), (p_{(\{c\},\{d\})}, d),$$
$$(e, p_{(\{e\},\{f\})}), (p_{(\{e\},\{f\})}, f), (a, p_{(\{a,d\},\{b\})}), (d, p_{(\{a,d\},\{b\})}),$$
$$(p_{(\{a,d\},\{b\})}, b), (b, p_{(\{b\},\{c,f\})}), (p_{(\{b\},\{c,f\})}, c), (p_{(\{b\},\{c,f\})}, f),$$
$$(i_L, a), (f, o_L)\}$$

$$\alpha(L) = (P_L, T_L, F_L)$$

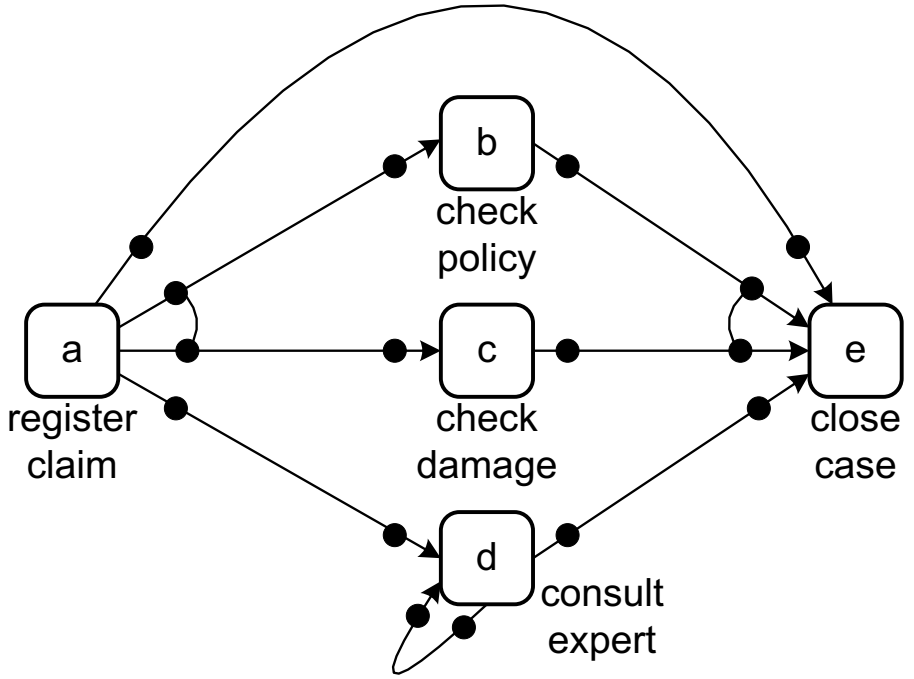
Discovered model



$$X_L = \{(\{a\},\{b\}),(\{a\},\{e\}),(\{b\},\{c\}),(\{b\},\{f\}),(\{c\},\{d\}),$$
$$(\{d\},\{b\}),(\{e\},\{f\}),(\{a,d\},\{b\}),(\{b\},\{c,f\})\}$$
$$Y_L = \{(\{a\},\{e\}),(\{c\},\{d\}),(\{e\},\{f\}),(\{a,d\},\{b\}),(\{b\},\{c,f\})\}$$

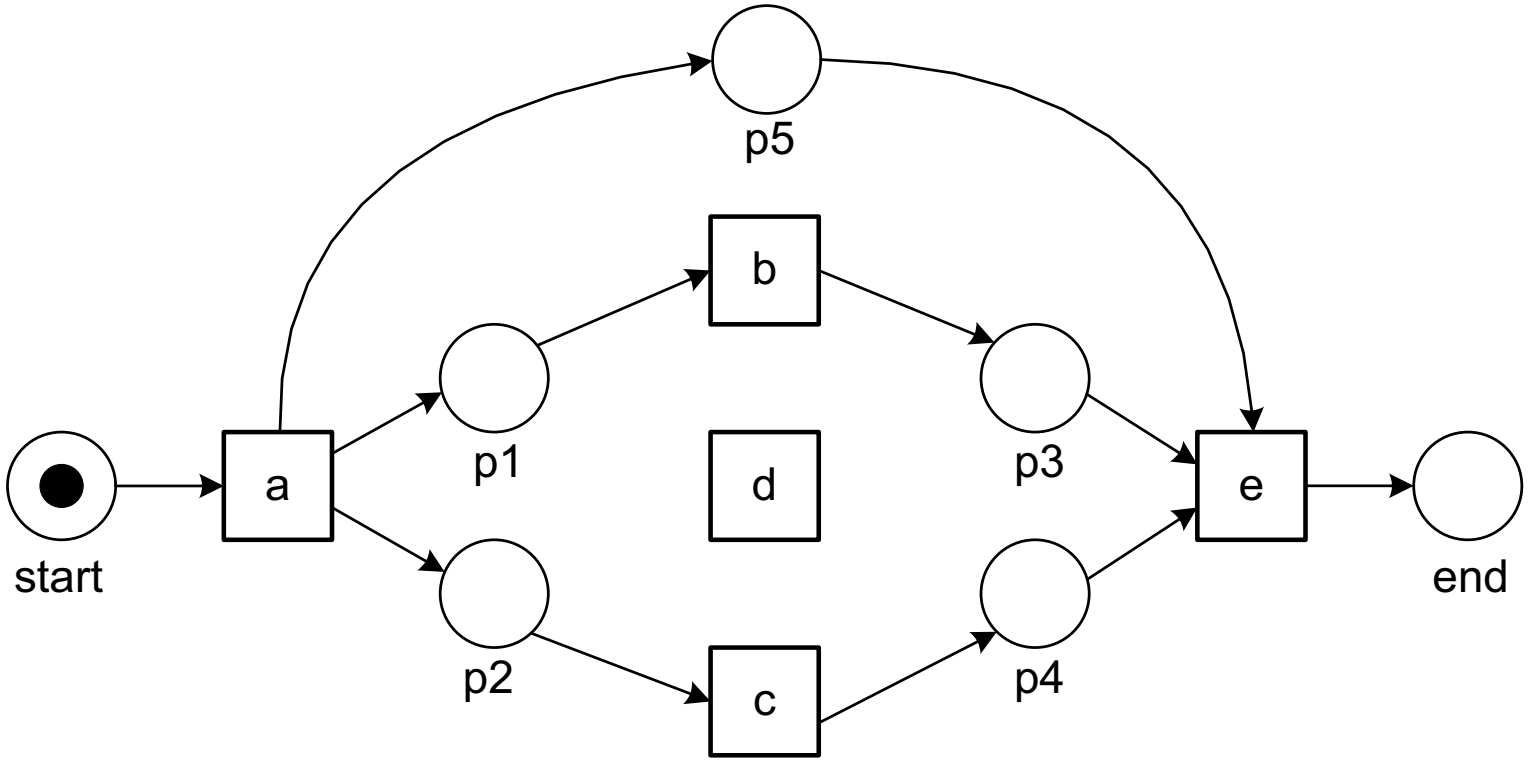
Heuristic mining

- To deal with noise and incompleteness.
- To have a better representational bias than the α algorithm (AND/XOR/OR/skip).
- Uses C-nets.



Example log; problem α algorithm

$$L = [\langle a,e\rangle^{5}, \langle a,b,c,e\rangle^{10}, \langle a,c,b,e\rangle^{10}, \langle a,b,e\rangle^{1}, \langle a,c,e\rangle^{1},$$
$$\langle a,d,e\rangle^{10}, \langle a,d,d,e\rangle^{2}, \langle a,d,d,d,e\rangle^{1}]$$



Taking into account frequencies

$$L = [\langle a,e\rangle^{5}, \langle a,b,c,e\rangle^{10}, \langle a,c,b,e\rangle^{10}, \langle a,b,e\rangle^{1}, \langle a,c,e\rangle^{1},$$
$$\langle a,d,e\rangle^{10}, \langle a,d,d,e\rangle^{2}, \langle a,d,d,d,e\rangle^{1}]$$

$$|a >_L b| = \sum_{\sigma \in L} L(\sigma) \times |\{1 \leq i < |\sigma| \mid \sigma(i) = a \wedge \sigma(i+1) = b\}|$$

$\|>_L\|$	a	b	c	d	e
a	0	11	11	13	5
b	0	0	10	0	11
c	0	10	0	0	11
d	0	0	0	4	13
e	0	0	0	0	0

Dependency measure

$$|a >_L b| = \sum_{\sigma \in L} L(\sigma) \times |\{1 \leq i < |\sigma| \mid \sigma(i) = a \wedge \sigma(i+1) = b\}|$$

$|a \Rightarrow_L b|$ is the value of the dependency relation between a and b:

$$|a \Rightarrow_L b| = \begin{cases} \dfrac{|a >_L b| - |b >_L a|}{|a >_L b| + |b >_L a| + 1} & \text{if } a \neq b \\ \dfrac{|a >_L a|}{|a >_L a| + 1} & \text{if } a = b \end{cases}$$

Example

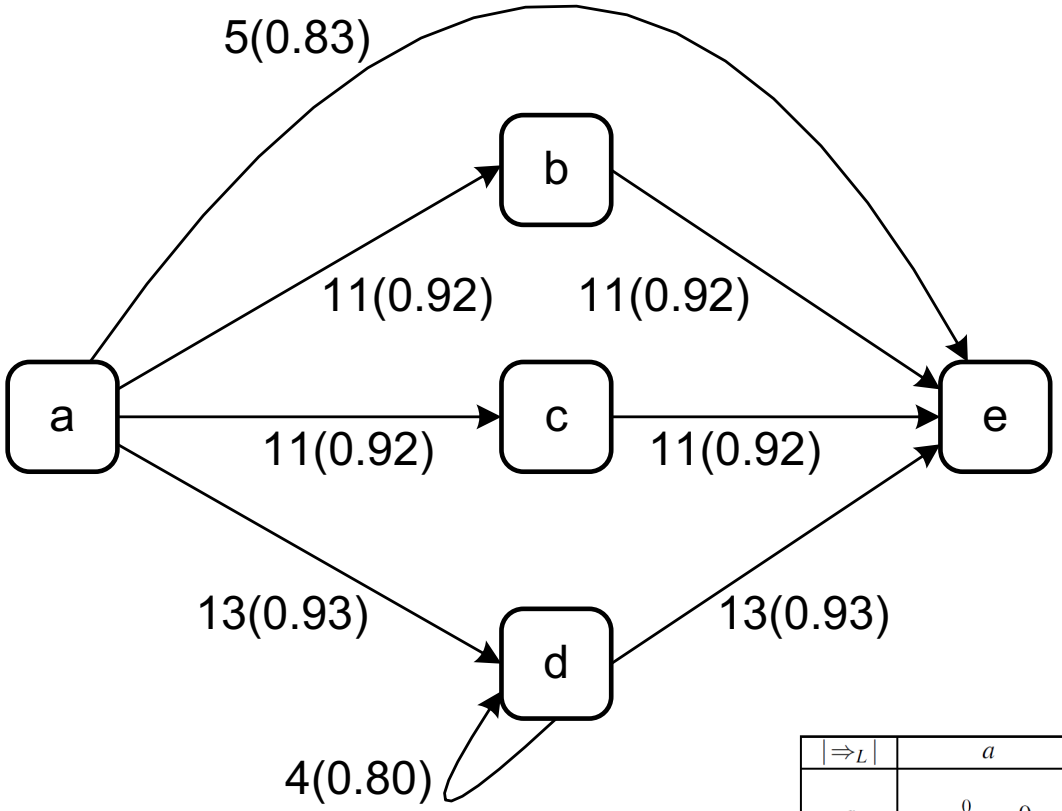
$\lvert\Rightarrow_L\rvert$	a	b	c	d	e
a	$\frac{0}{0+1}=0$	$\frac{11-0}{11+0+1}=0.92$	$\frac{11-0}{11+0+1}=0.92$	$\frac{13-0}{13+0+1}=0.93$	$\frac{5-0}{5+0+1}=0.83$
b	$\frac{0-11}{0+11+1}=-0.92$	$\frac{0}{0+1}=0$	$\frac{10-10}{10+10+1}=0$	$\frac{0-0}{0+0+1}=0$	$\frac{11-0}{11+0+1}=0.92$
c	$\frac{0-11}{0+11+1}=-0.92$	$\frac{10-10}{10+10+1}=0$	$\frac{0}{0+1}=0$	$\frac{0-0}{0+0+1}=0$	$\frac{11-0}{11+0+1}=0.92$
d	$\frac{0-13}{0+13+1}=-0.93$	$\frac{0-0}{0+0+1}=0$	$\frac{0-0}{0+0+1}=0$	$\frac{4}{4+1}=0.80$	$\frac{13-0}{13+0+1}=0.93$
e	$\frac{0-5}{0+5+1}=-0.83$	$\frac{0-11}{0+11+1}=-0.92$	$\frac{0-11}{0+11+1}=-0.92$	$\frac{0-13}{0+13+1}=-0.93$	$\frac{0}{0+1}=0$

$\lvert a \Rightarrow_L b \rvert$ is the value of the dependency relation between a and b:

$$\lvert a \Rightarrow_L b \rvert = \begin{cases} \dfrac{\lvert a >_L b \rvert - \lvert b >_L a \rvert}{\lvert a >_L b \rvert + \lvert b >_L a \rvert + 1} & \text{if } a \neq b \\ \dfrac{\lvert a >_L a \rvert}{\lvert a >_L a \rvert + 1} & \text{if } a = b \end{cases}$$

$\lvert >_L \rvert$	a	b	c	d	e
a	0	11	11	13	5
b	0	0	10	0	11
c	0	10	0	0	11
d	0	0	0	4	13
e	0	0	0	0	0

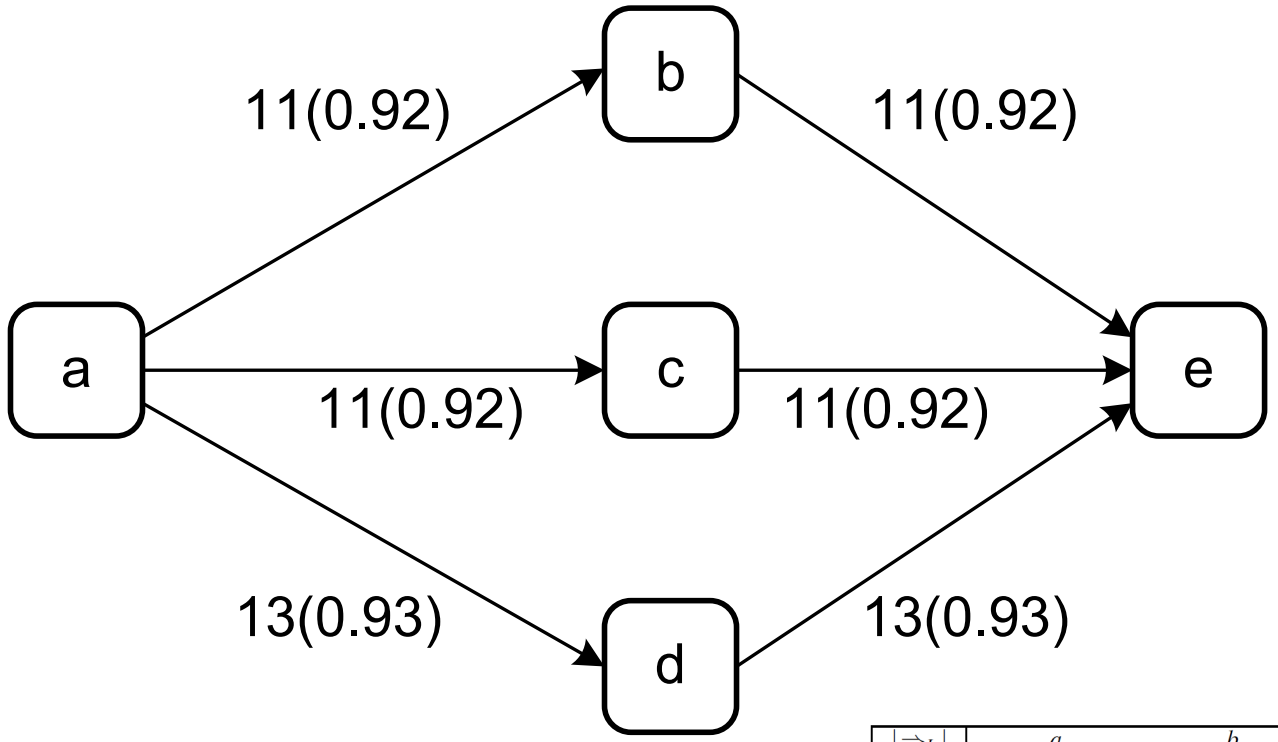
Lower threshold (2 direct successions and a dependency of at least 0.7)



$\lvert >_L \rvert$	a	b	c	d	e
a	0	11	11	13	5
b	0	0	10	0	11
c	0	10	0	0	11
d	0	0	0	4	13
e	0	0	0	0	0

$\lvert \Rightarrow_L \rvert$	a	b	c	d	e
a	$\frac{0}{0+1} = 0$	$\frac{11-0}{11+0+1} = 0.92$	$\frac{11-0}{11+0+1} = 0.92$	$\frac{13-0}{13+0+1} = 0.93$	$\frac{5-0}{5+0+1} = 0.83$
b	$\frac{0-11}{0+11+1} = -0.92$	$\frac{0}{0+1} = 0$	$\frac{10-10}{10+10+1} = 0$	$\frac{0-0}{0+0+1} = 0$	$\frac{11-0}{11+0+1} = 0.92$
c	$\frac{0-11}{0+11+1} = -0.92$	$\frac{10-10}{10+10+1} = 0$	$\frac{0}{0+1} = 0$	$\frac{0-0}{0+0+1} = 0$	$\frac{11-0}{11+0+1} = 0.92$
d	$\frac{0-13}{0+13+1} = -0.93$	$\frac{0-0}{0+0+1} = 0$	$\frac{0-0}{0+0+1} = 0$	$\frac{4}{4+1} = 0.80$	$\frac{13-0}{13+0+1} = 0.93$
e	$\frac{0-5}{0+5+1} = -0.83$	$\frac{0-11}{0+11+1} = -0.92$	$\frac{0-11}{0+11+1} = -0.92$	$\frac{0-13}{0+13+1} = -0.93$	$\frac{0}{0+1} = 0$

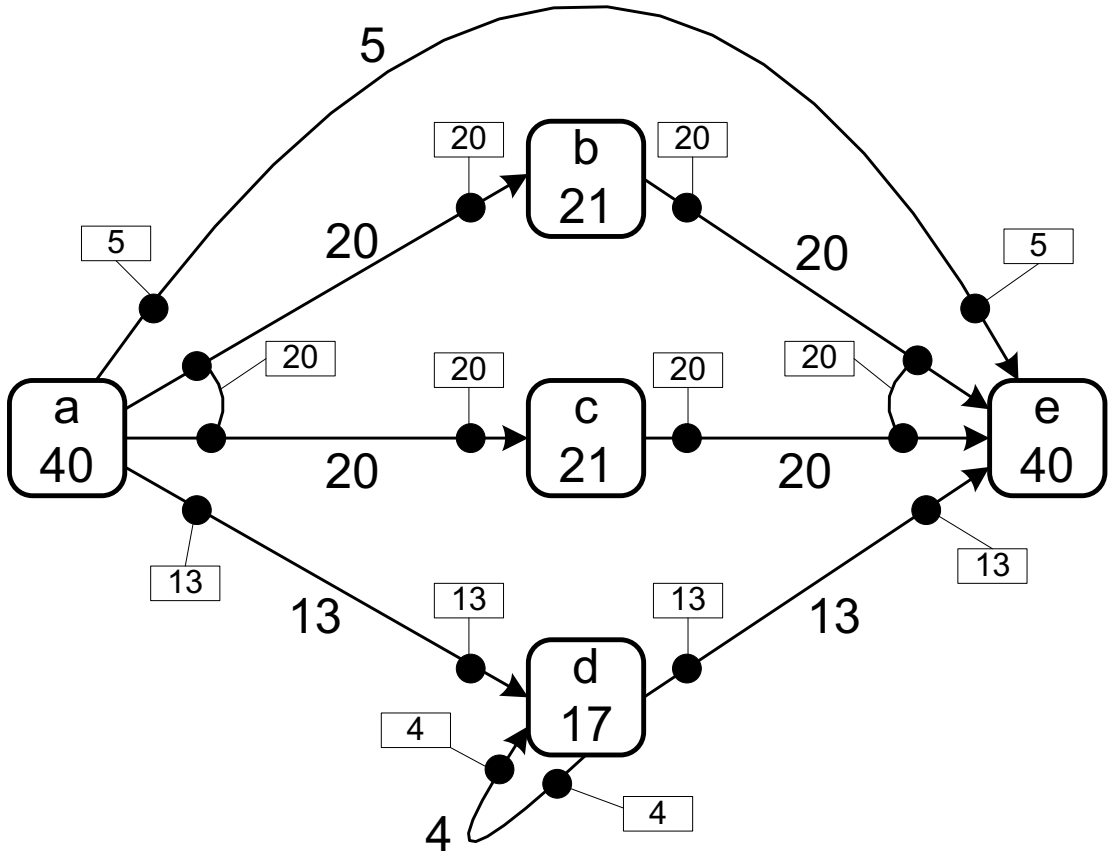
Higher threshold (5 direct successions and a dependency of at least 0.9)



$\lvert >_L \rvert$	a	b	c	d	e
a	0	11	11	13	5
b	0	0	10	0	11
c	0	10	0	0	11
d	0	0	0	4	13
e	0	0	0	0	0

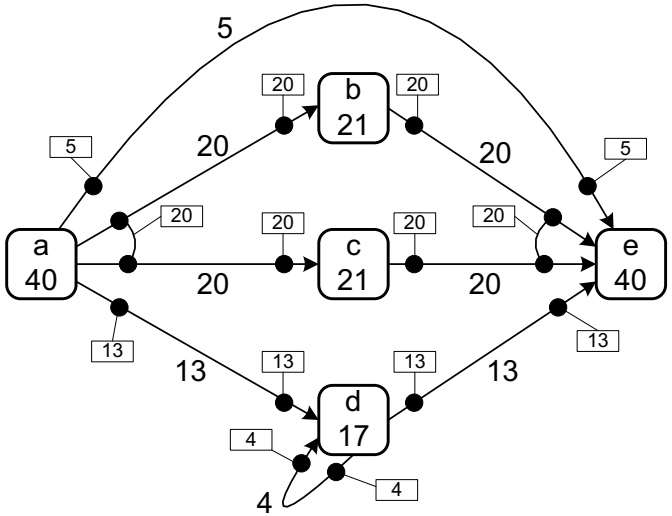
$\lvert \Rightarrow_L \rvert$	a	b	c	d	e
a	$\frac{0}{0+1}=0$	$\frac{11-0}{11+0+1}=0.92$	$\frac{11-0}{11+0+1}=0.92$	$\frac{13-0}{13+0+1}=0.93$	$\frac{5-0}{5+0+1}=0.83$
b	$\frac{0-11}{0+11+1}=-0.92$	$\frac{0}{0+1}=0$	$\frac{10-10}{10+10+1}=0$	$\frac{0-0}{0+0+1}=0$	$\frac{11-0}{11+0+1}=0.92$
c	$\frac{0-11}{0+11+1}=-0.92$	$\frac{10-10}{10+10+1}=0$	$\frac{0}{0+1}=0$	$\frac{0-0}{0+0+1}=0$	$\frac{11-0}{11+0+1}=0.92$
d	$\frac{0-13}{0+13+1}=-0.93$	$\frac{0-0}{0+0+1}=0$	$\frac{0-0}{0+0+1}=0$	$\frac{4}{4+1}=0.80$	$\frac{13-0}{13+0+1}=0.93$
e	$\frac{0-5}{0+5+1}=-0.83$	$\frac{0-11}{0+11+1}=-0.92$	$\frac{0-11}{0+11+1}=-0.92$	$\frac{0-13}{0+13+1}=-0.93$	$\frac{0}{0+1}=0$

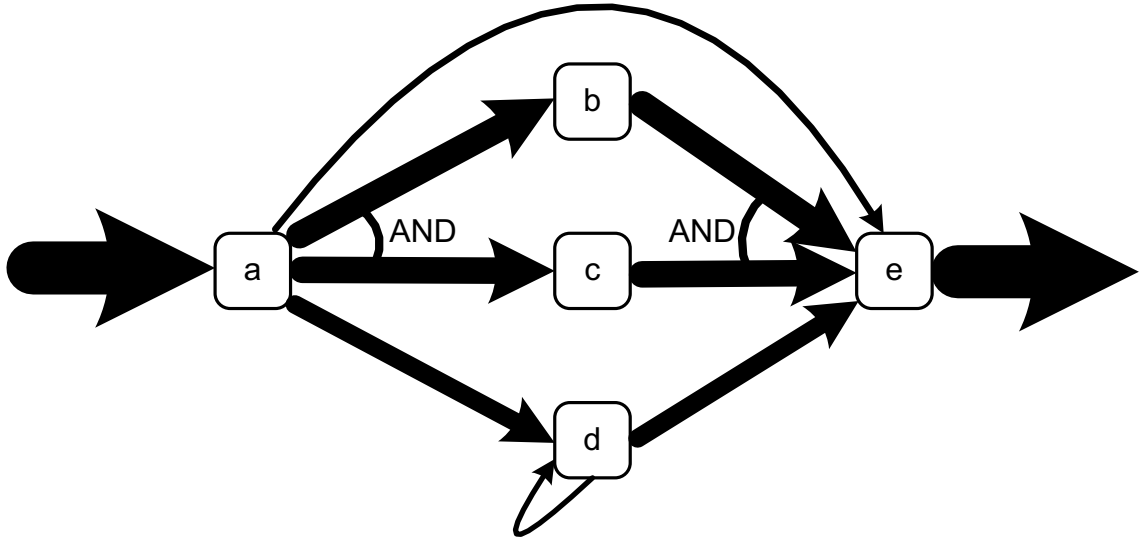
Learning splits and joins



$$L = [\langle a,e\rangle^{5}, \langle a,b,c,e\rangle^{10}, \langle a,c,b,e\rangle^{10}, \langle a,b,e\rangle^{1}, \langle a,c,e\rangle^{1},$$
$$\langle a,d,e\rangle^{10}, \langle a,d,d,e\rangle^{2}, \langle a,d,d,d,e\rangle^{1}]$$

Alternative visualization



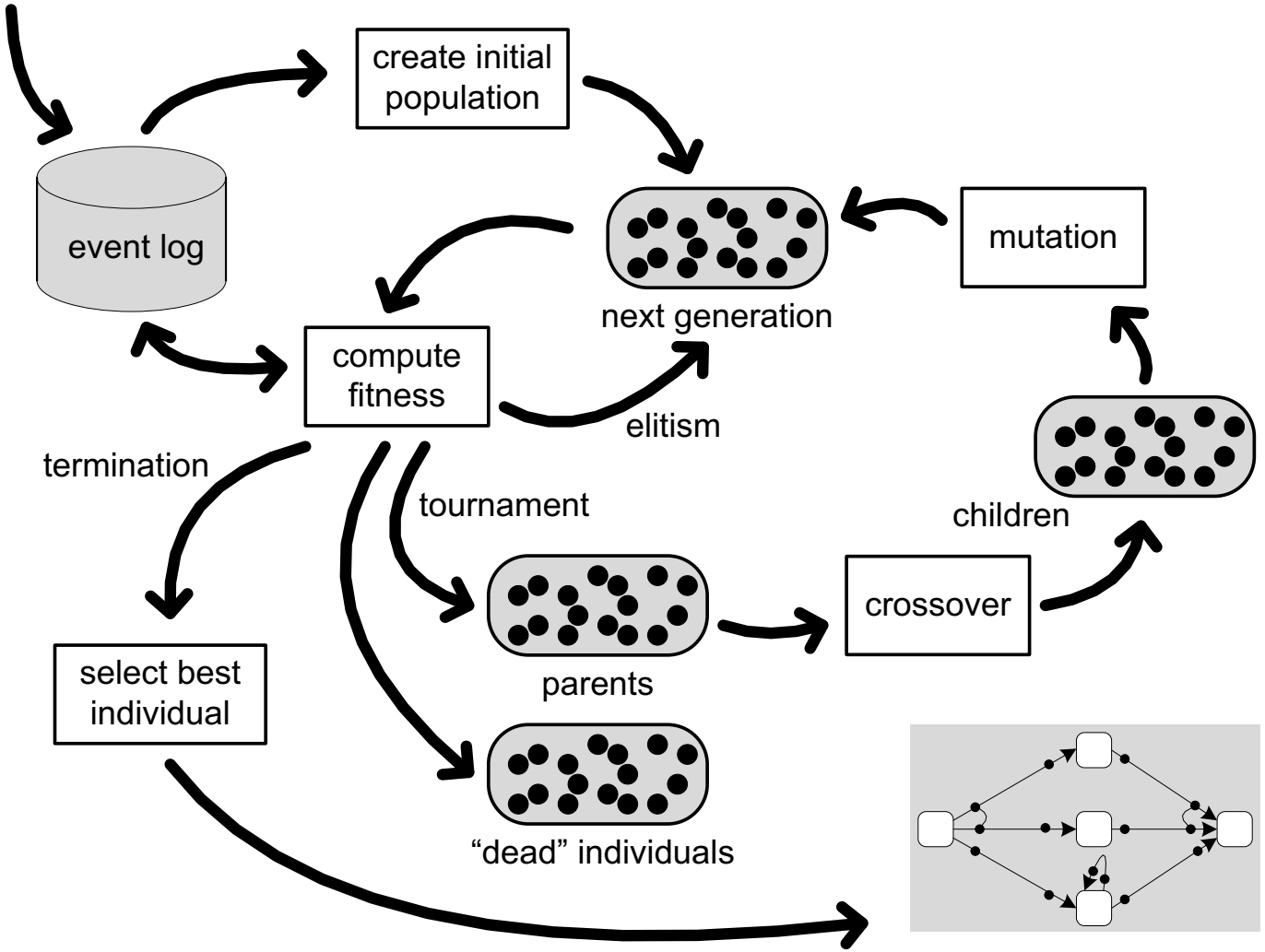


$$L = [\langle a,e\rangle^{5}, \langle a,b,c,e\rangle^{10}, \langle a,c,b,e\rangle^{10}, \langle a,b,e\rangle^{1}, \langle a,c,e\rangle^{1},$$
$$\langle a,d,e\rangle^{10}, \langle a,d,d,e\rangle^{2}, \langle a,d,d,d,e\rangle^{1}]$$

Characteristics of heuristic mining

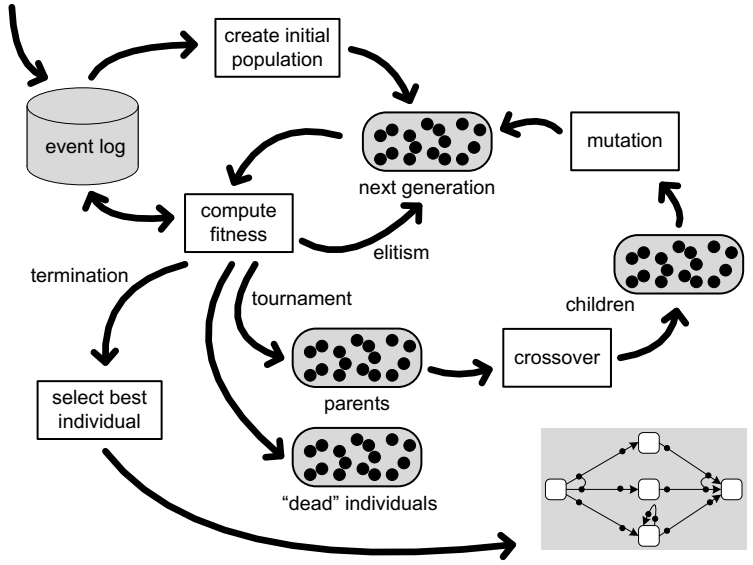
- Can deal with noise and therefore quite robust.
- Improved representational bias.
- Split and join rules are only considered locally (therefore most of the discovered model are not sound and require repair actions).

Genetic process mining

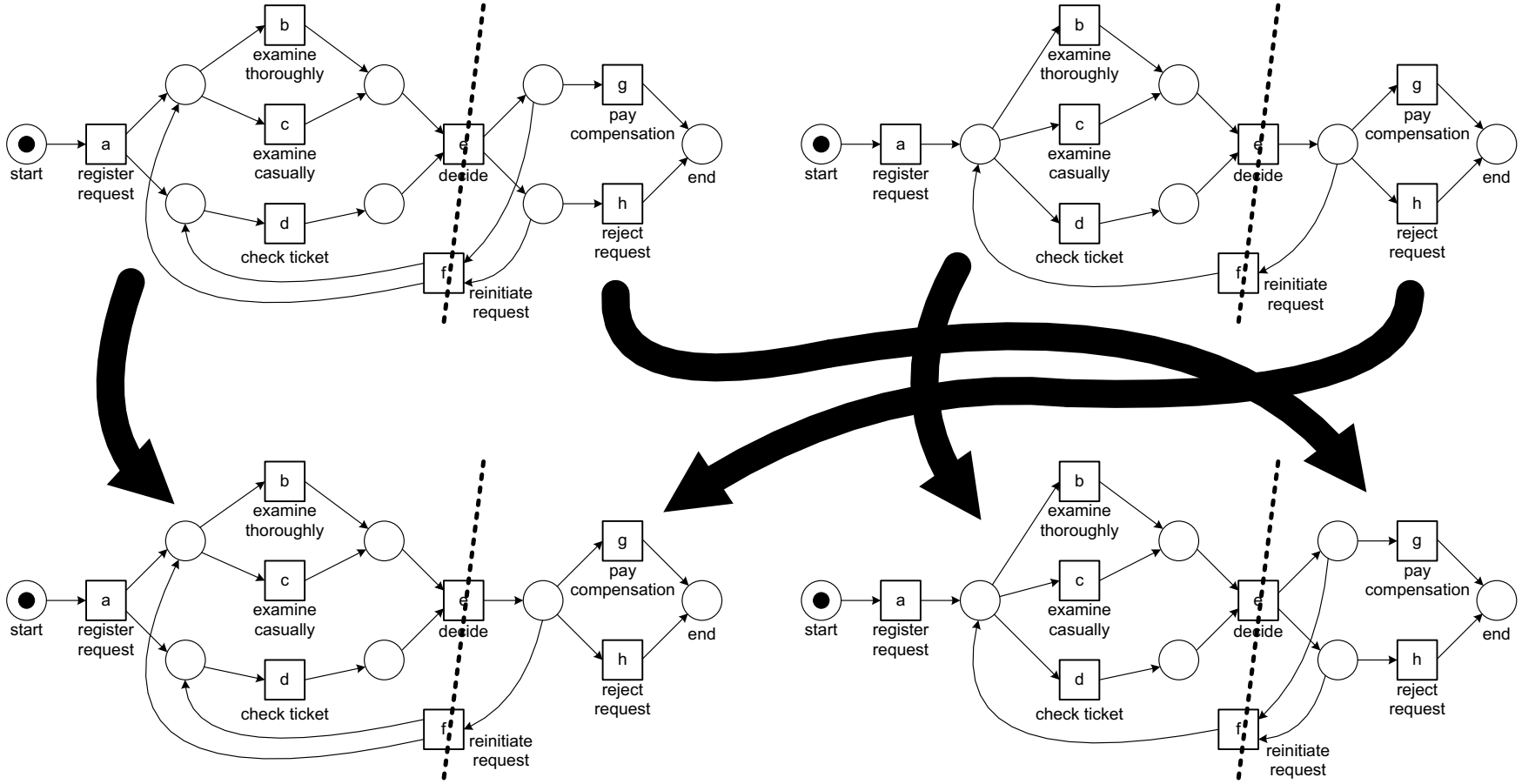


Design decisions

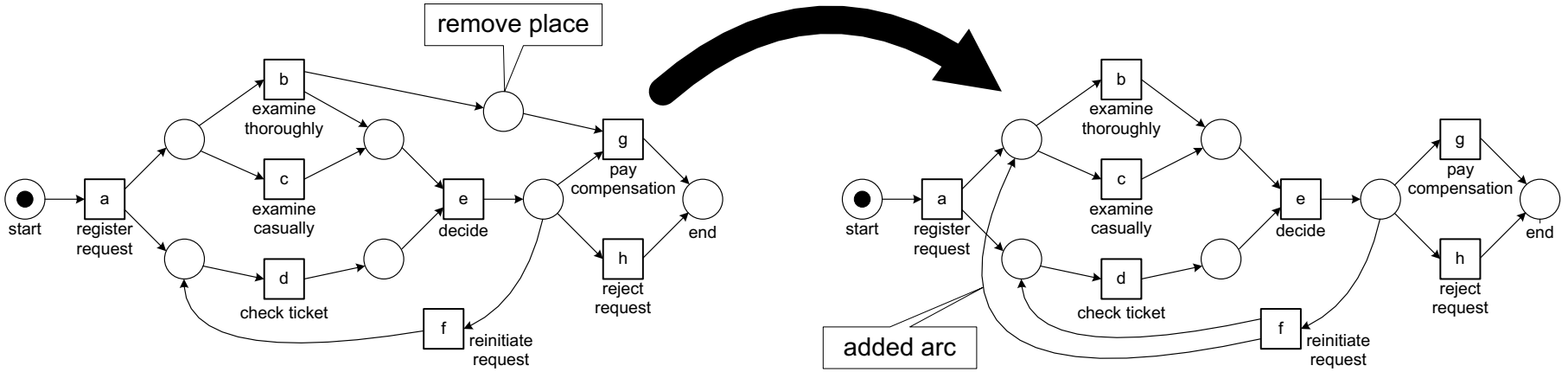
- Representation of individuals
- Initialization
- Fitness function
- Selection strategy (tournament and elitism)
- Crossover
- Mutation



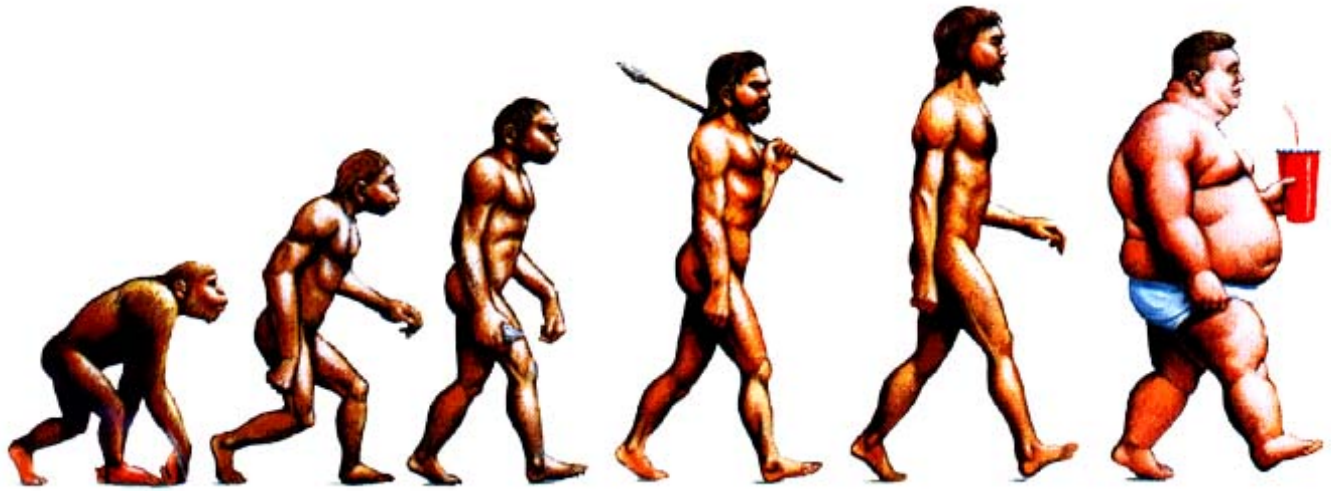
Example: crossover



Example: mutation



Characteristics of genetic process mining



- Requires a lot of computing power.
- Can be distributed easily.
- Can deal with noise, infrequent behavior, duplicate tasks, invisible tasks, etc.
- Allows for incremental improvement and combinations with other approaches (heuristics post-optimization, etc.).

Summary

- Process mining = data + processes
- Process discovery = events + learning
- Three different discovery algorithms covered
  - Alpha algorithm
  - Heuristic miner
  - Genetic miner
- But there are many many more! (Inductive Miner will be seen in the lab)
- **Next session: how good models are in describing reality ?**