30+ Years of modelling communicating systems

- what did I learn?

Muffy Calder

30+ years of modelling

Application driven foundational research

- models and formalisms

5 applications

- The question
- The techniques
- Novelty and what I learnt

30+ years of modelling

Application driven foundational research

- models and formalisms

Conclude with

- Recurring themes
- Future

Applications

1. Protocol languages
2. Signalling in biochemical networks
3. Domestic network management
4. Mixed-reality system
5. User interaction styles

The applications have changed over time -- and so have I

1. Protocol languages: ASN.1 and ACT ONE

1980s - a time for formalising protocols Sponsored by BT

two ISO data languages: **ASN.1** *[ISO 8824]* **ACT ONE** *[ISO 8807]*

Question: what is relationship/translation between the two languages?
Why? To integrate protocols/tools in/for both languages

Technique: ***ASN.1*** ⟶ ***ACT ONE***

denotational semantics

3 functions: *Eval* for values
Tval for types
Mval for modules

Tval: (Type x Environment) --> (Pexpr x Environment)

Example

Tval (SEQUENCE OF SEQUENCE INTEGER,e) =

(T *is* SEQUENCE *actualised* by Dummy *using* sortnames Seq *for* Data
where Dummy *is* SEQUENCE *actualised by* INTEGER *using*
sortname Int *for* Data, e)

Full semantics - 75 pages
9 additional reports, e.g. ASN.1 subtypes, functions, …

Novelty and what did I learn?

- fiercely faithful to ASN.1 and all its peculiarities
- deeply satisfying to define my own denotational semantics
- incredibly boring details to read
- FORTE conference comment

  we preferred it when everything was informal and

  we could implement our ASN.1 any way we liked

Novelty and what did I learn?

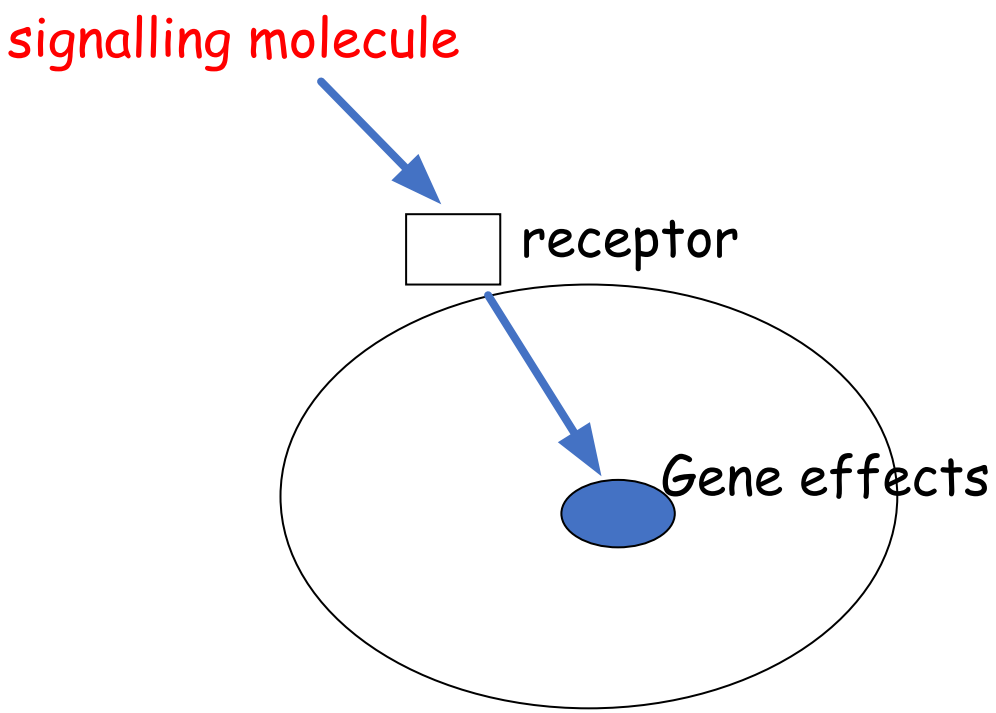
no impact at BT

until

- Implemented the semantics as an interpreter (Miranda)
- Valuable lesson – make your model come alive (find errors!)

2. Biochemical signalling pathways

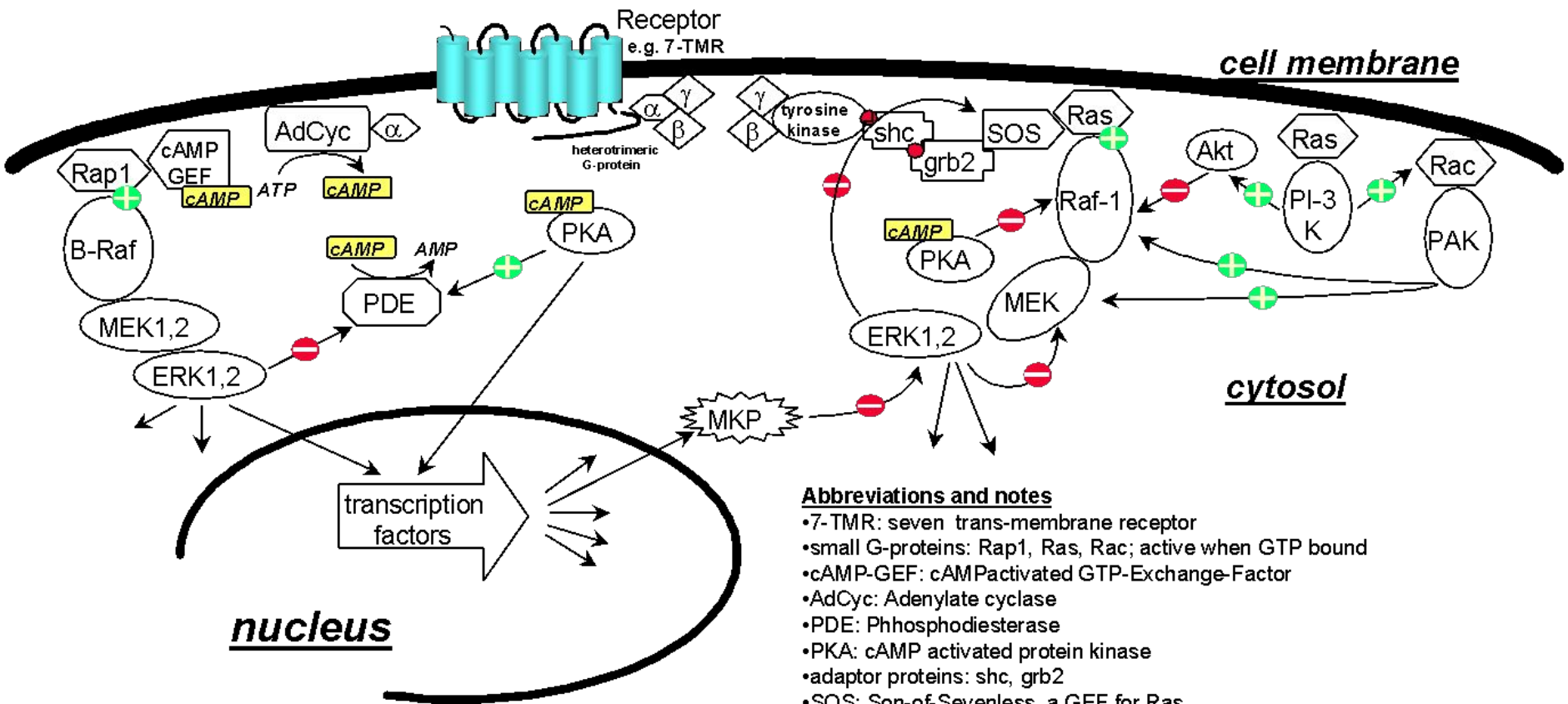
Intracellular pathways



Question: can we *model* pathways to

- understand interactions, sensitivities
- study effects of interventions
- study effects of faults, degradations
- test hypotheses

Intracellular pathways



Abbreviations and notes

- 7-TMR: seven trans-membrane receptor
- small G-proteins: Rap1, Ras, Rac; active when GTP bound
- cAMP-GEF: cAMPactivated GTP-Exchange-Factor
- AdCyc: Adenylate cyclase
- PDE: Phhosphodiesterase
- PKA: cAMP activated protein kinase
- adaptor proteins: shc, grb2
- SOS: Son-of-Sevenless, a GEF for Ras
- PI-3 K: Phosphatidylinositol-3 kinase
- Akt: a kinase activated by PI-3 K via PI-3 and another kinase, PDK
- PAK: a kinased activated by binding to Rac
- MKP: MAPK phosphatase, dephosphorylates MAPKs

Key observations:

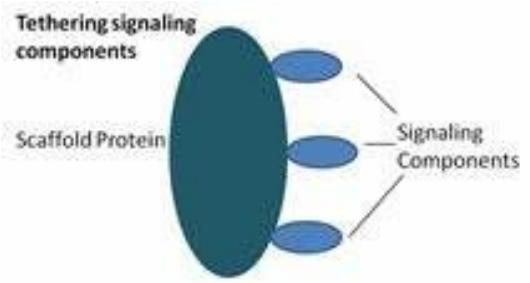
Communicating processes

Phosphorylation is the signal

Rates are important

Techniques: **models** CTMCs stochastic process algebra
PRISM reactive modules
properties temporal logic CSL

Models:
processes represent ***molar*** concentrations
populations, *not* individuals
plug and play processes for assembling different networks
scaffolds are additional processes



Example Raf/MEK/ERK pathway

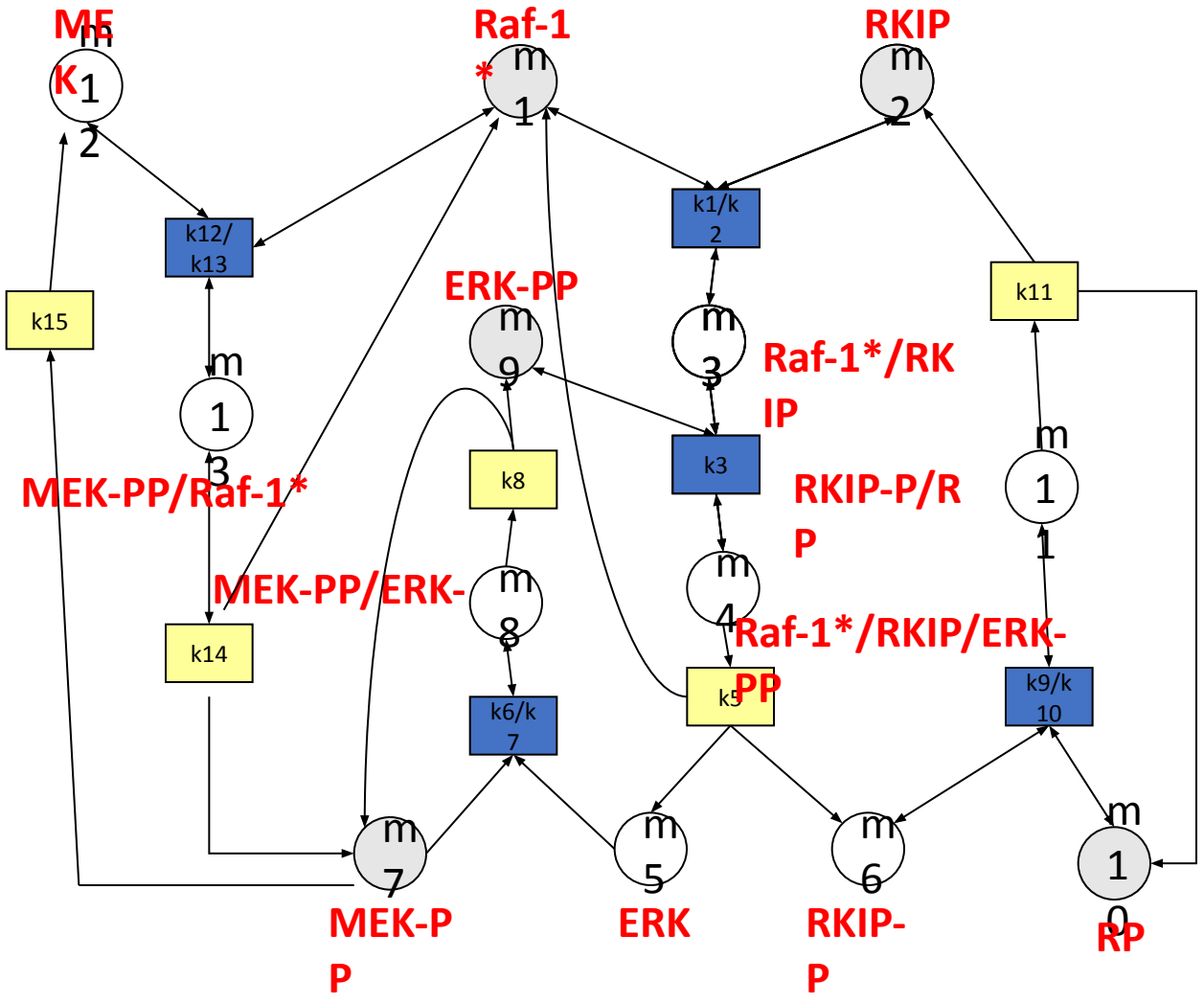
Raf* phosphorylates MEK phosphorylates ERK

Raf* → MEK-PP → ERK-PP

Question: how does RKIP* affect the pathway?

*RKIP – Raf kinase inhibitor protein

Raf/MEK/ERK pathway



CANCER RESEARCH UK
BEATSON LABORATORIES

proteins

m1, m2 concentrations

k9/k10

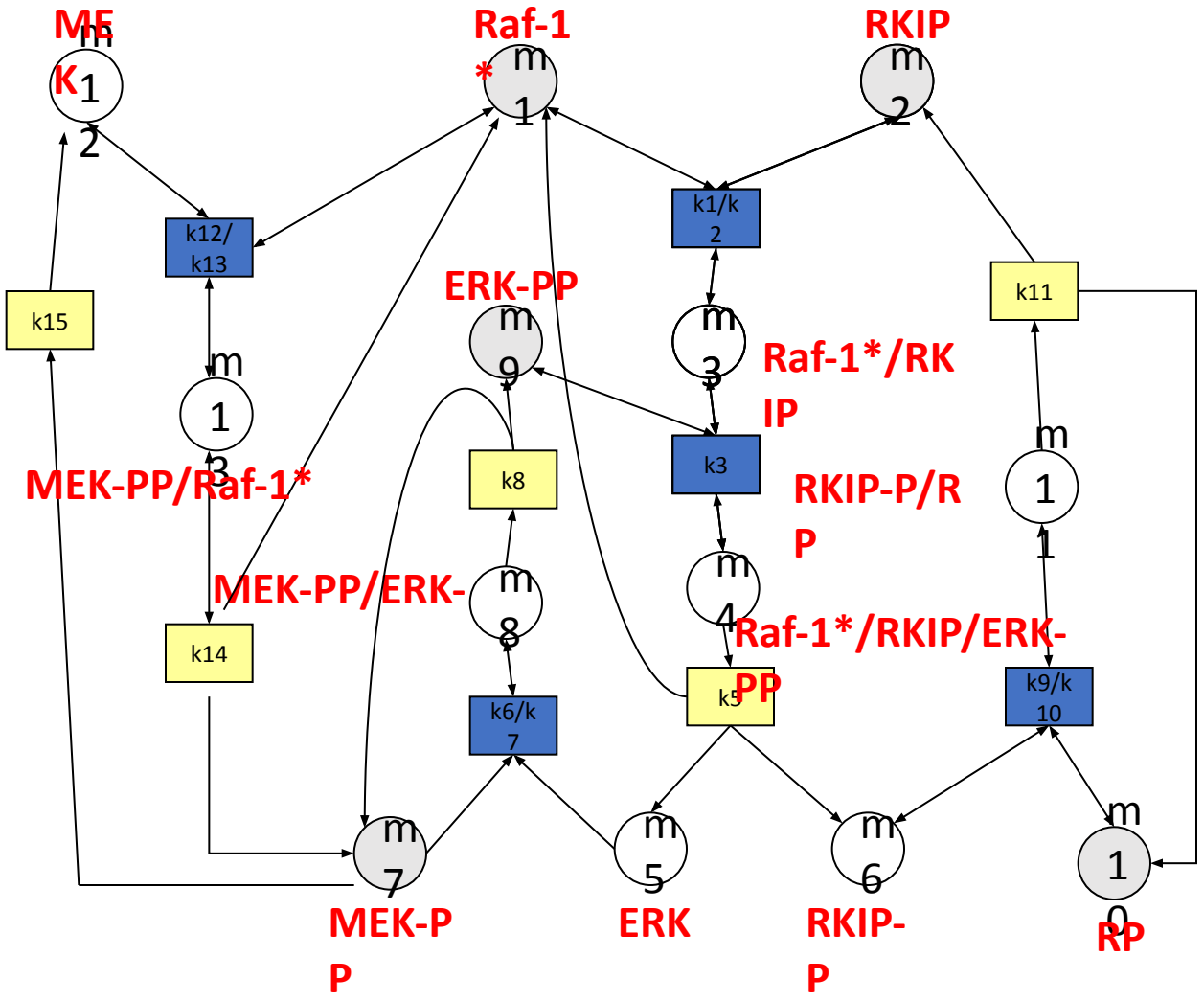
forward /backward reactions

k11

products (disassociations)

k1,k2 .. rate (performance) coefficients

Raf/MEK/ERK pathway

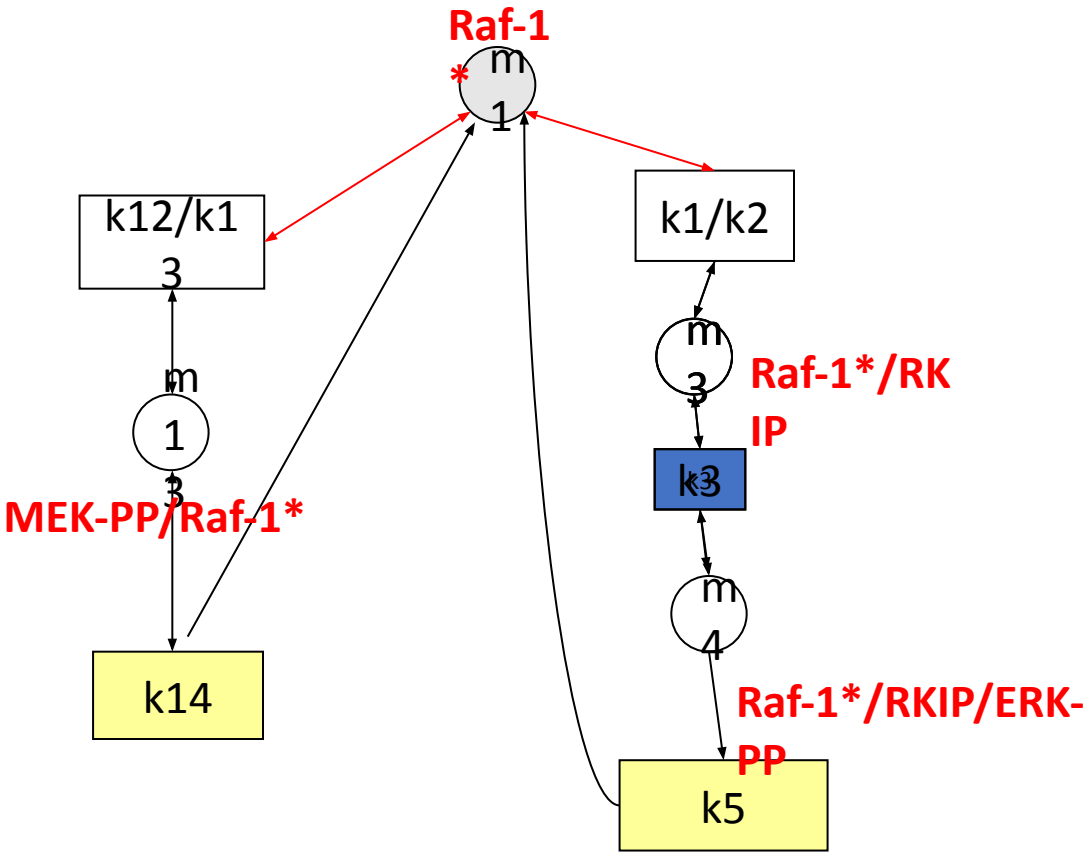


Questions:

what are sensitivities in pathways

can we detect and classify cross-talk

how do scaffolds work – to inhibit or speed up reactions

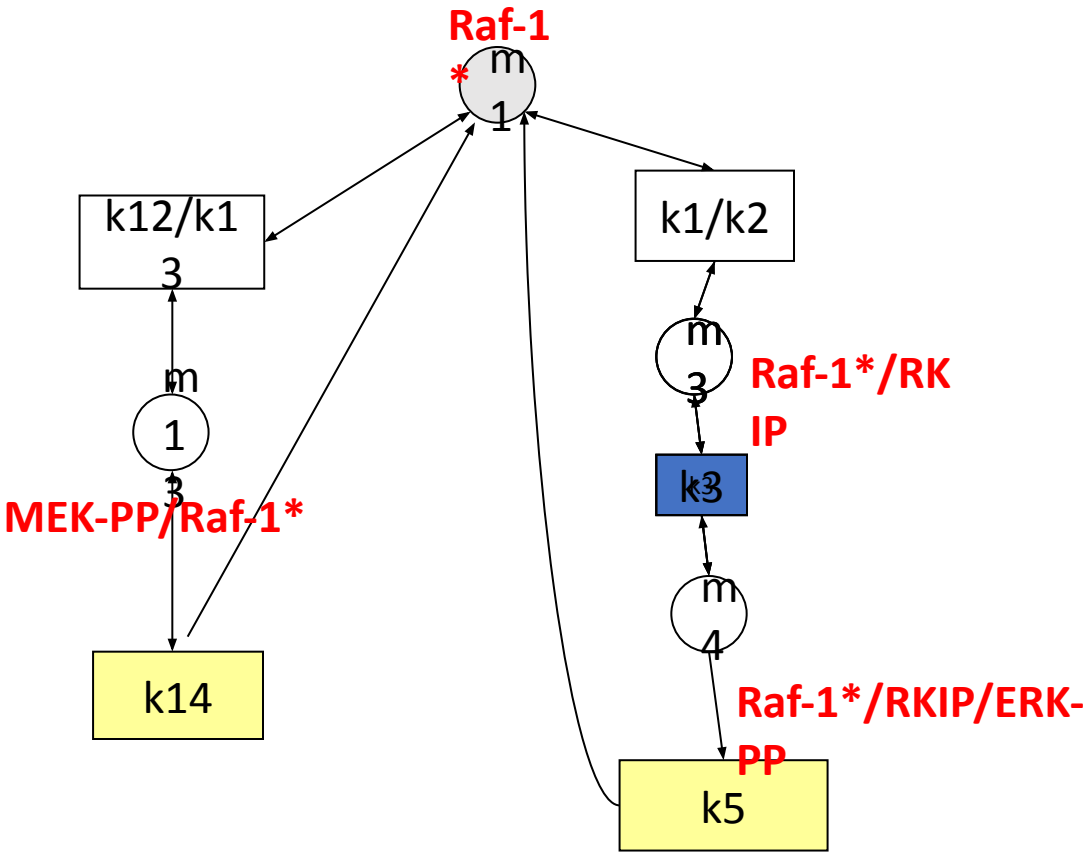


Process Algebra Model

High or Low quantity

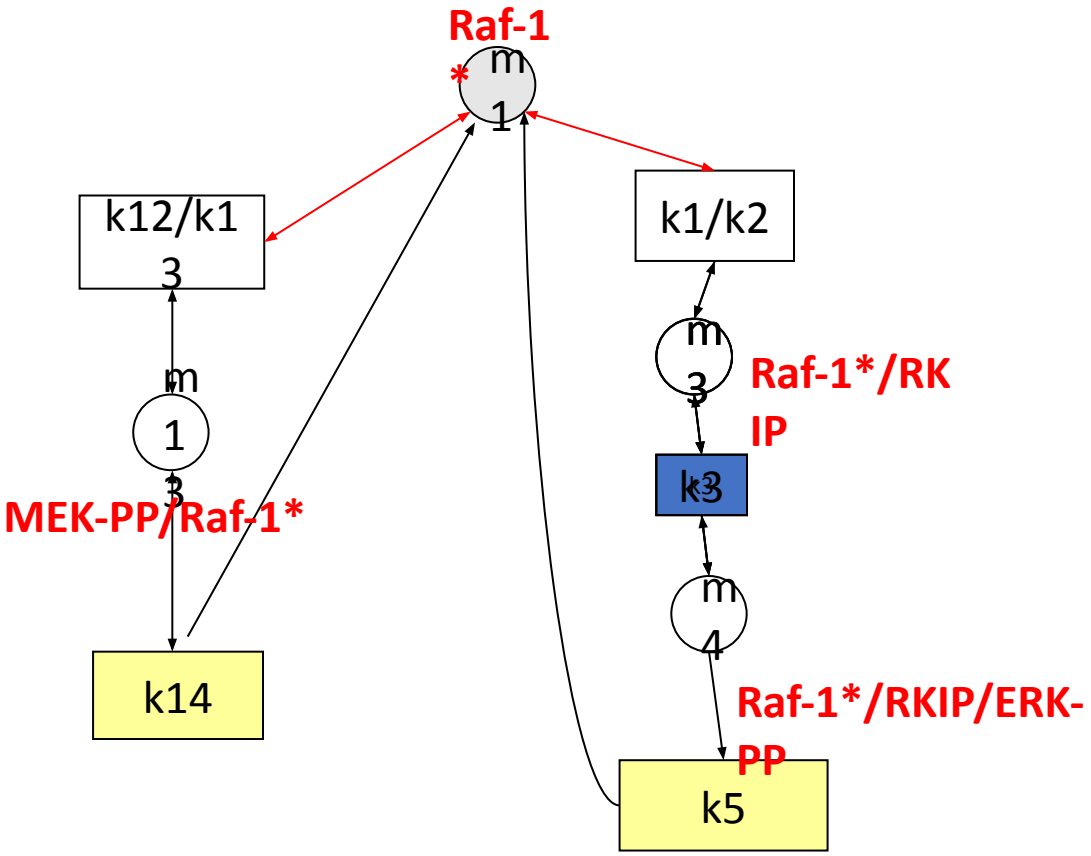
Raf-1* is high

=> k1 or k12 reaction



$$Raf\text{-}1^*_H = (k1react,k1).\ Raf\text{-}1^*_L + (k12react,k12).\ Raf\text{-}1^*_L$$

$$Raf\text{-}1^*_L = (k5product\ ,k5).\ Raf\text{-}1^*_H + (k14product,k14).\ Raf\text{-}1^*_H + (k2react,k2).\ Raf\text{-}1^*_H + (k13react,k13).\ Raf\text{-}1^*_H +$$

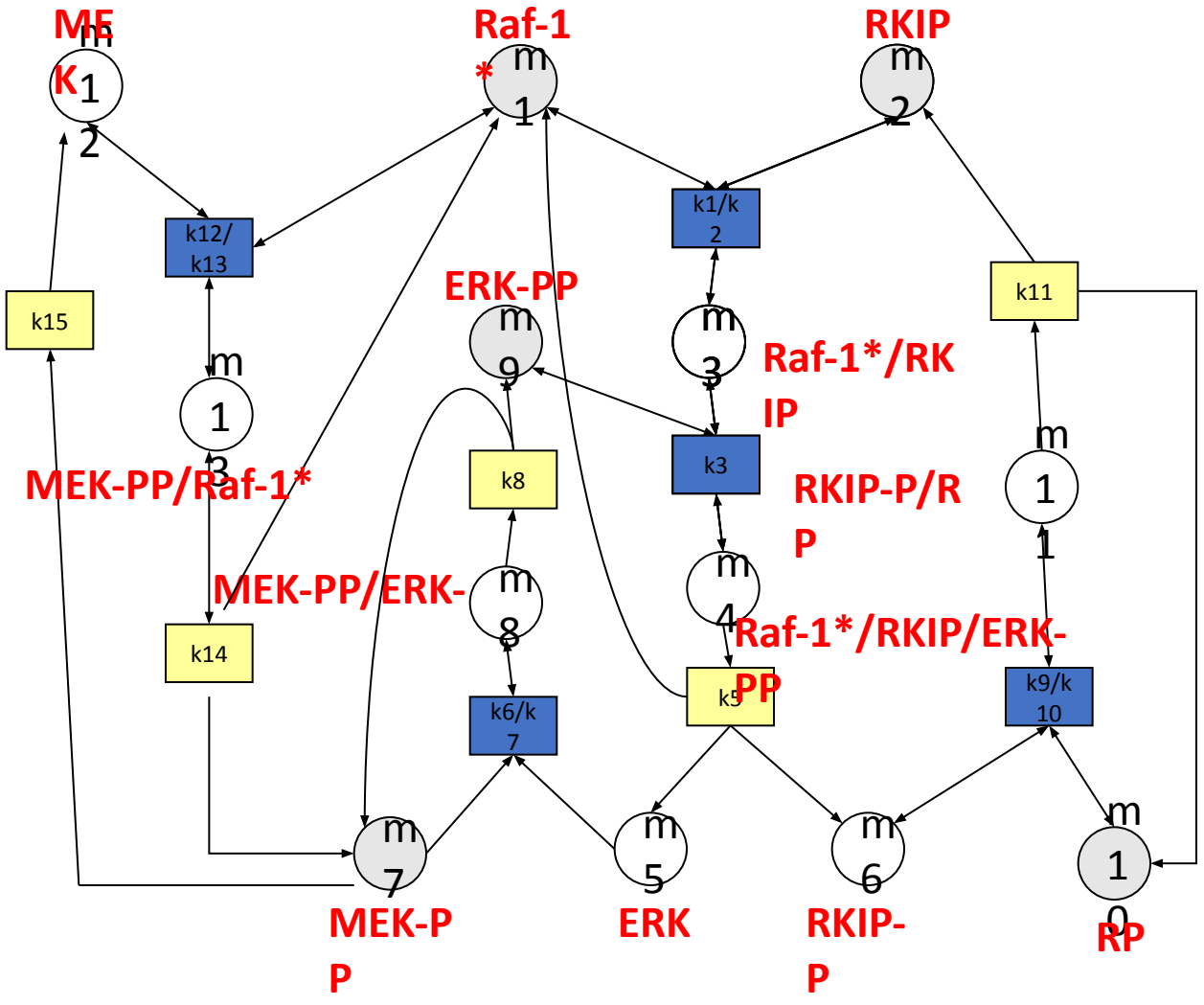


Process Algebra Model

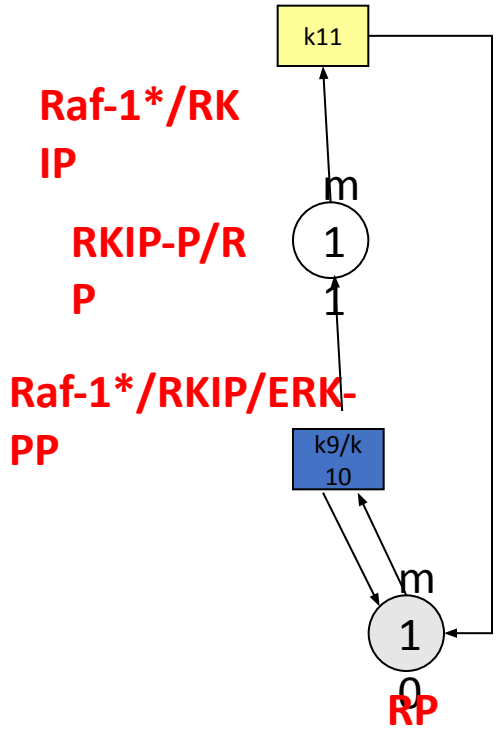
Another perspective

Sub-pathways

Raf/MEK/ERK pathway



sub-pathway



Pathway10 =

(k9react,k9). Pathway11

Pathway11 =

(k11product,k11). Pathway10

+ (k10react,k10). Pathway10

Reagent view:

Raf-1*$_H$ = (k1react,k1). Raf-1*$_L$ + (k12react,k12). Raf-1*$_L$

Raf-1*$_L$ = (k5product,k5). Raf-1*$_H$ + (k2react,k2). Raf-1*$_H$

+ (k13react,k13). Raf-1*$_H$ + (k14product,k14). Raf-1*$_H$

…

(13 proteins - 26 equations)

Pathway view:

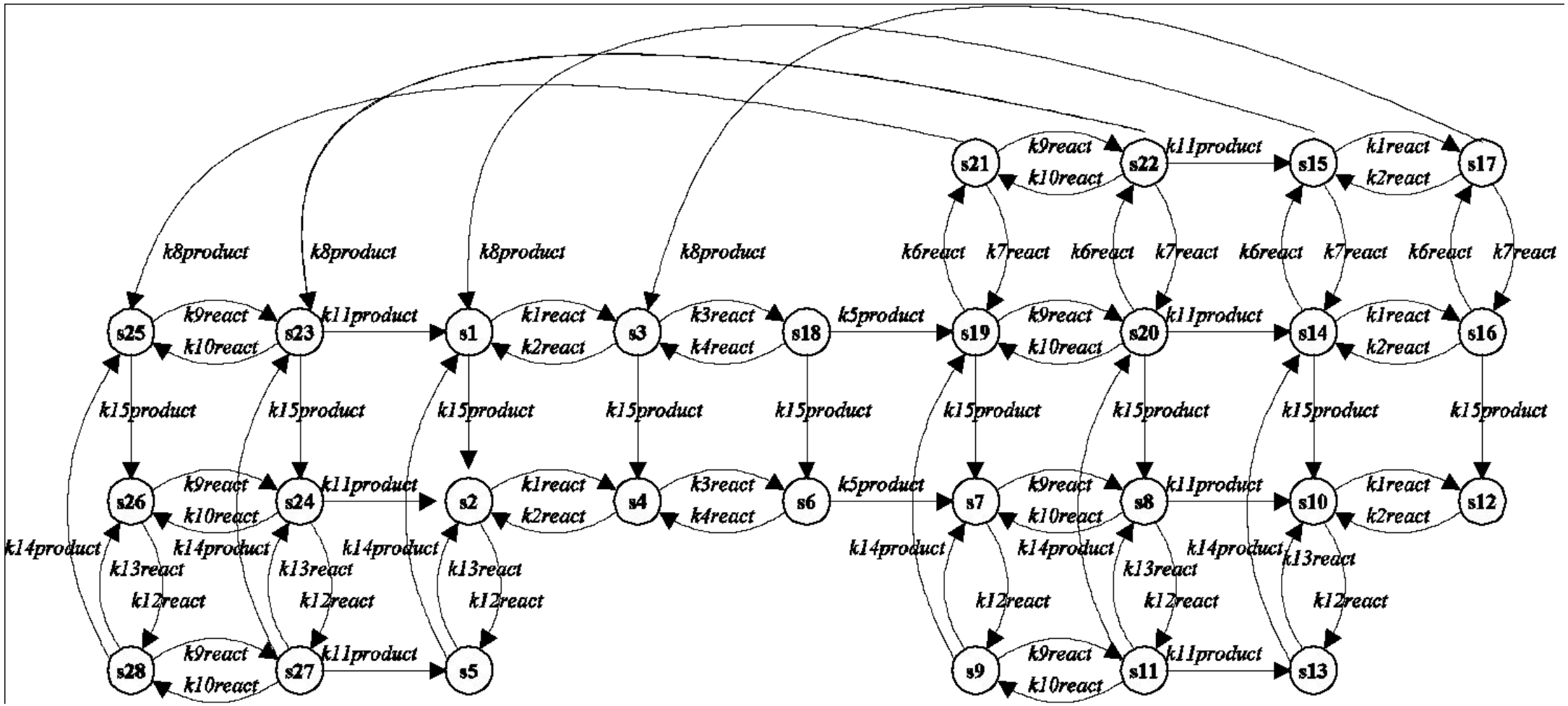
Pathway10 = (k9react,k9). Pathway11

Pathway11 = (k11product,k11). Pathway10 + (k10react,k10). Pathway10

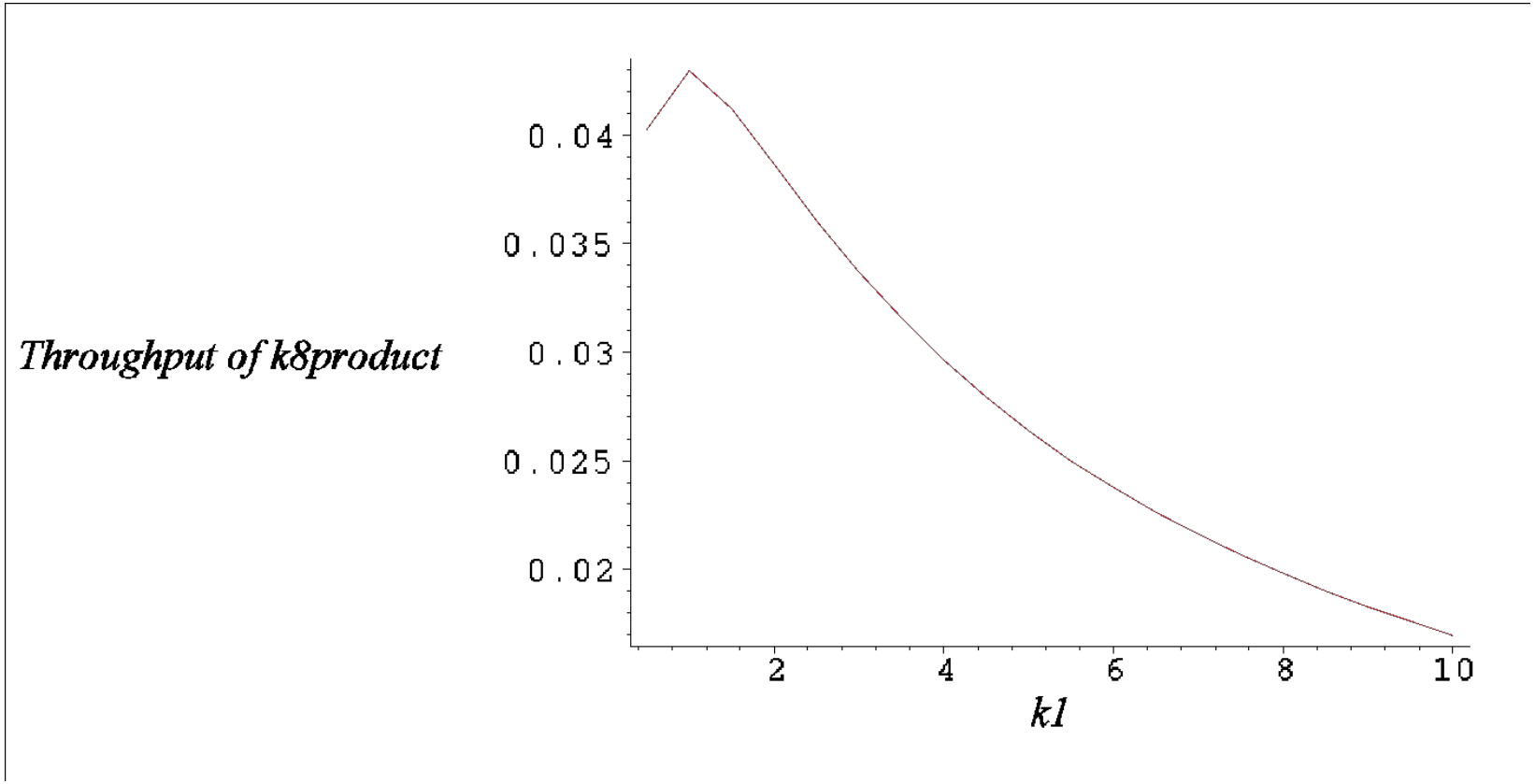
…

(5 pathways - 5 equations)

CTMC state space



Quantitive analysis: What is the effect of binding RKIP to Raf-1*on ERK-PP?



Effect of increasing the *rate* of k1 on k8product throughput (rate x probability)

Multiple pathways: detect crosstalk
categorise crosstalk

Example CSL properties

Substrate Availability

Pathways compete for a protein: it is not possible to activate protein in both pathways

$AG \sim (X^*_1 = 1 \wedge X^*_2 = 1)$

Signal Flow

Possible to activate a pathway without activating the receptor

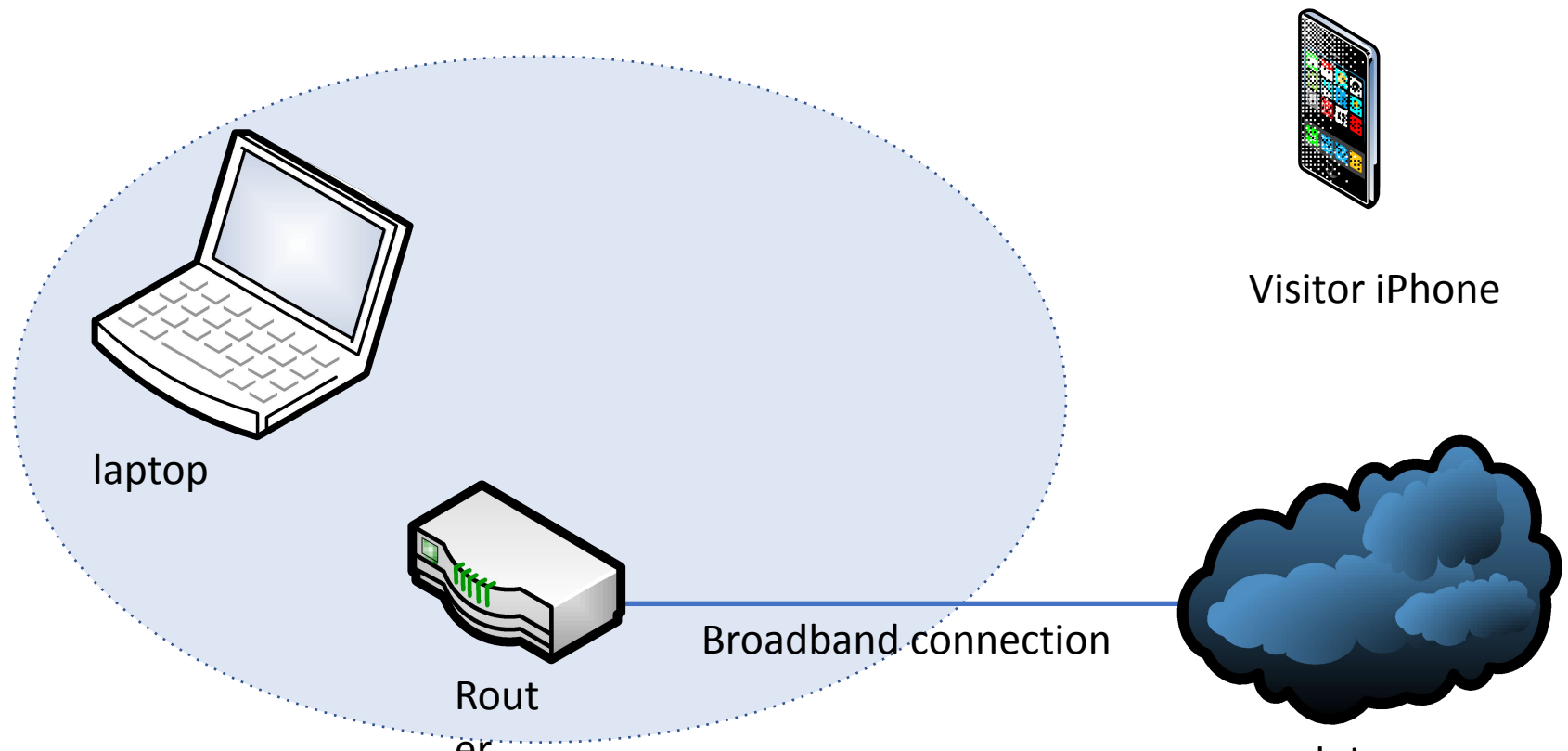
$EF (R^*_1 = 0 \wedge Protein_1 = 1)$

Novelty and what did I learn

- reactions are processes
- individuals versus populations; representing *quantities*
- CTMC models
- (Re-learnt) ODEs and Eulers method
- CSL and propositions for quantitative trends
- Back to science – reflections on science and engineering

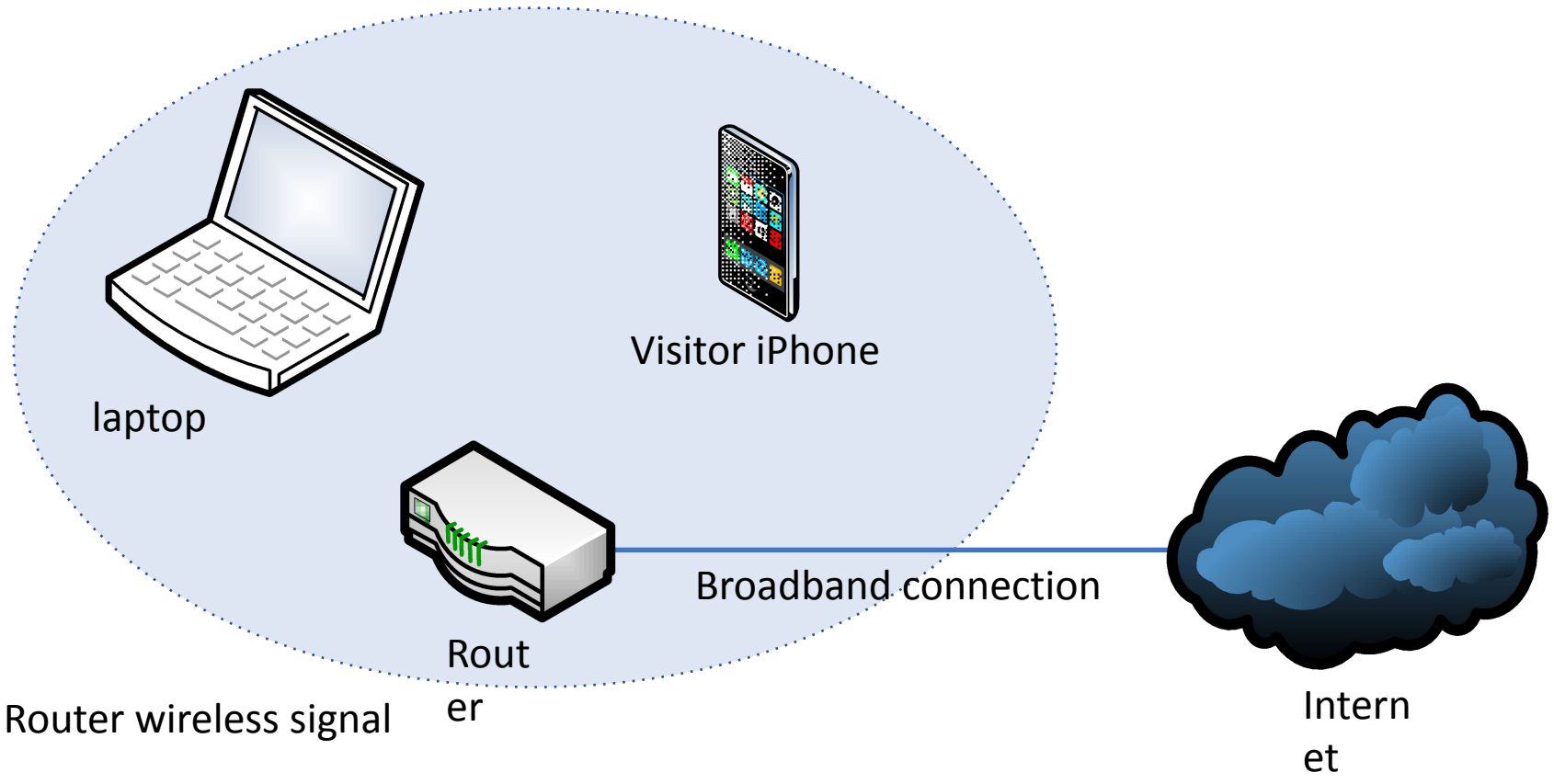
3. Home network management

3. Home network management



3. Home network management

Question: Does it *work*?



- Did the iPhone actually join the home network?
- Did the router assign a valid IP address?
- Is the iPhone allowed to access the Internet?
- Will the firewall stop any traffic?

Technique: online models

to inform users about the state of system, detect and diagnose problems, check policy compliance

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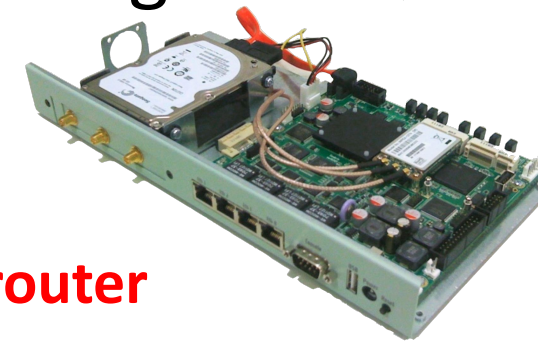
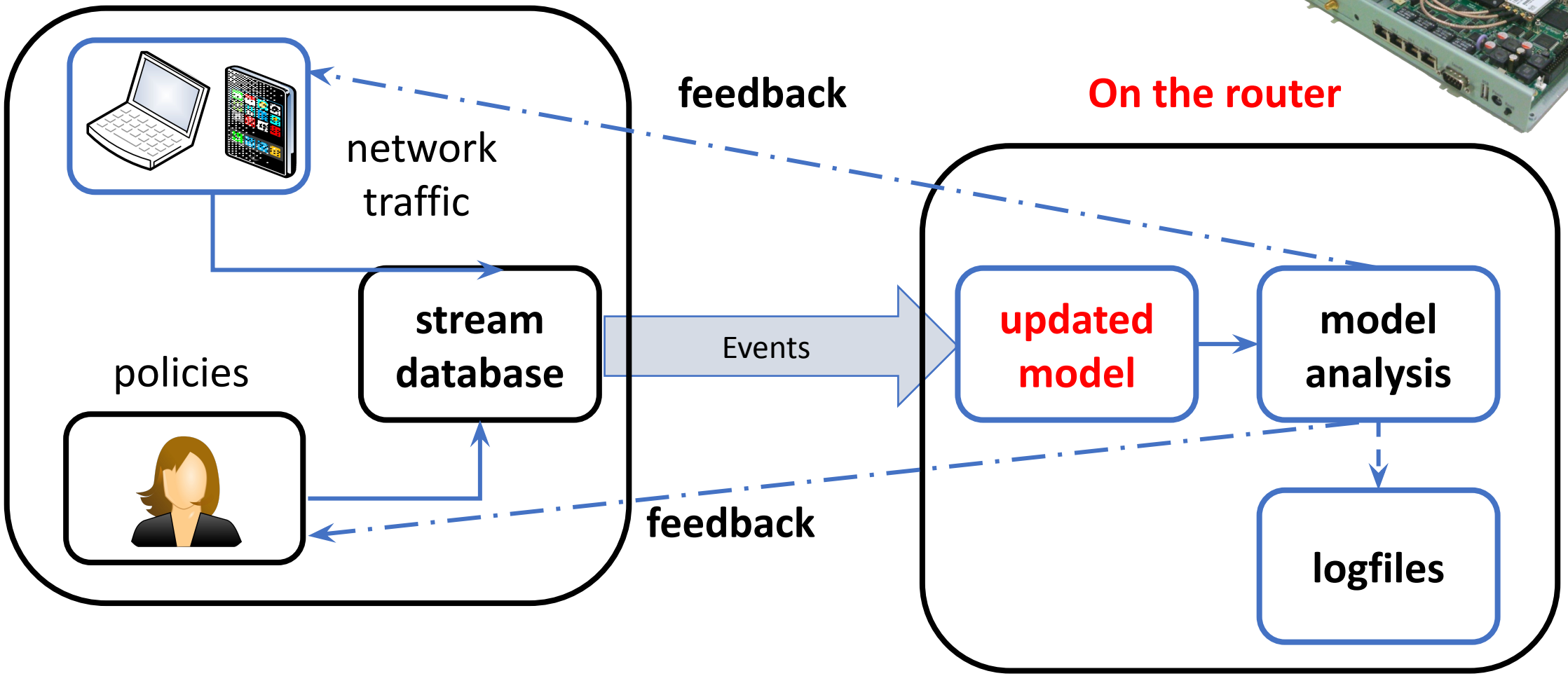
to inform users about the state of system, detect and diagnose problems, check policy compliance





Models: network events and access control policies

Bigraphs with sharing

- process algebra for space and time

- entities and rewrite rules are ***user-defined***

- algebraic and graphical form

Analysis:

compliance with a ***policy*** (invariant)

system |= property *iff*

bigraph (property) ***matches*** bigraph (system)

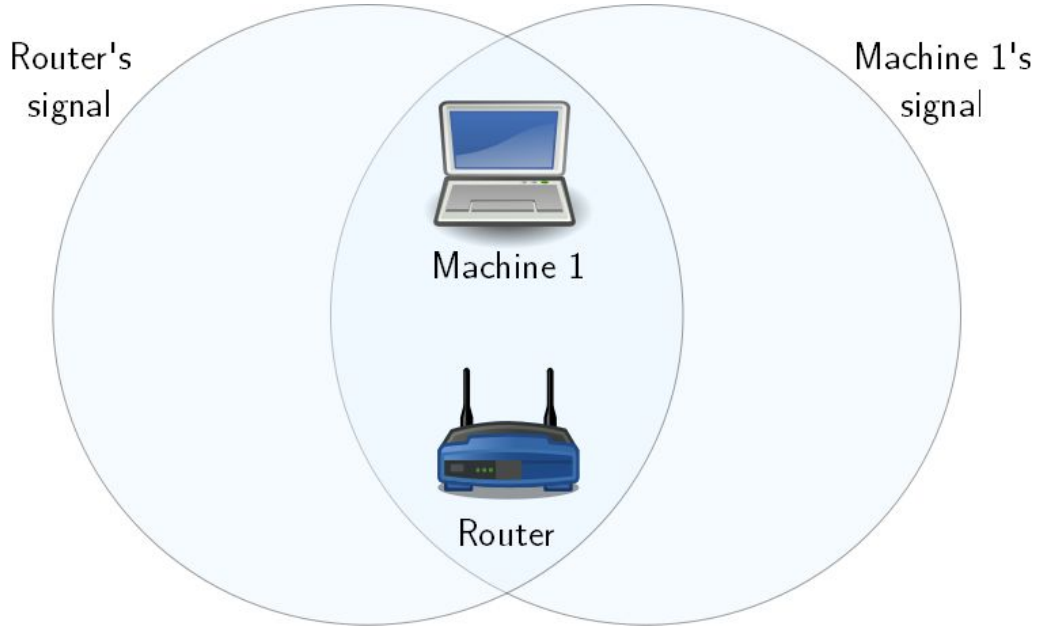
Check after every event/model update!

Machine 1	**M1**
Router	**R**
Wireless signals	**S**

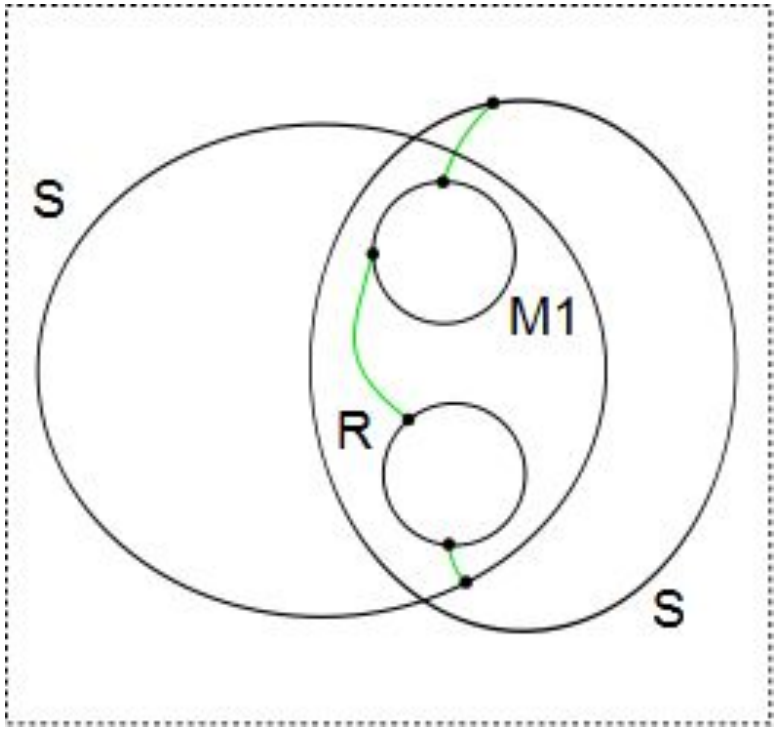
R and M1 are linked to their signals

R can sense M1's signal and vice versa
(intersection between signals)

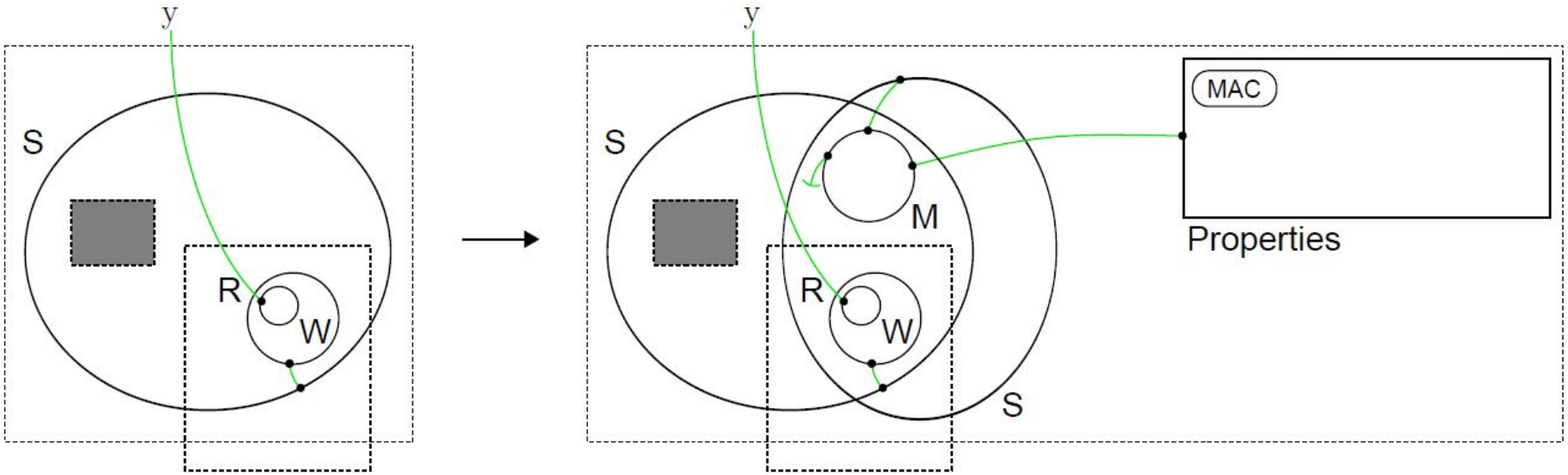
R and M1 are linked -- part of the WLAN



Bigraph



Network event: add a machine M – bigraph *rule*



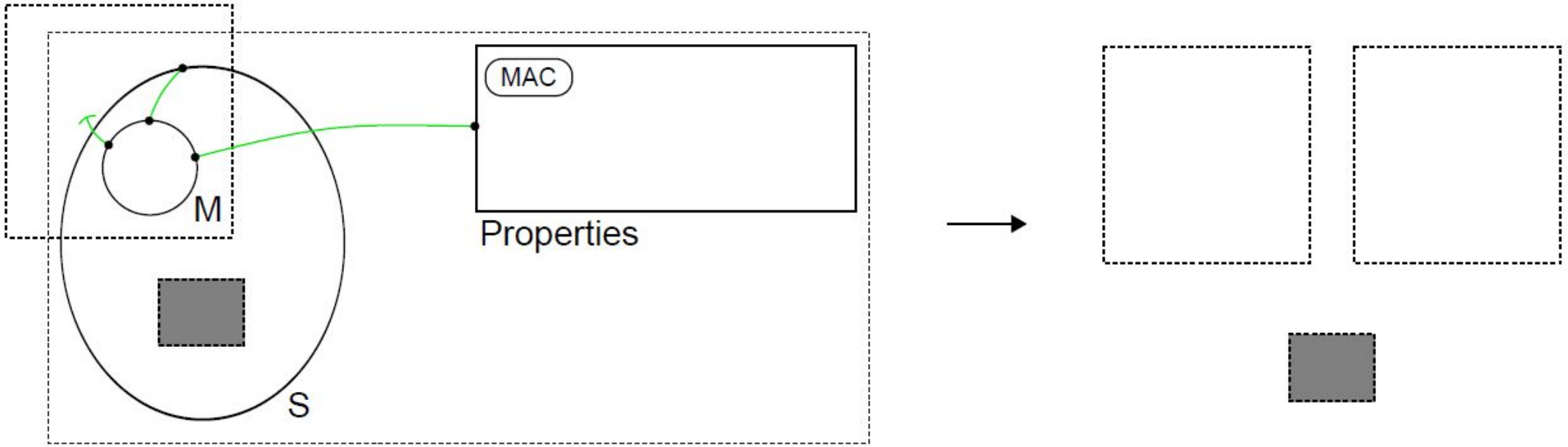
R may be in the range of other signals (extra region)

W may be linked to other machines (with name y)

M is linked to its signal and properties, but not to **W**

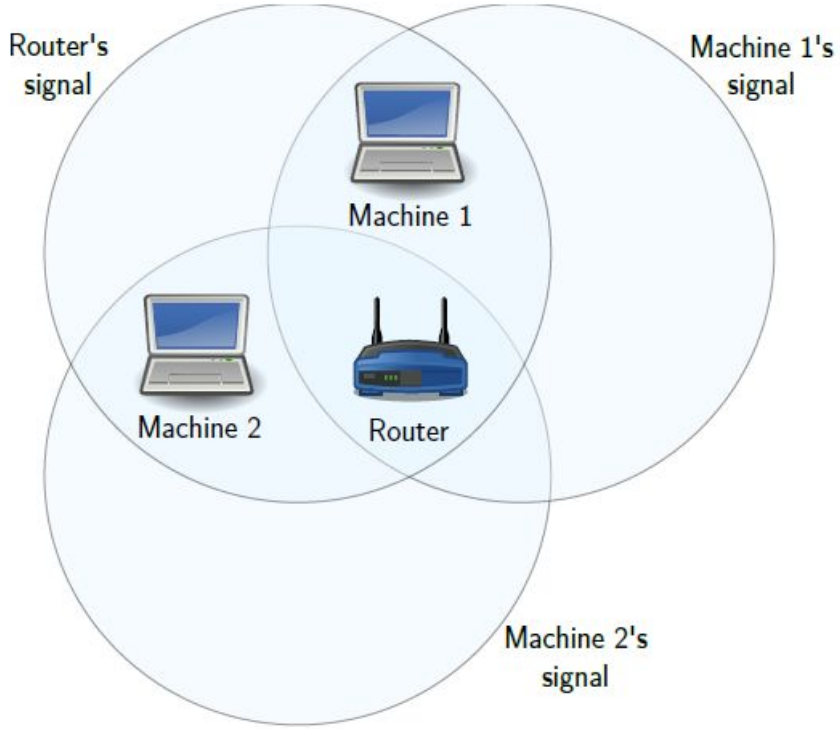
M and **R** are in the intersection of the two S nodes

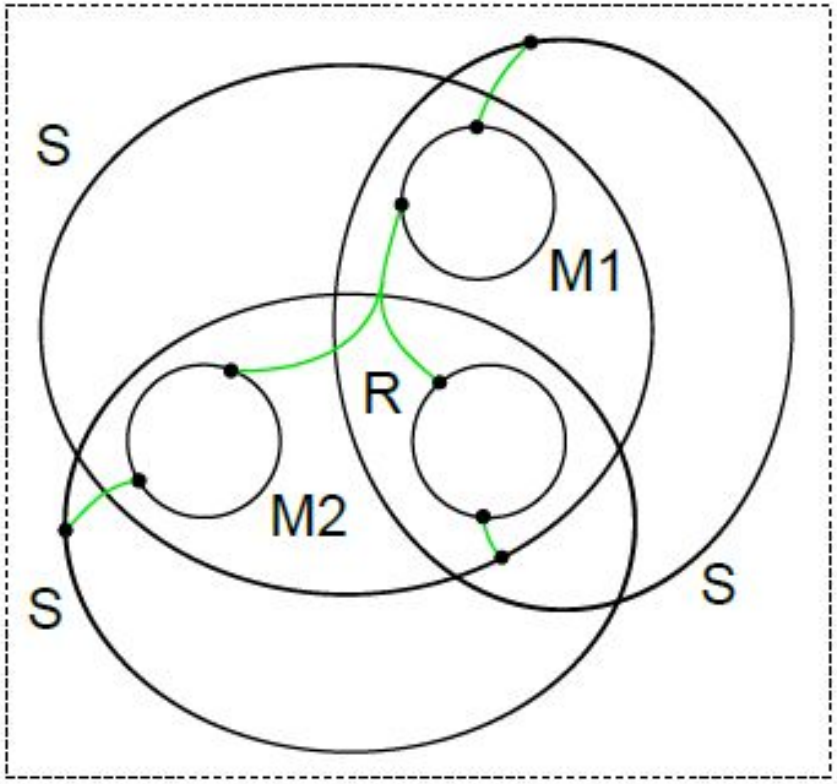
Network event: remove machine – bigraph rule



Remove machine M in range of Signal S

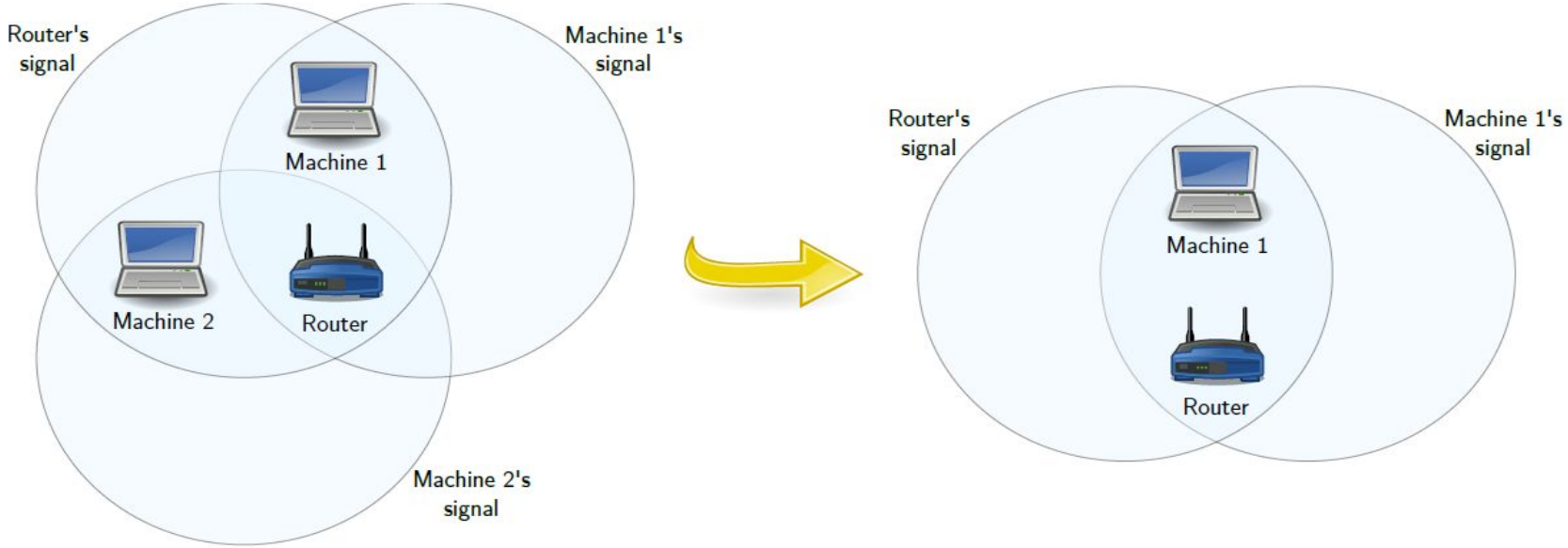
Two machines M1 and M2

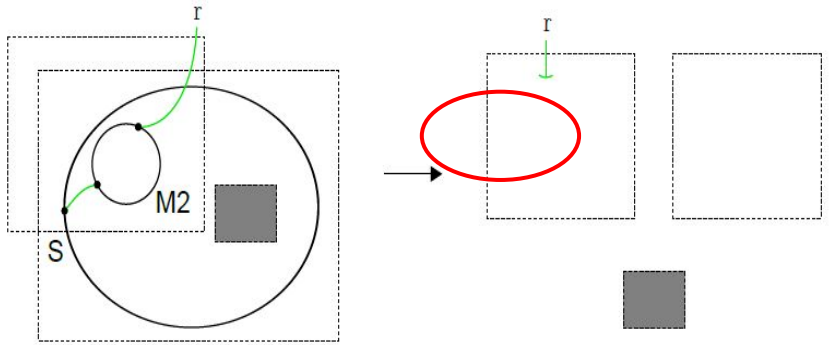


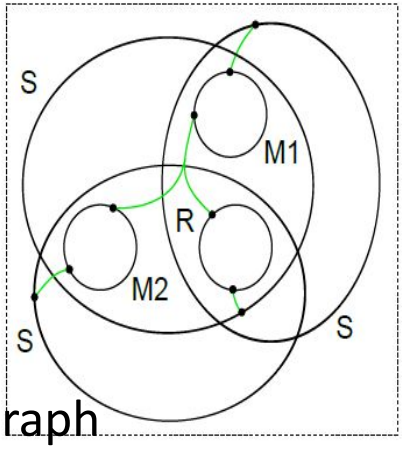


Bigraph

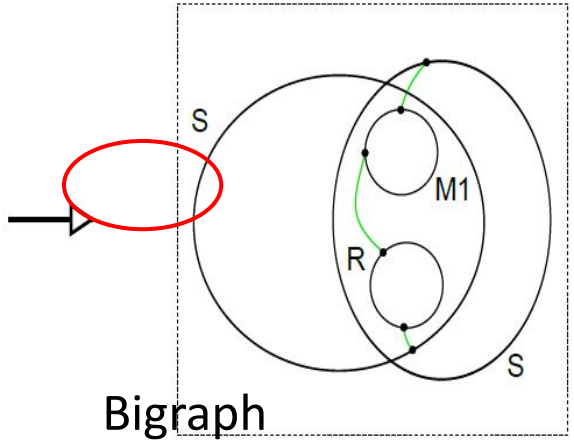
Remove machine: update model – apply bigraph rule





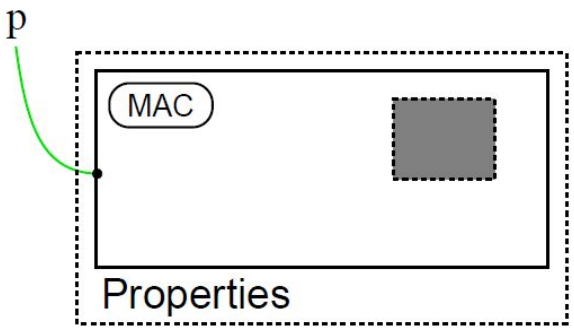


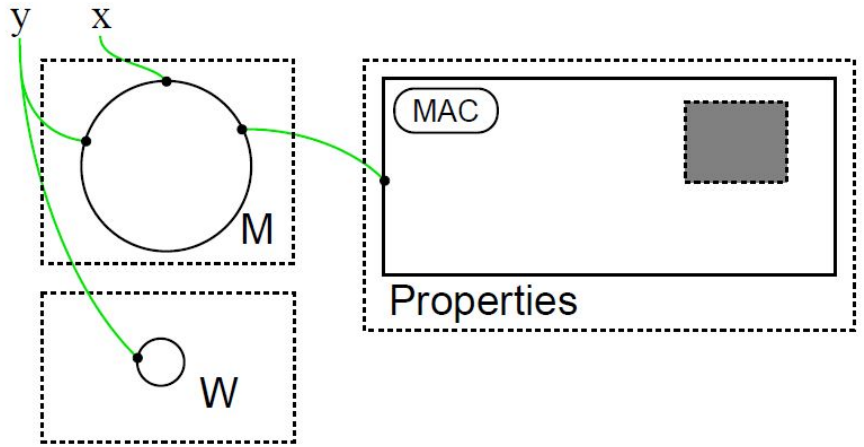
Bigraph



Bigraph

Check network status: predicates - bigraphs





Machine MAC is present in the system

Iff

this bigraph is a match

Machine MAC is part of the WLAN

iff

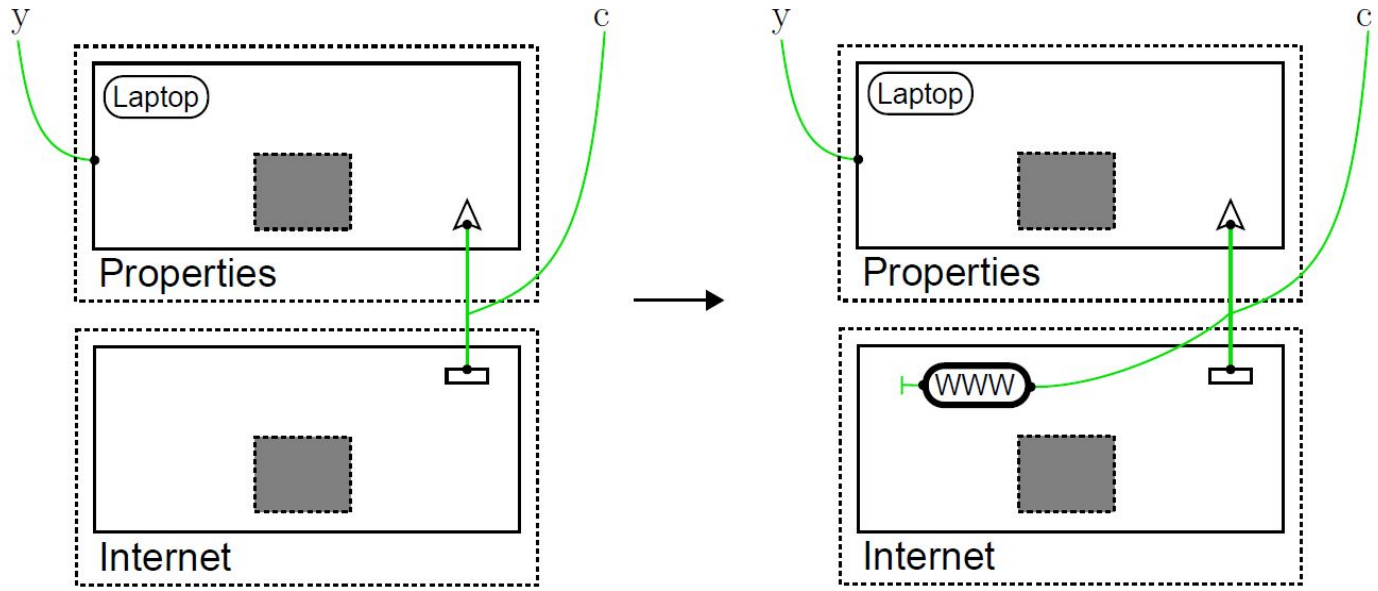
this bigraph is a match

Policy events

- Policies allow or forbid
- Policies can be enforced, dropped or checked

- Forbid policies *introduce* constraints in the system
- Allow policies *remove* constraints from the system

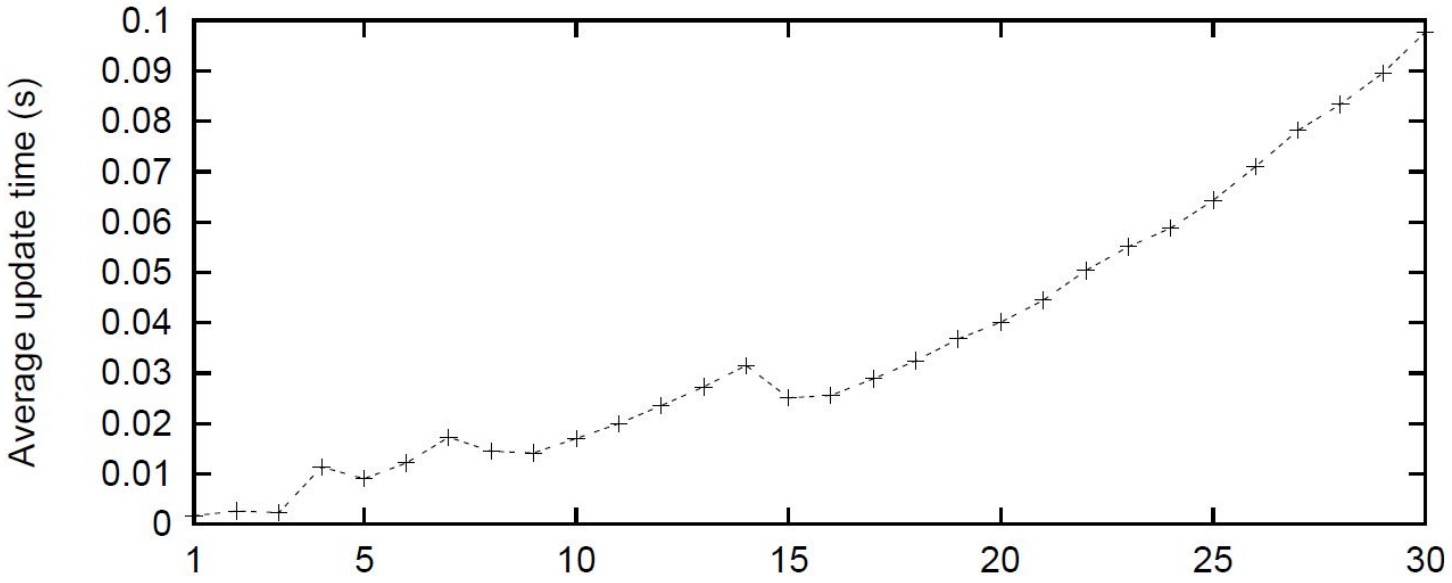
Policies can be active or revoked - bigraph rules



policy

block all incoming traffic from remote host WWW to machine Laptop

Check active policies (predicates) after every network event - in real time



Average time to perform an update

(Average over 100 updates)

Novelty and what did I learn

- online models (2011 – before digital twins!)
- bigraphs with sharing (overlapping spaces)*
- no need for temporal logics, just state predicates
- predicates == bigraph matching (sub graph isomorphism)
- policies can interfere with each other in unanticipated ways

* BigraphER - Michele Sevegnani

4. Savannah game: location, time, sensing and cognition in mixed reality systems

virtual Savannah is overlaid on a physical playing field

players are instrumented: GPS and PDA

players are **lions** and check their PDAs

- to determine *locale*
- "see" nearby animals
- attack, drink, etc. when possible

social interactions are required to

form hunting **groups** – 3 players needed

User trials

The **“three girls, a boy, and an impala problem”**

Question: Why was there cognitive dissonance?
What is wrong with the design?

Techniques: Bigraphs for spatio temporal evolution
Bigraph predicates for reasoning
Graphical notation
Four design perspectives

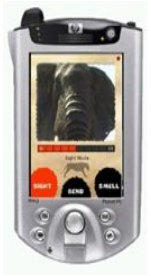
4 design perspectives

Physical

Social interactions

Human

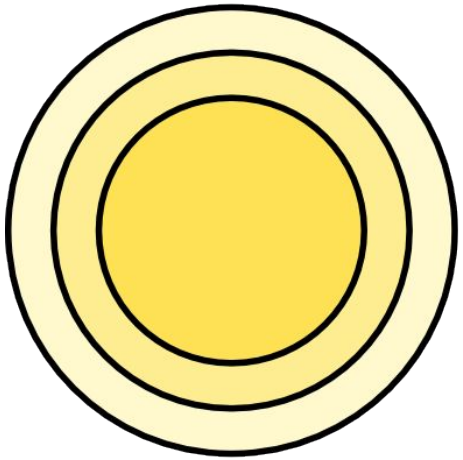
GPS sensors



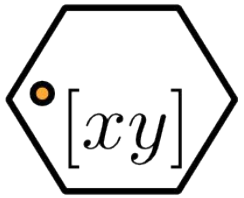
Technology

Computational

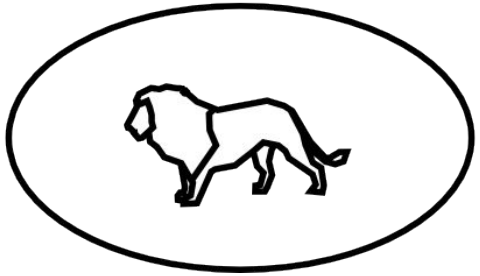
Bigraphical model



Human



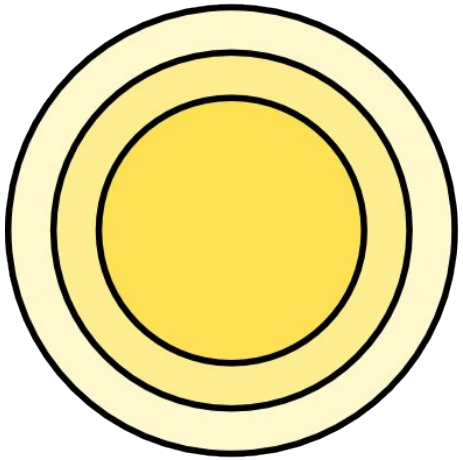
Technology

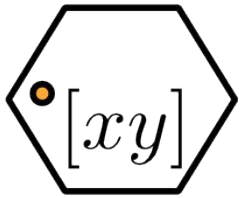


Computational

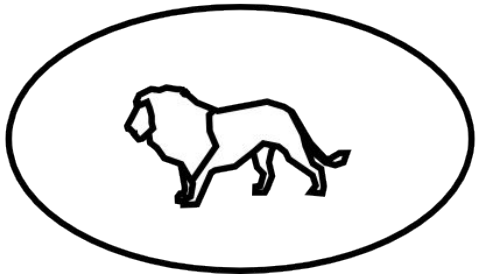
Bigraphical model

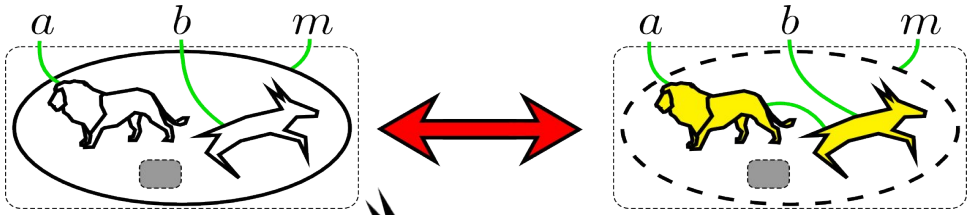
Human

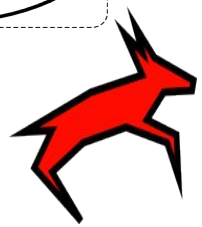




Technology





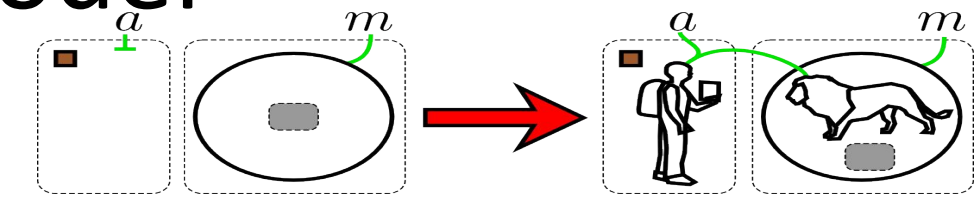


Computational lions, impala in locales

Rules: eating, drinking, hunting

Bigraphical model

Physical

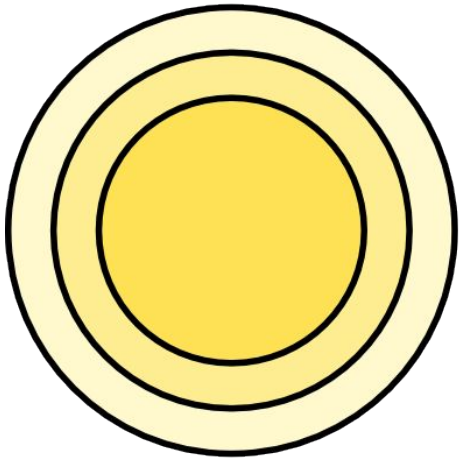


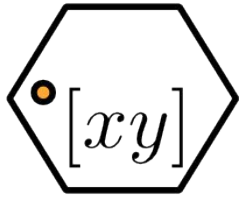
players on field

Rules: pair child/lion

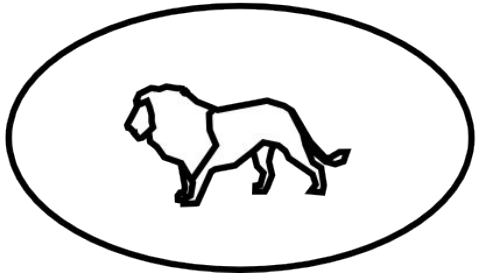
initiate attack or in group

Human





Technology

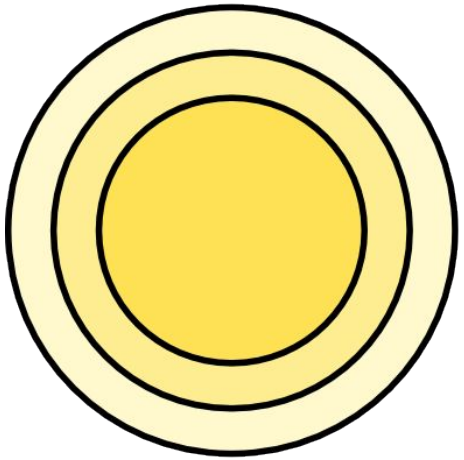


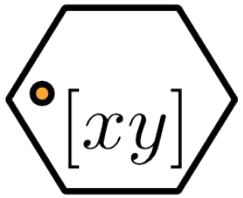
Computational

Bigraphical model

Physical

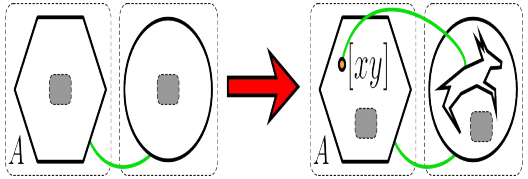
Human

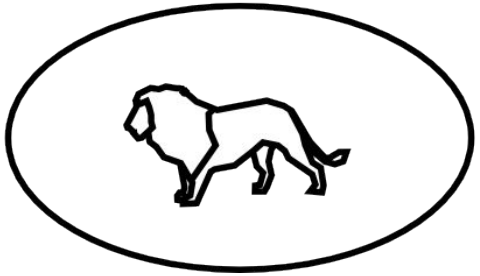




Technology

GPS positions
in areas

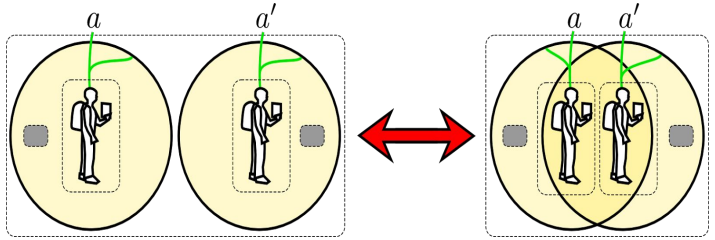




Computational

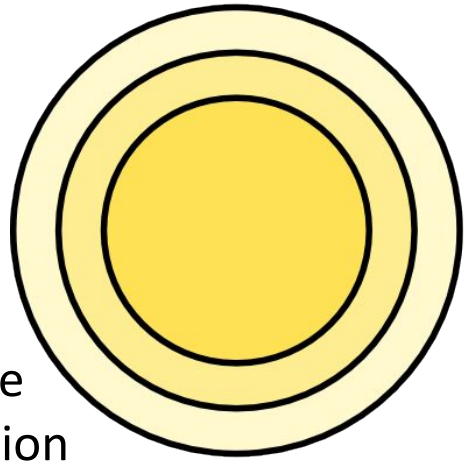
Rules: enter game, move, die

Bigraphical model



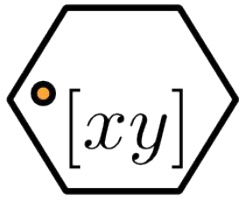
Physical

Human

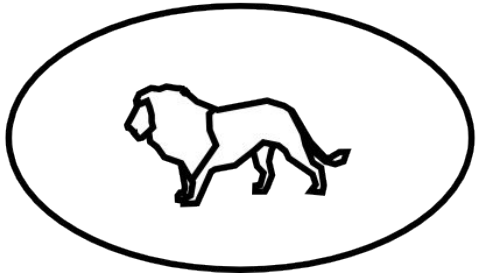


Proxemics

Rules: personal space
social interaction



Technology



Computational

Bigraphical model – summary

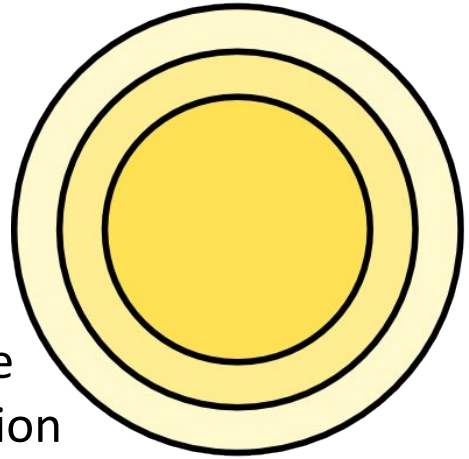
Physical

Players on field

Rules: pair child/lion

initiate attack or in group

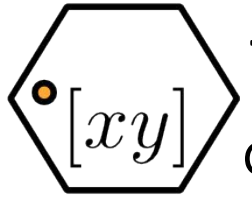
Human



Proxemics

Rules: personal space

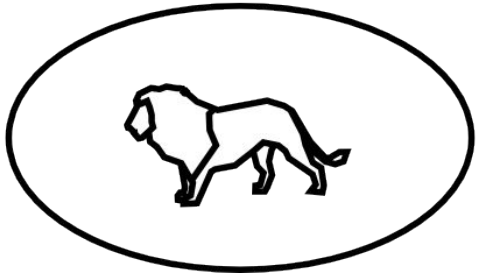
social interaction



Technology

GPS positions/areas

Rules: enter game, move, die



Computational

lions, impala in locales

Rules: eating drinking, hunting

The

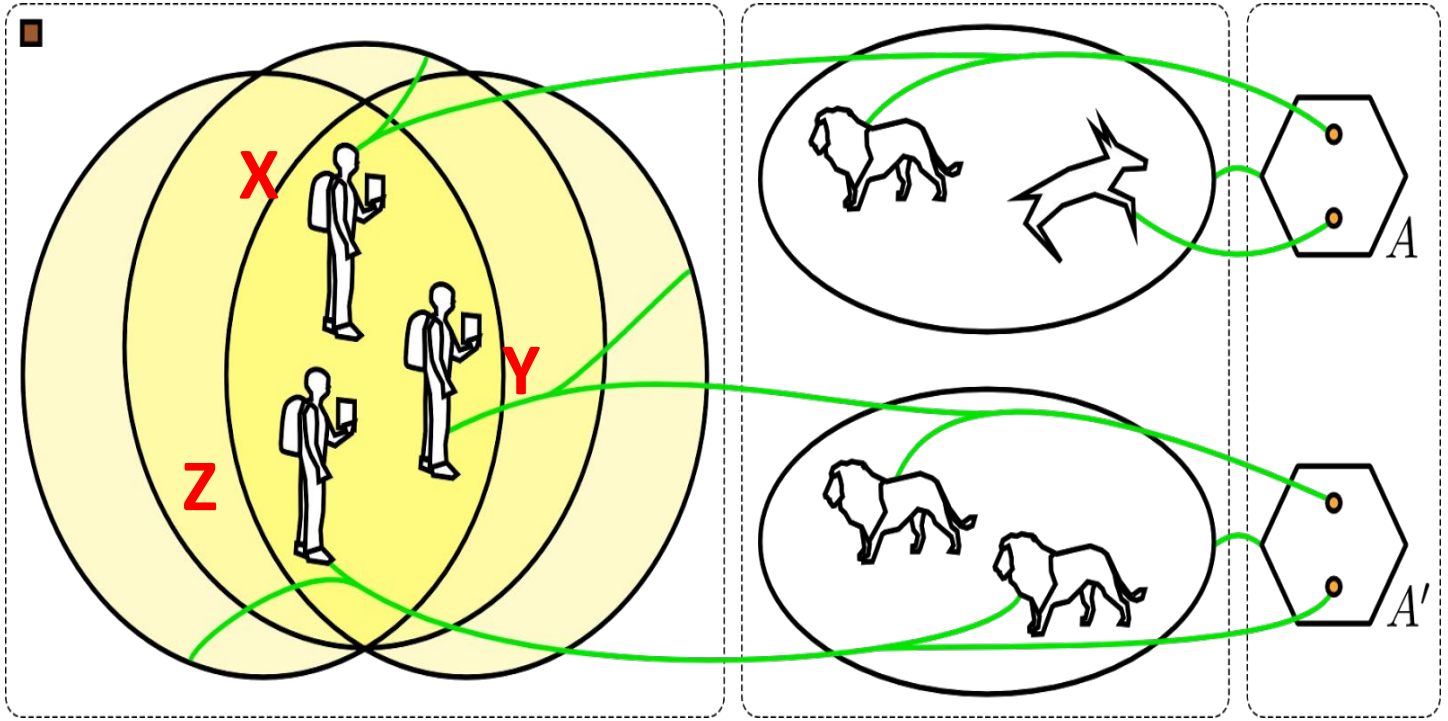
“three girls, a boy, and an impala problem”

state 0

Three girls X, Y, Z in a shared aura

X is in locale mapped to area A, an impala is in this locale

Y and Z are in locale mapped to area A’



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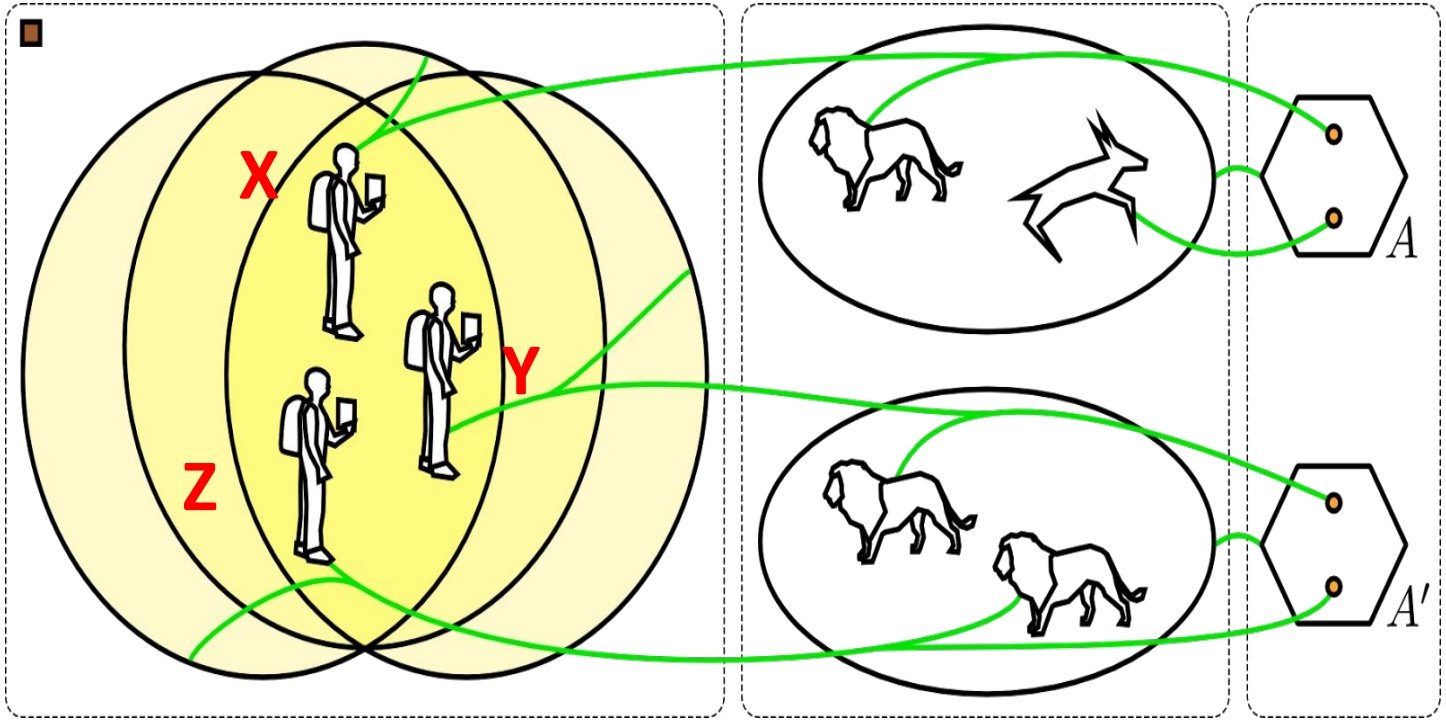
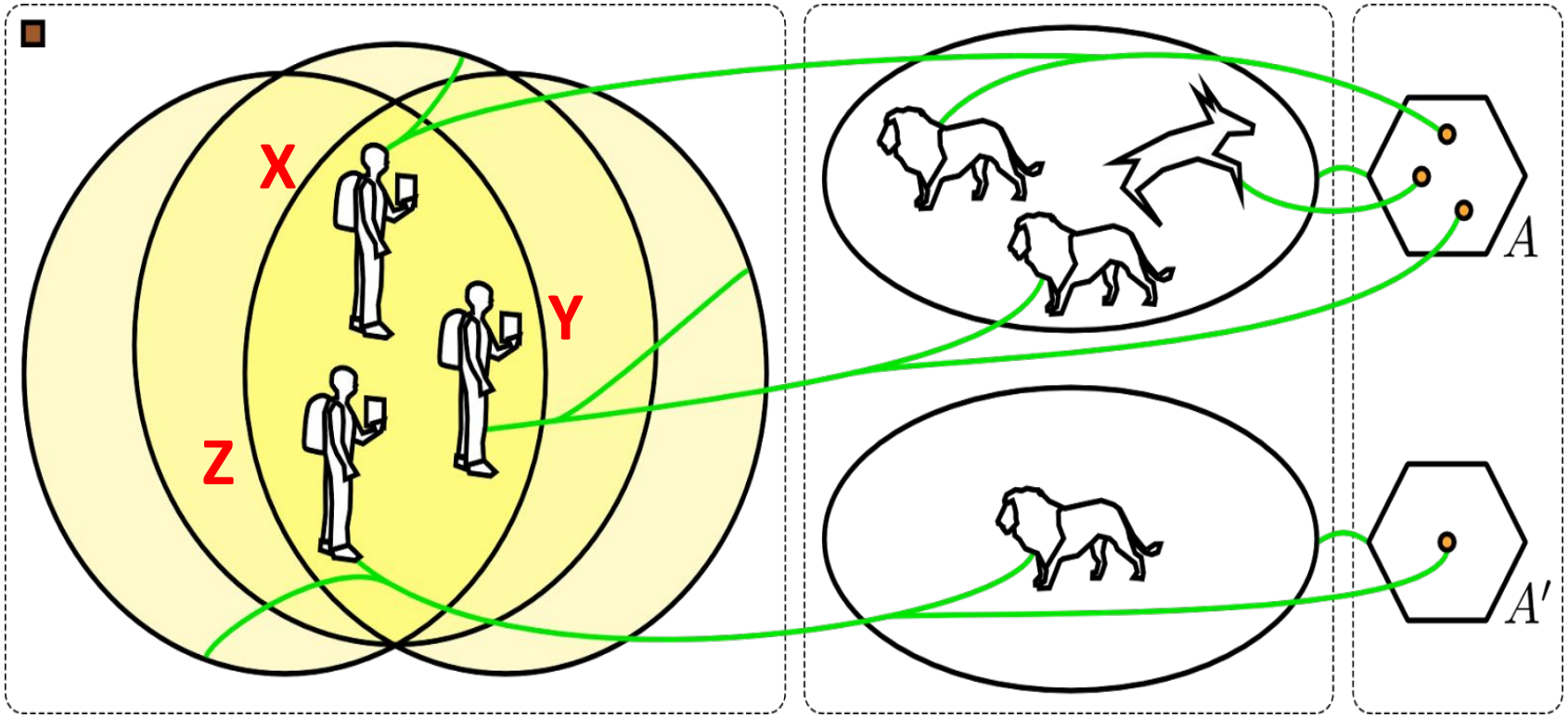


state 1

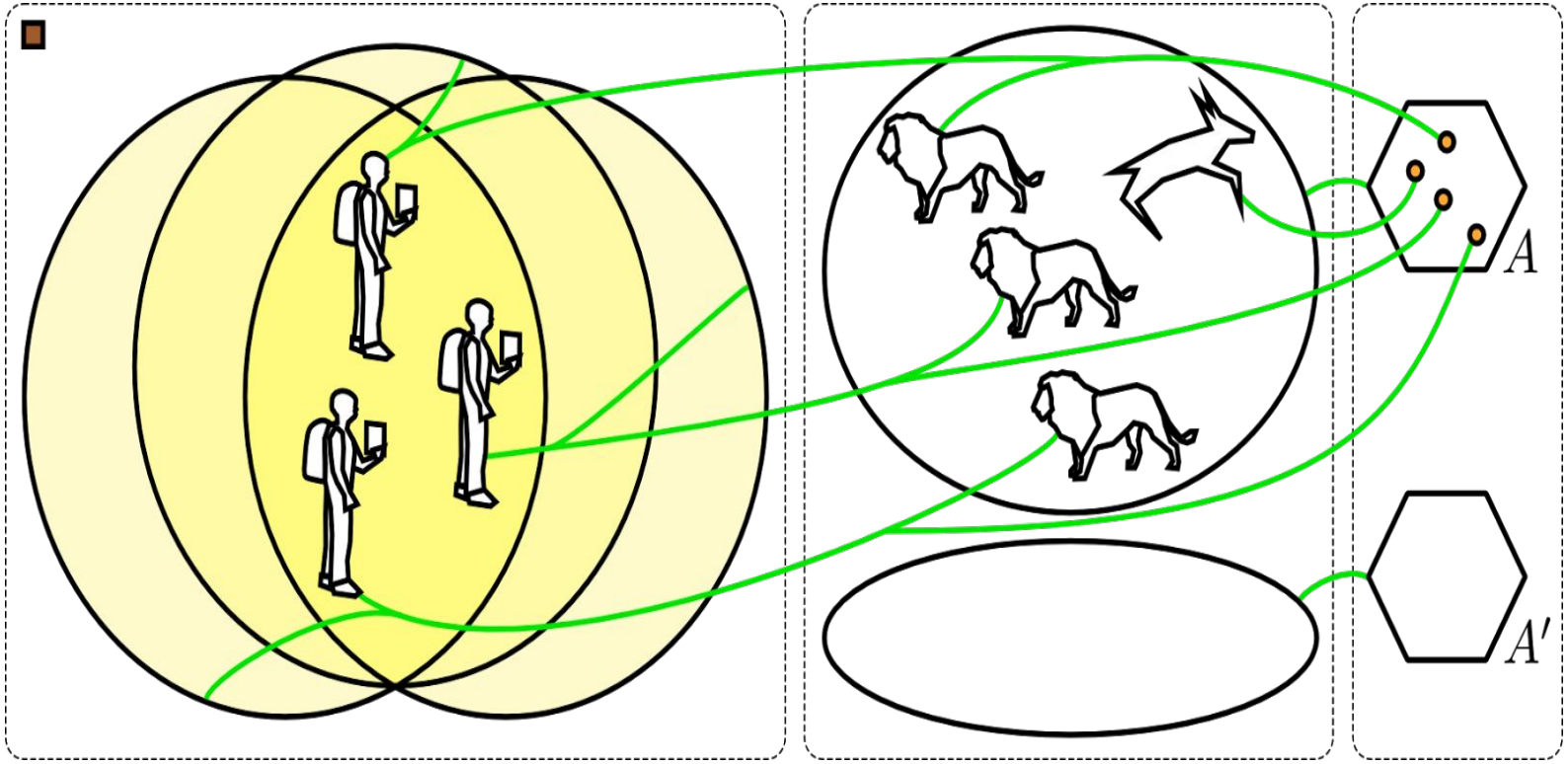
Y enters the same locale as X and the impala (area A)



state 2

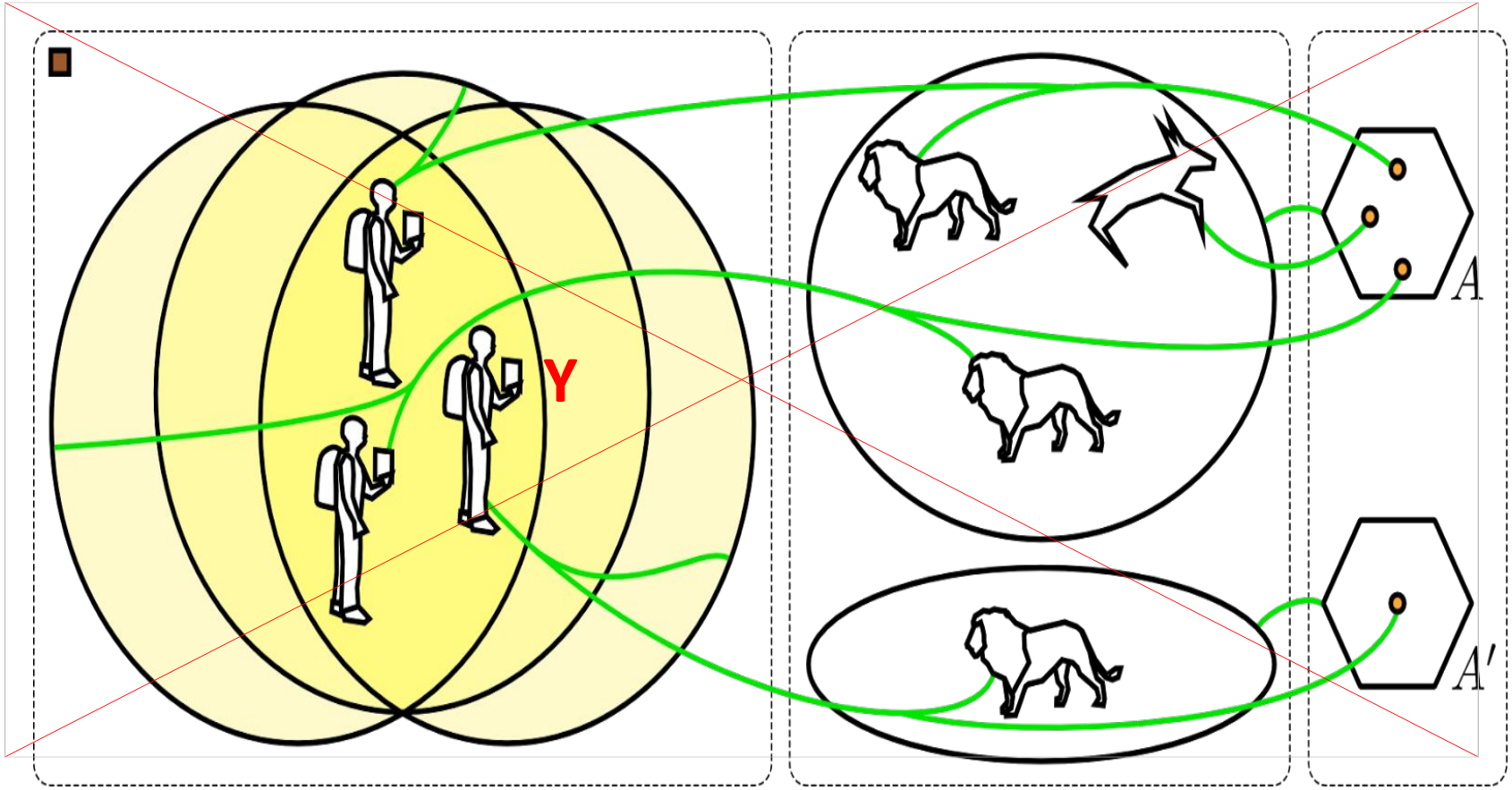
Z enters the same locale as the other two girls and the impala

All girls are in the same locale - *any* girl could initiate an attack



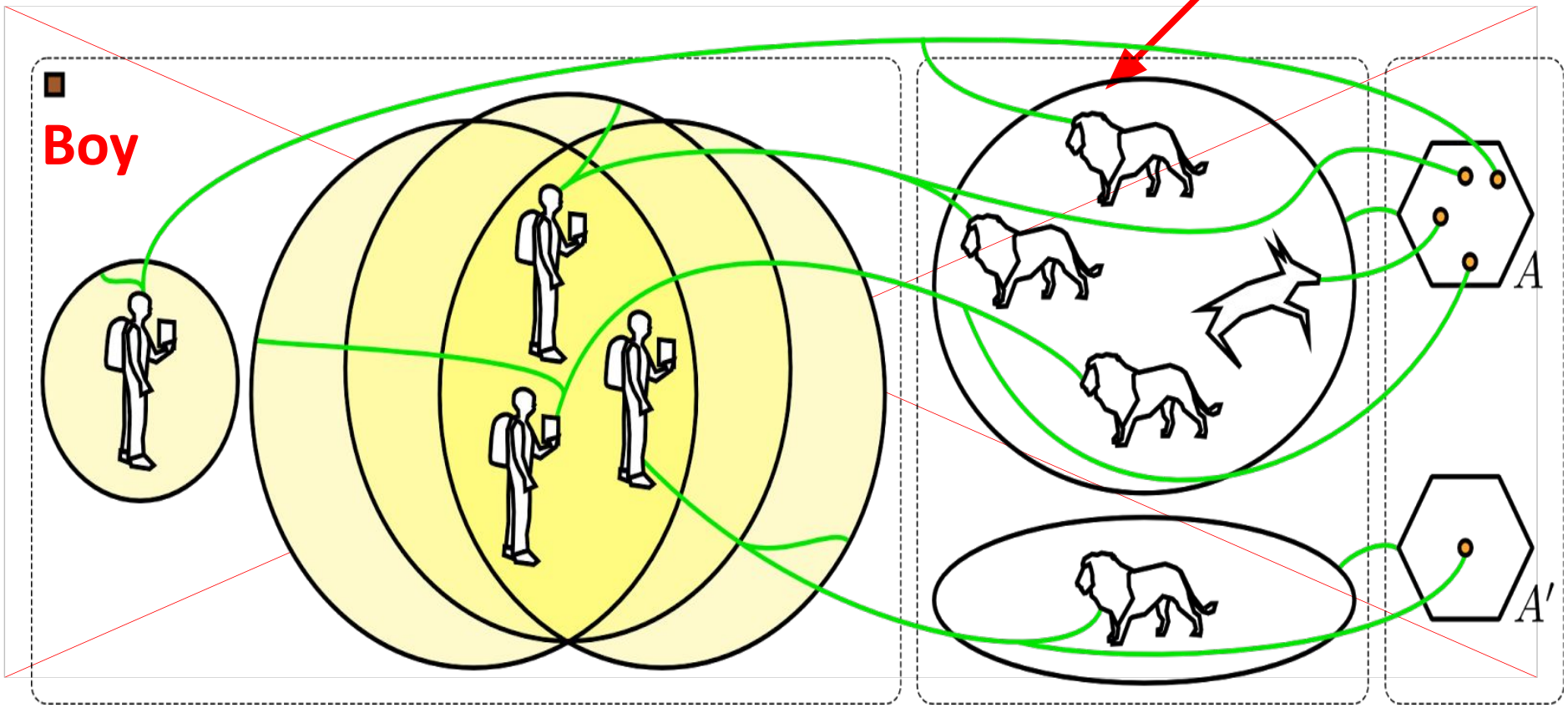
state 3

Y's GPS drifts out of locale



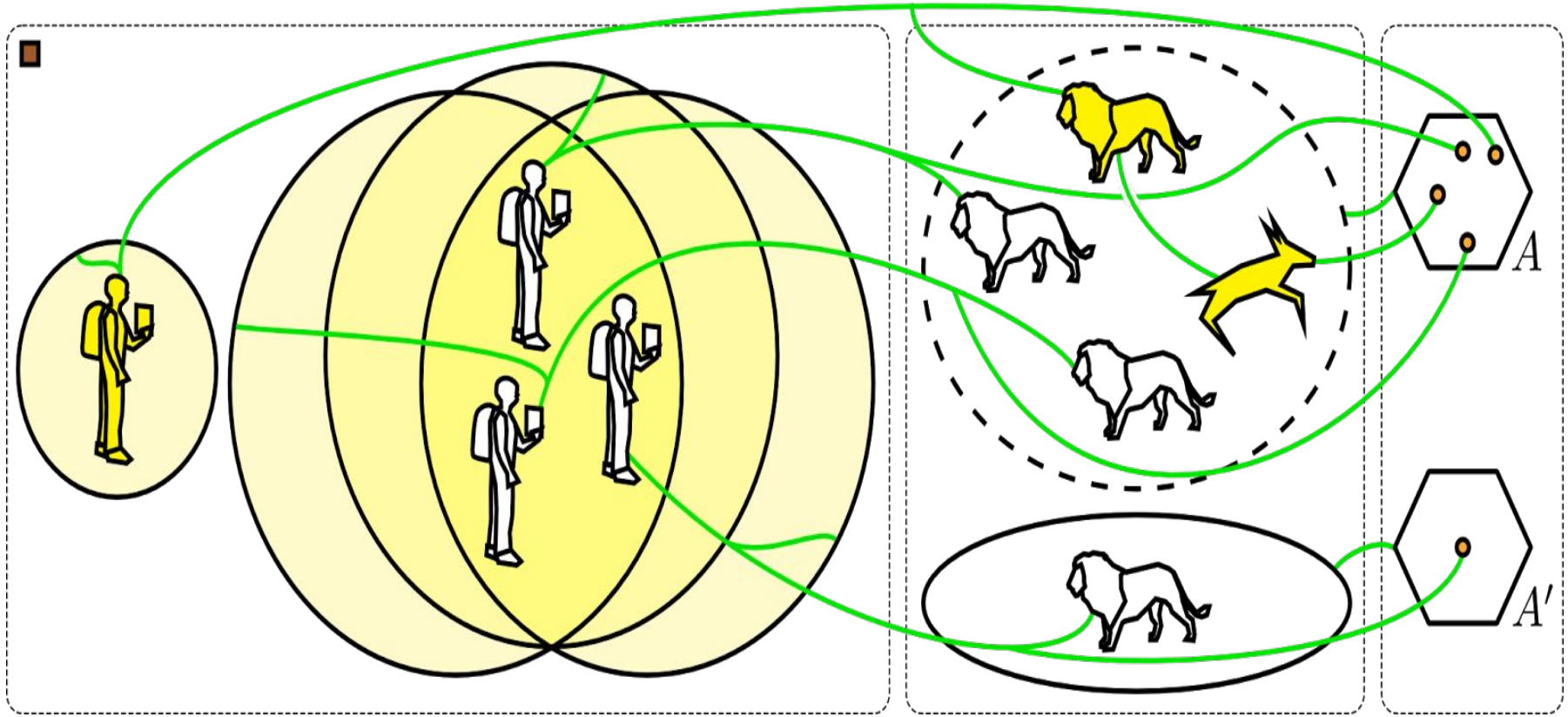
state 4

Boy enters the locale *but not the shared aura*



state 5

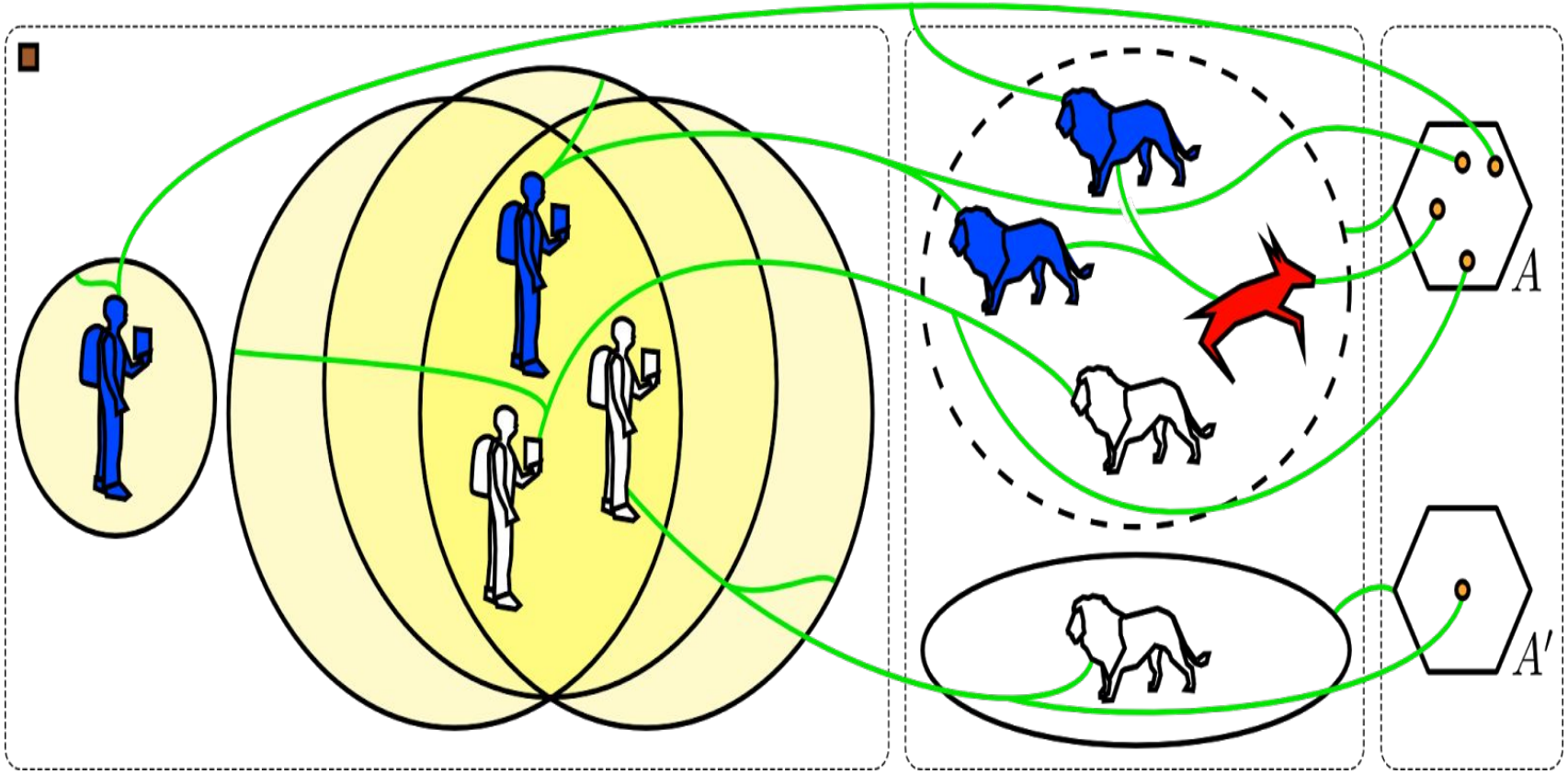
Boy sees the impala and initiates a kill (recall: kill requires a group)



state 6

X joins the group

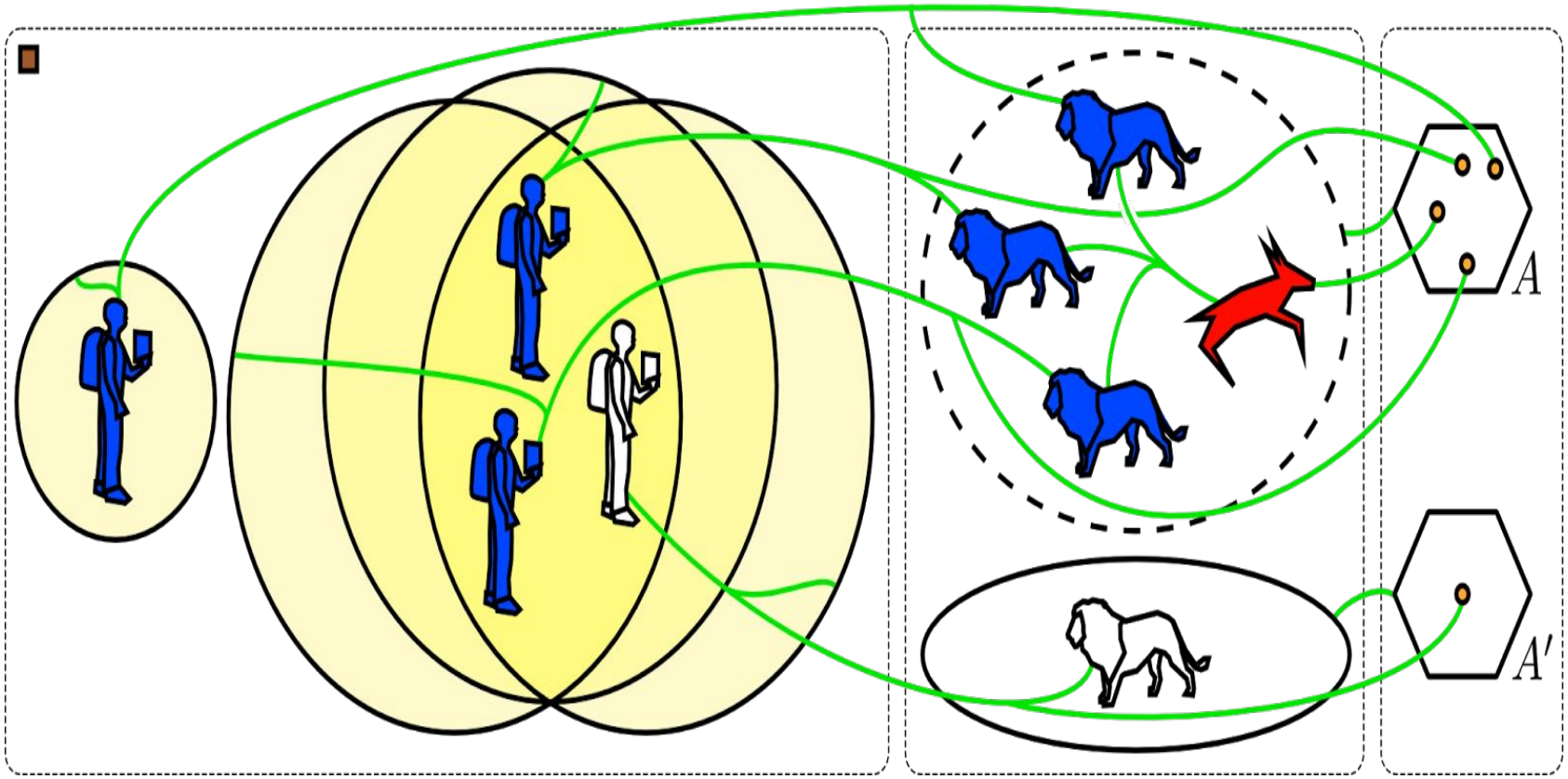
She (mistakenly) thinks she initiated the kill



state 7

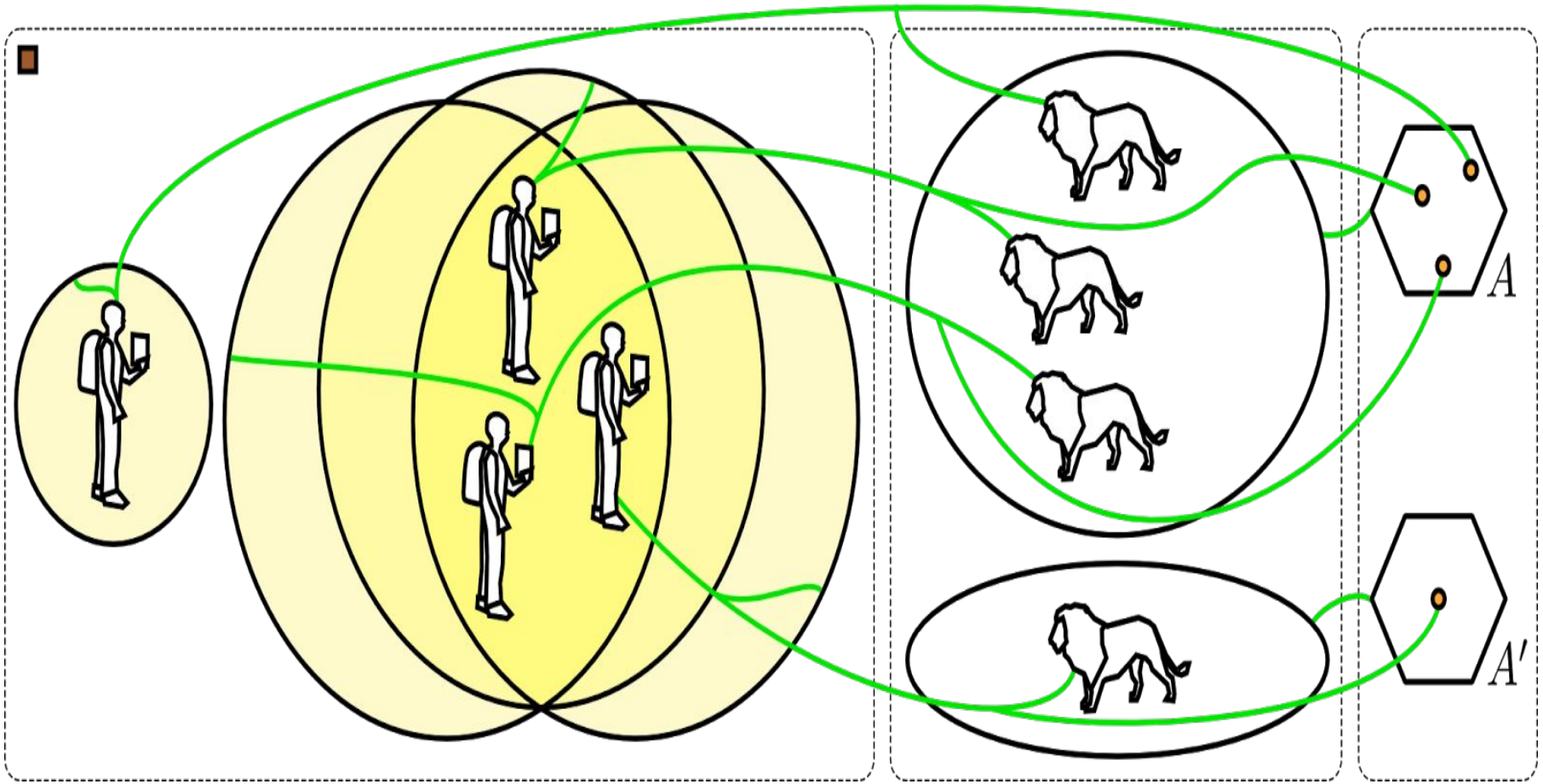
Z joins the group

Three children in the attack group (not all girls!)



state 8

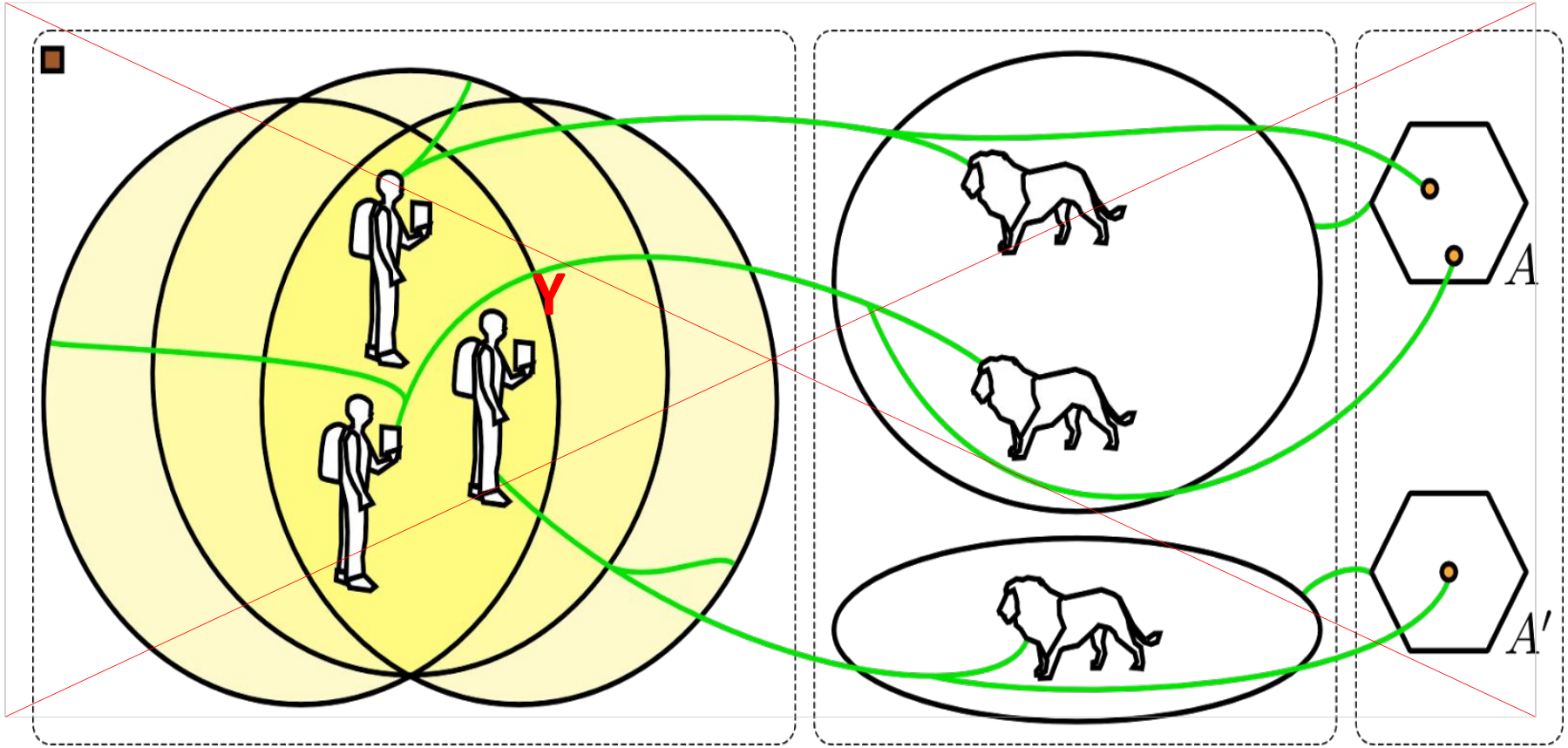
Impala is killed and disappears



state 9

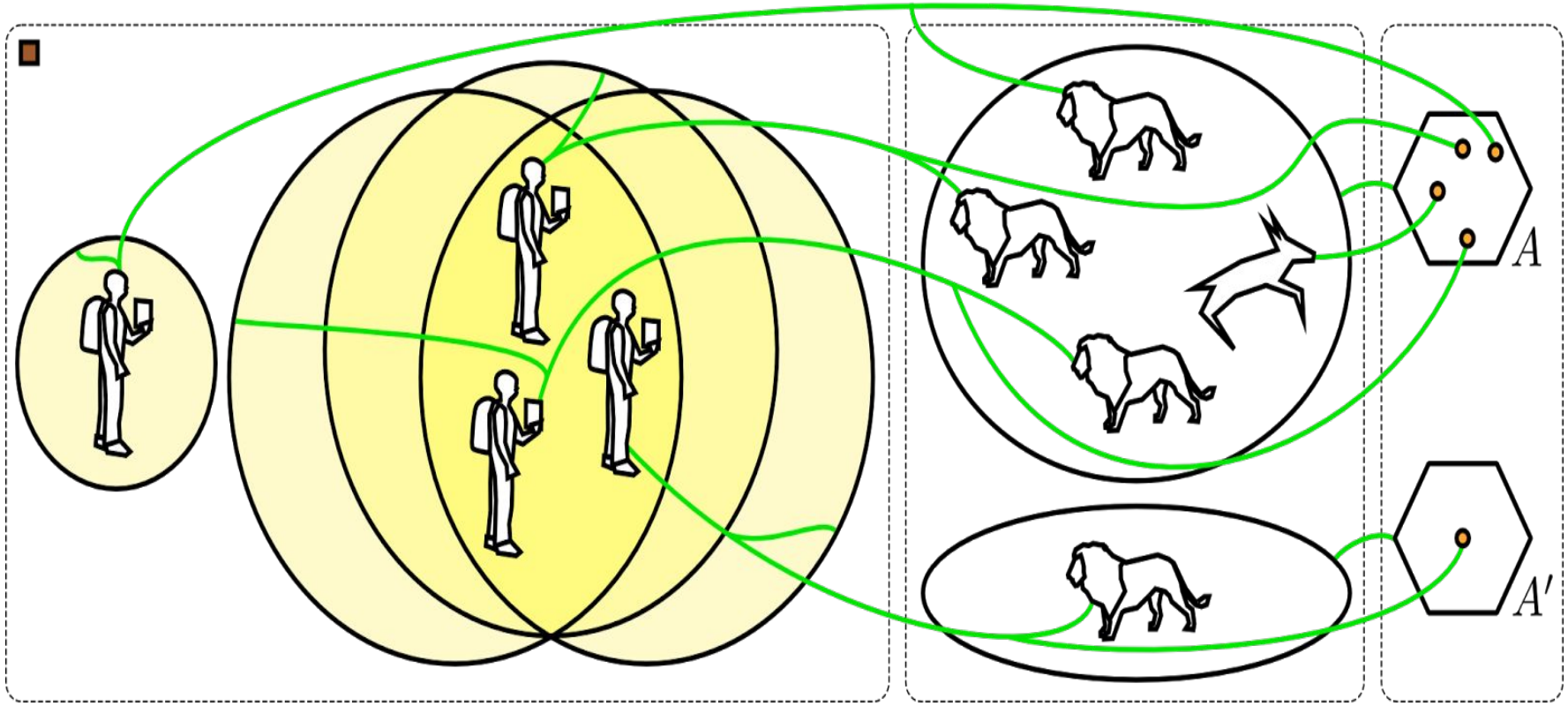
Boy leaves the locale

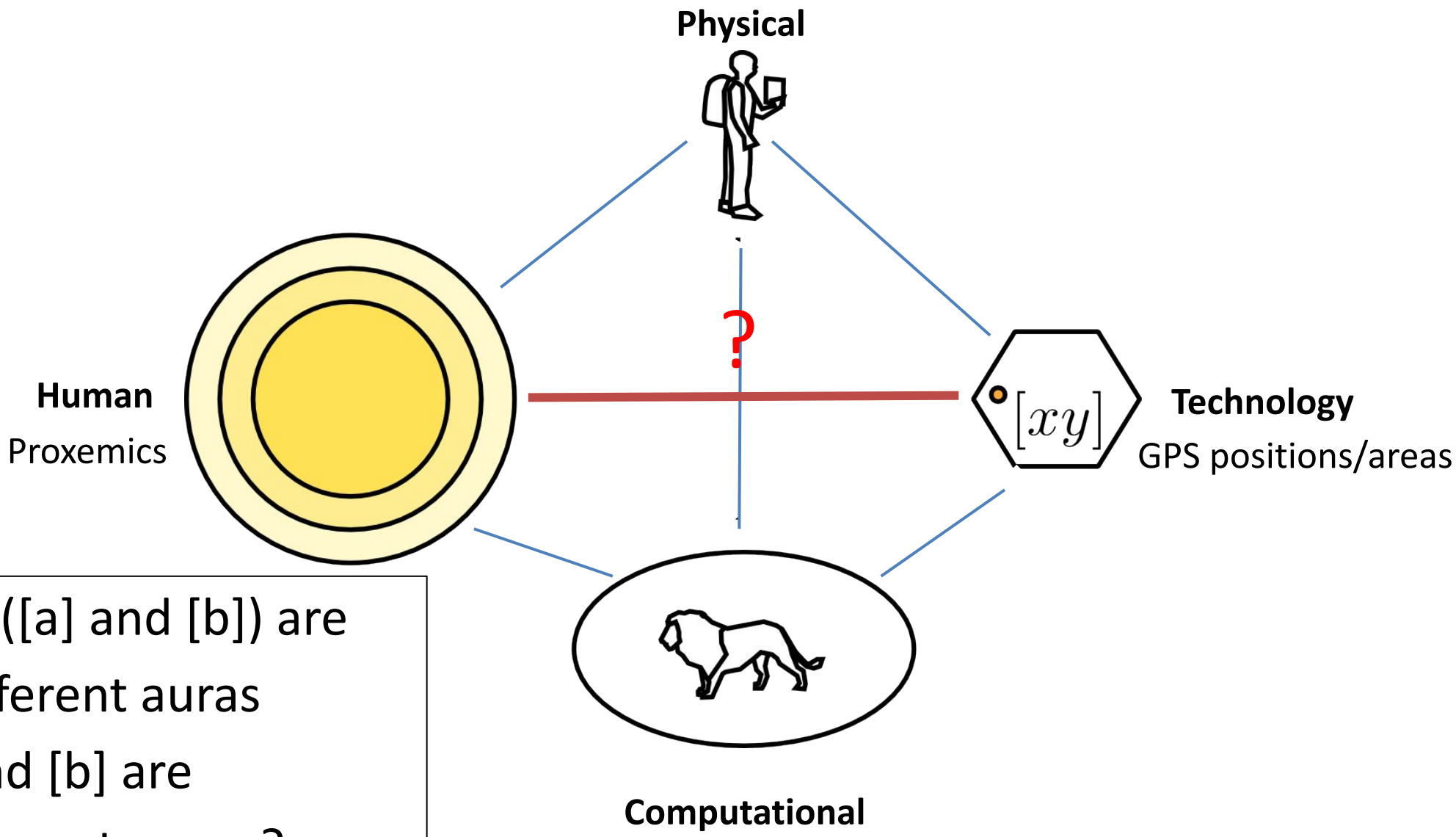
Y is hungry and confused



Cognitive dissonance – why?

state 4 boy, X and Z are in the **same** locale but **not same** aura
girls are unaware of the presence of the boy in the locale

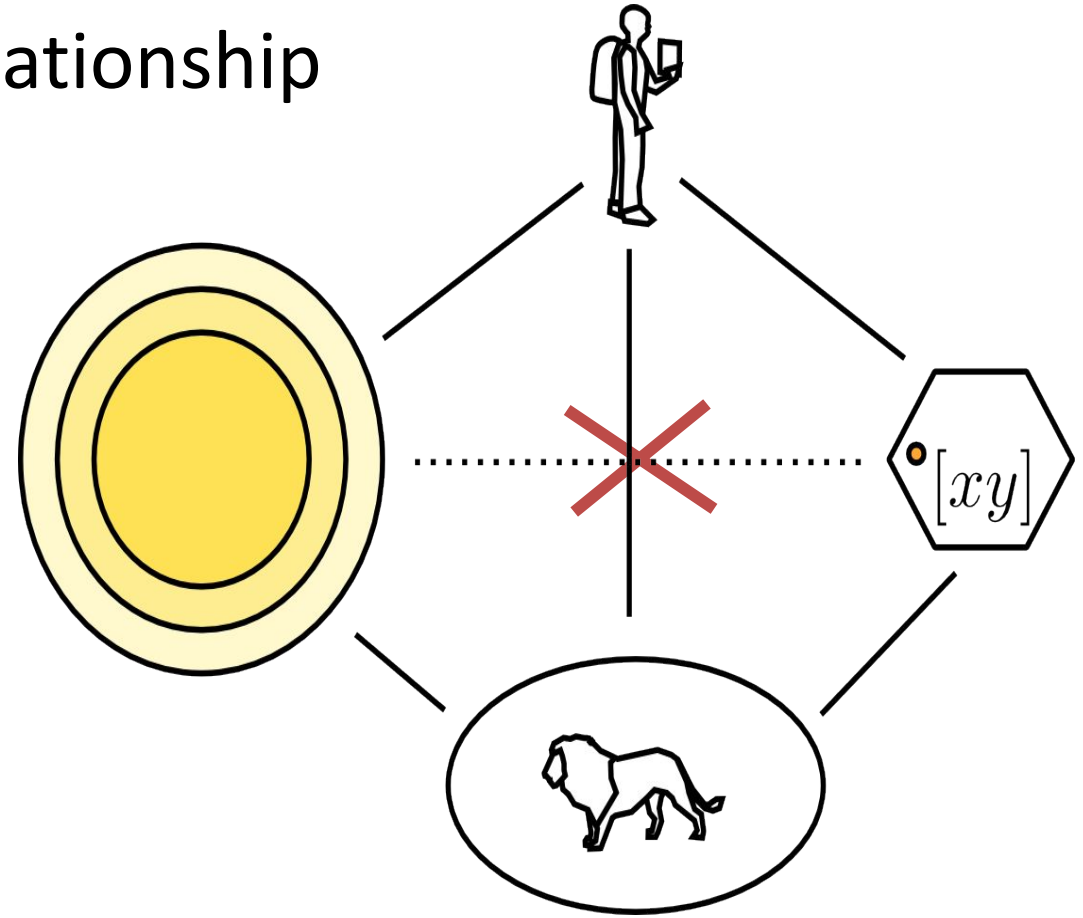




children ([a] and [b]) are
in different auras
⇒ [a] and [b] are
in different areas ?

Technology/human relationship

We proved aspects of a *good* relationship
technology ↔ human
is missing



children ([a] and [b]) are
in different auras
⇒ [a] and [b] are
in different areas ?

Novelty and what did I learn

- bigraphs - powerful graphical notation for communication with designers especially colour and shape for types
- human, physical, technology, computational perspectives

  users - physical world - sensors - software

- level of abstraction is key (proxemics)
- modelling for *analysis of user trials* (actual behaviour)
  - *logged* system behaviours for replay in model

Finally ...

5. User Interaction Styles: inferred models

Question

How do users *actually* interact with an app – can we re-design to suit interaction styles

Techniques and **models:**

Log interactions (state changes)

Segment datasets days/weeks/months

Infer AR-HMMs models

Analyse models with temporal logic properties

User traces

User1  ....

User2  ....

User3  ....

....

User M  ....

User traces – segment over days and months

User1  ....

User2  ....

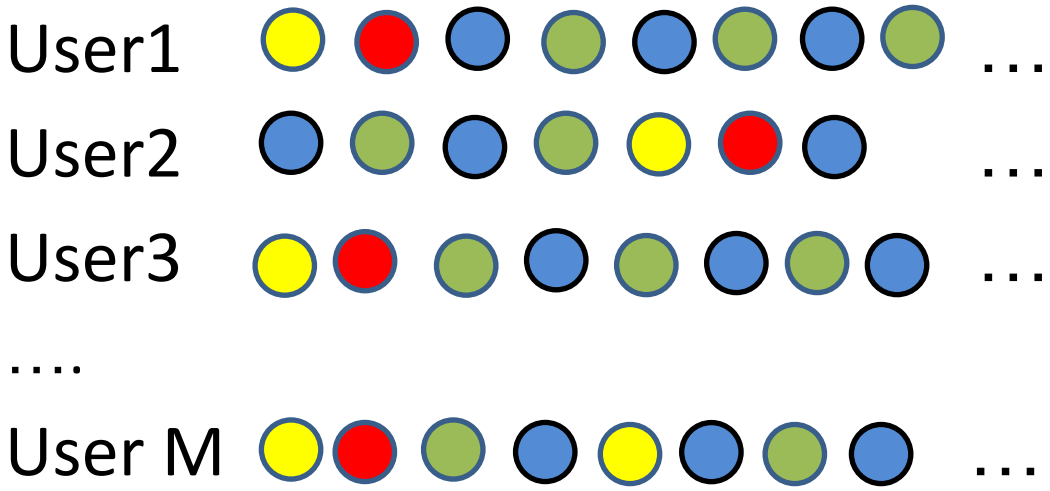
User3  ....

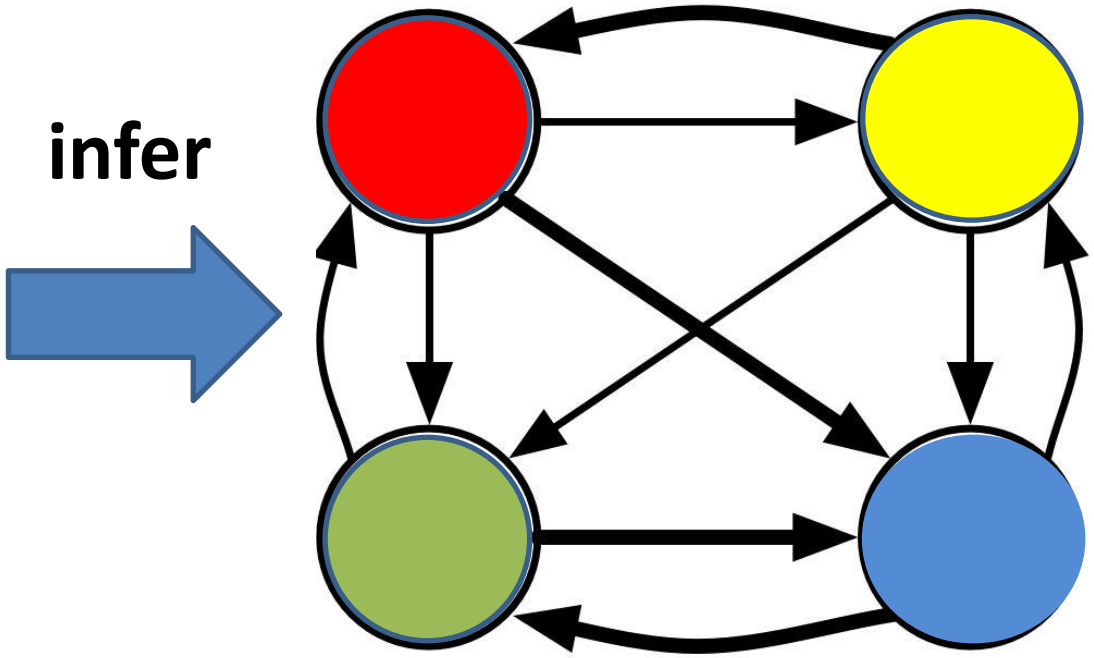
....

User M  ....

		Day 1	Day 2		Day 30	Day 31	
α^1	$=$	$\sigma_1^1\sigma_2^1\sigma_3^1\sigma_4^1\sigma_5^1$	$\sigma_6^1\sigma_7^1\sigma_8^1$	$\dots$	$\sigma_{90}^1\sigma_{91}^1\sigma_{92}^1$		
α^2	$=$	$\sigma_1^2\sigma_2^2\sigma_3^2$		$\dots$	$\sigma_{81}^2\sigma_{82}^2$	$\sigma_{83}^2\sigma_{84}^2\sigma_{85}^2$	$\dots$
α^3	$=$	$\sigma_1^3\sigma_2^3\sigma_3^3\sigma_4^3$					
$\dots$		$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$
α^M	$=$	$\sigma_1^M\sigma_2^M$	$\sigma_3^M\sigma_4^M$	$\dots$	$\sigma_{23}^M\sigma_{24}^M\sigma_{25}^M$	σ_{36}^M	$\dots$

Infer activity patterns





Activity Pattern

DTMC discrete-time Markov chain

Probabilities to transition between observable states

Infer activity patterns and probability to change pattern

User1 …

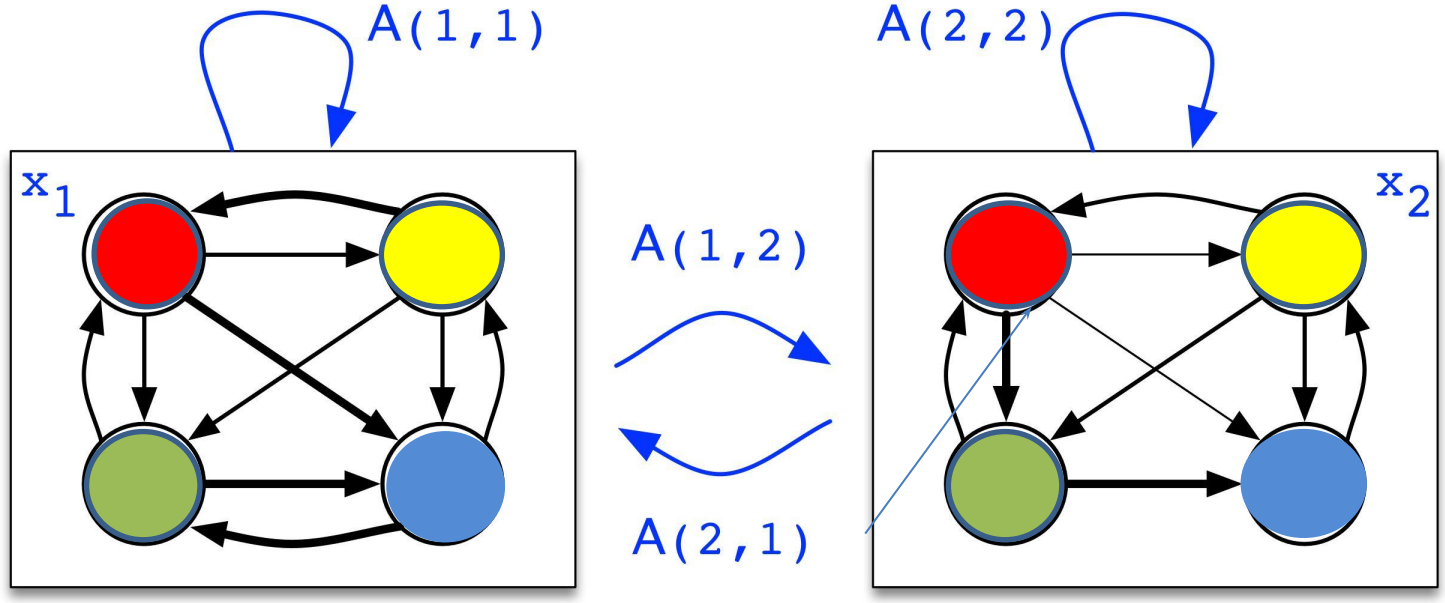
User2 …

User3 …

….

User m …

infer



A user moves *between* activity patterns

because they

haven't used the app for a while

are tired/fed up

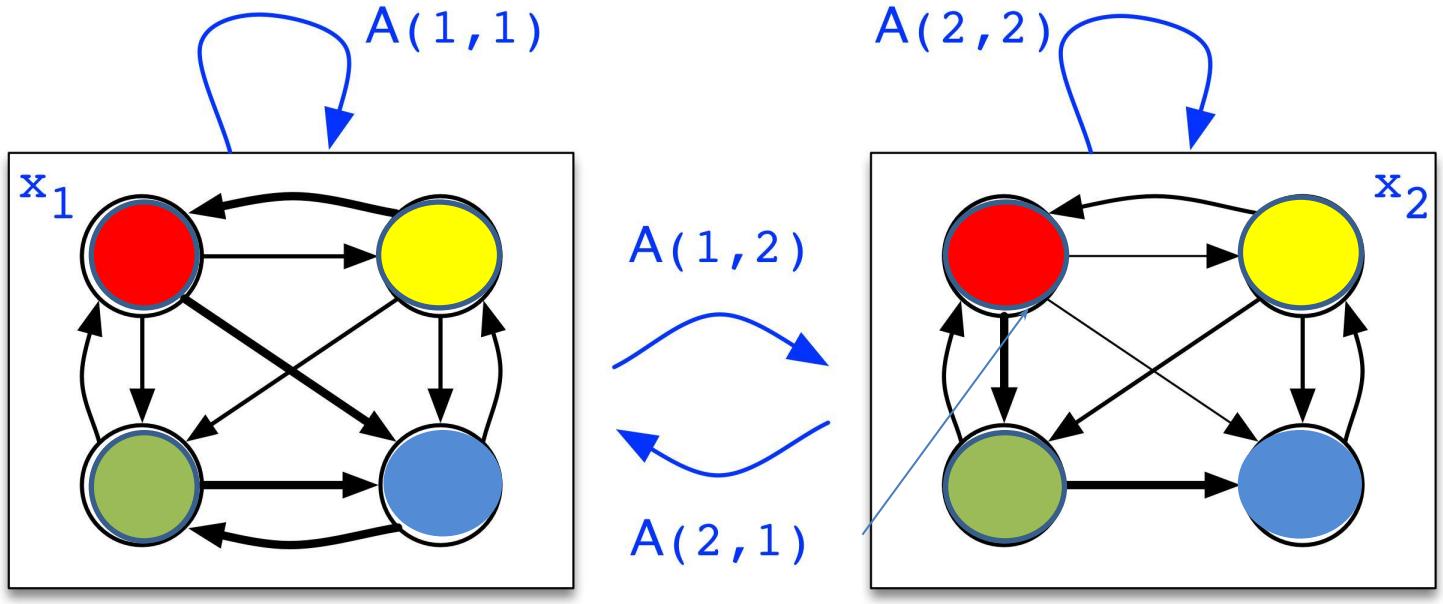
want to explore the app

know exactly what they want to do today

are on a train and using the app is difficult

…..

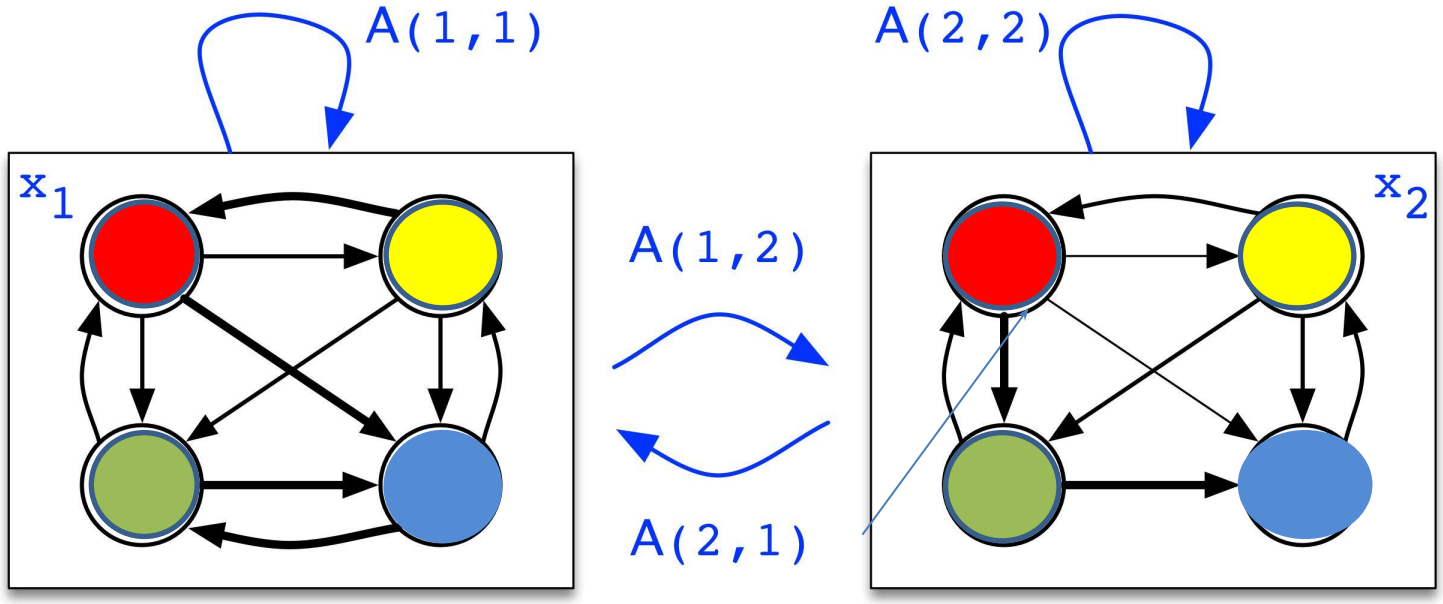
First-order auto-regressive hidden Markov models



The same observable states in each DTMC

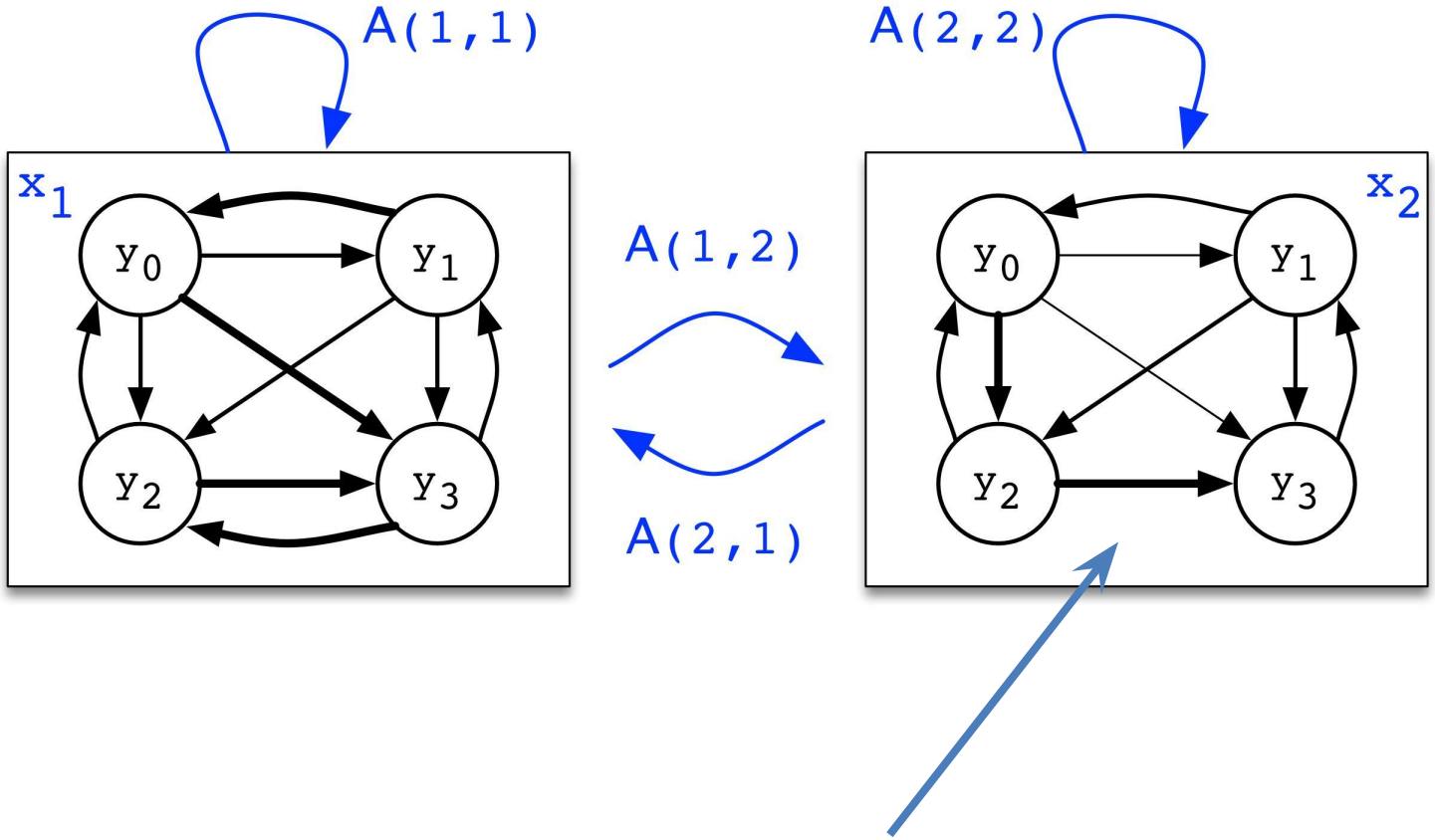
The *probabilities* of transition in the DTMCs change

First-order auto-regressive hidden Markov models



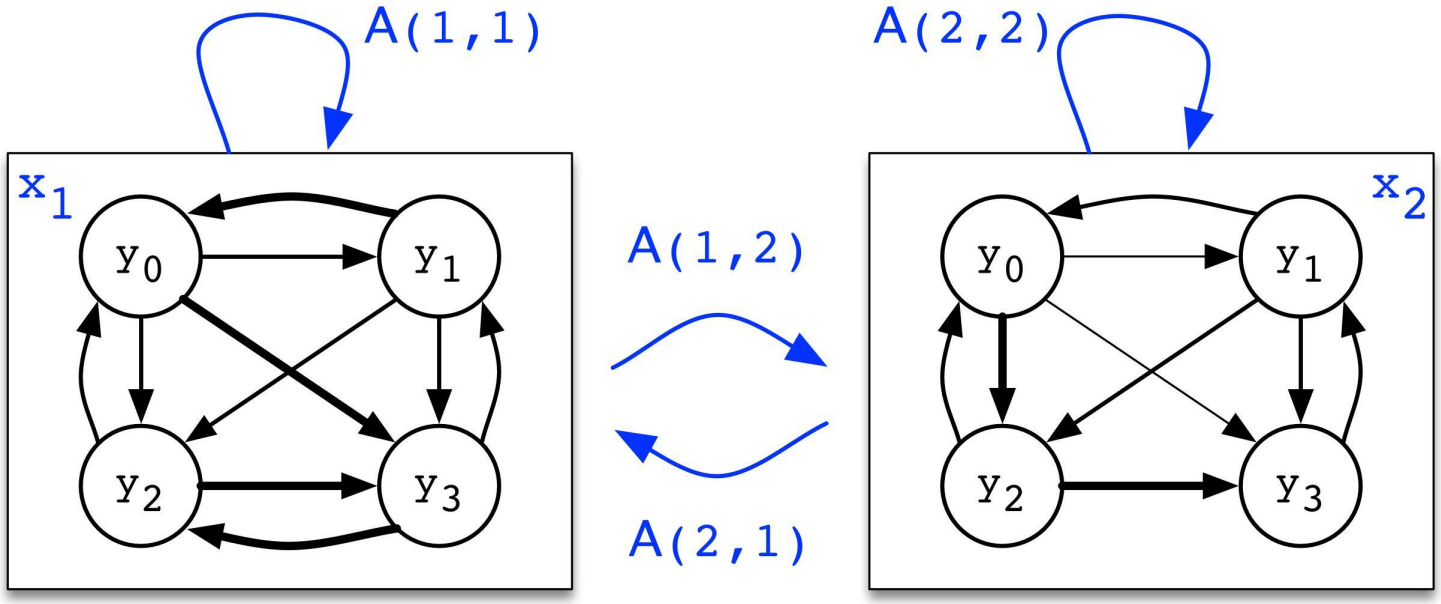
Infer using Baum-Welch

(non-linear optimisation Expectation–Maximisation (EM) algorithm)



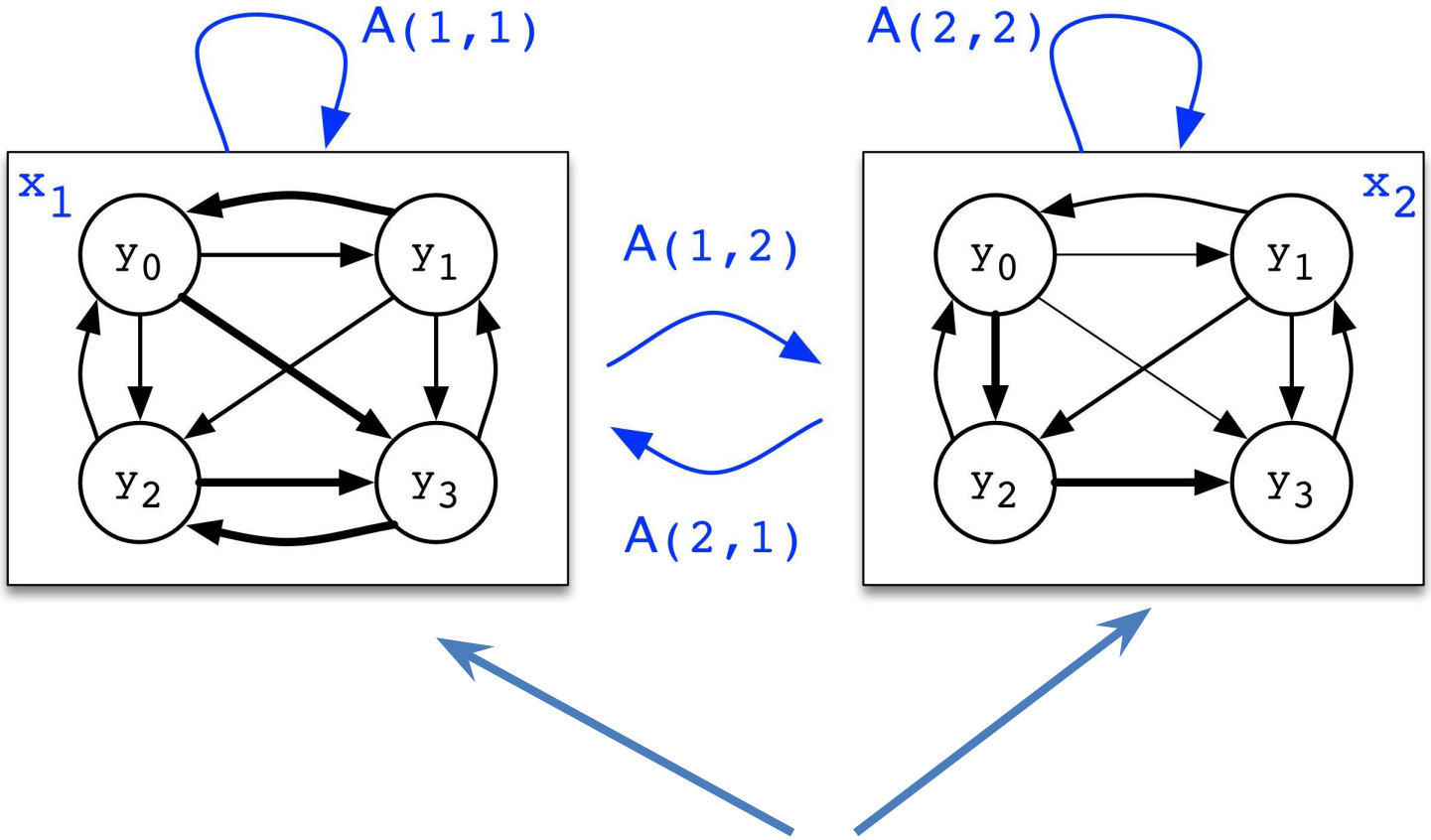
properties behaviour ***within*** an activity pattern
refer to variable **y** (a state in a pattern)

***single* activity pattern**



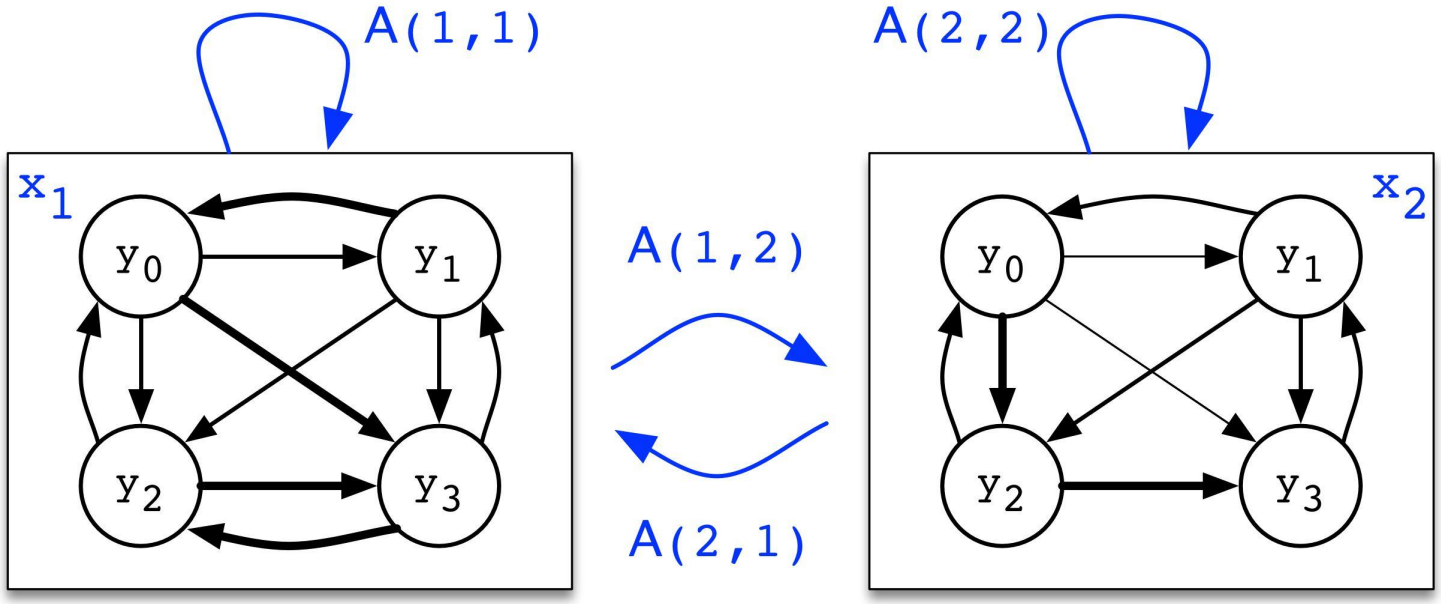
VisitProb $P_{=?}[\text{true } U^{\leq N} (y = j)]$

probability to **reach state j** from the initial state within N steps



properties behaviour ***over*** activity patterns
refer to variables **x** and **y**
(states in patterns and patterns)

multiple **activity pattern**



Probability: **state j** in **pattern i_1** leads to change to **pattern i_2**

$$P_{\geq 1}[\, F\,(x = i_1 \wedge y = j)] \wedge P_{\geq 1}[G\,((x = i_1 \wedge y = j) \Rightarrow P_{>p}\,[(x = i_1 \wedge \neg \text{stopS}) U (x = i_2)])]$$

Case Study: AppTracker

Personal informatics

App usage

Charts and statistics

Runs in the background

Over **35,000** downloads

Case Study: AppTracker

Personal informatics

App usage

Charts and statistics

Runs in the background

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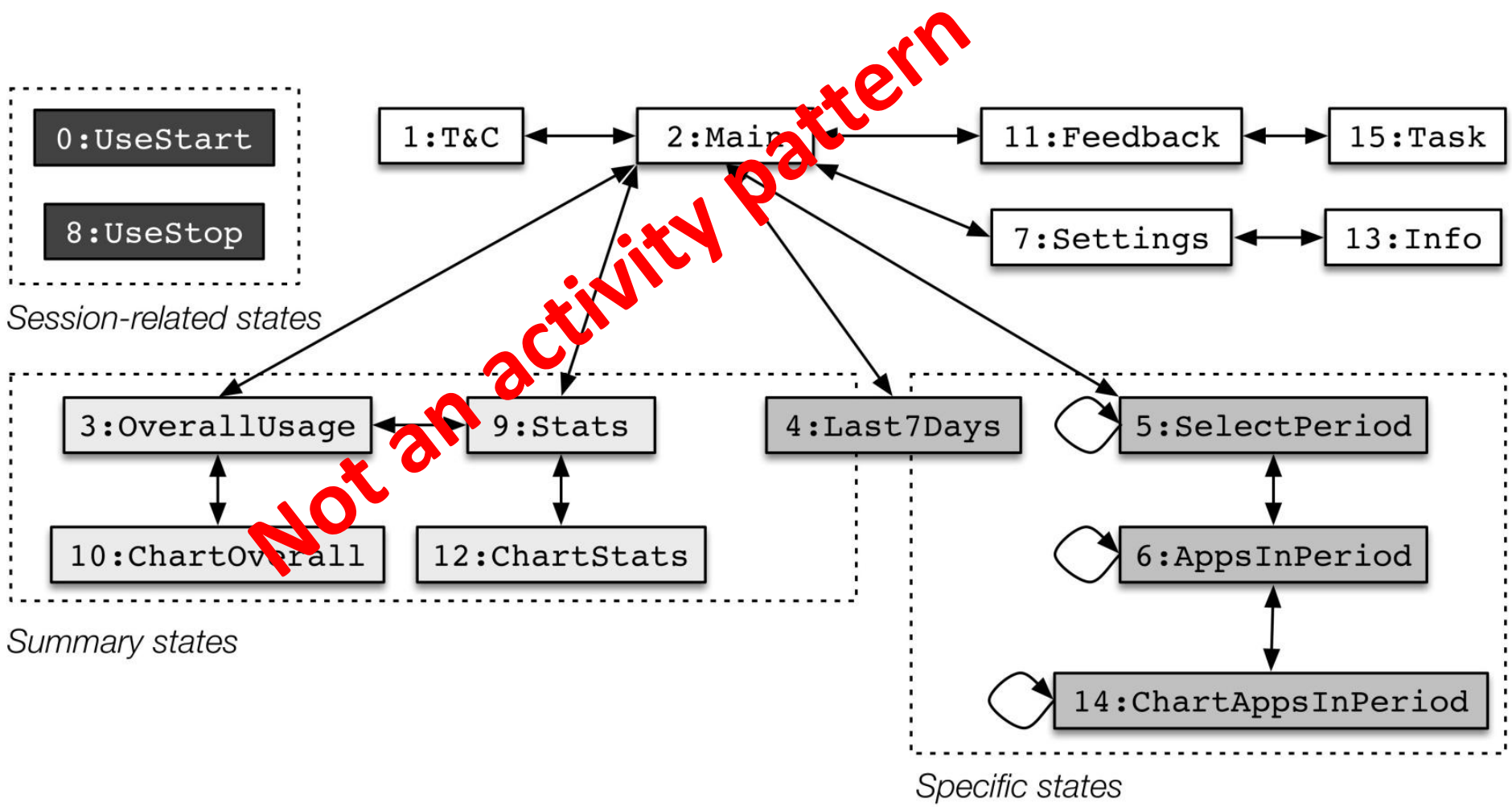
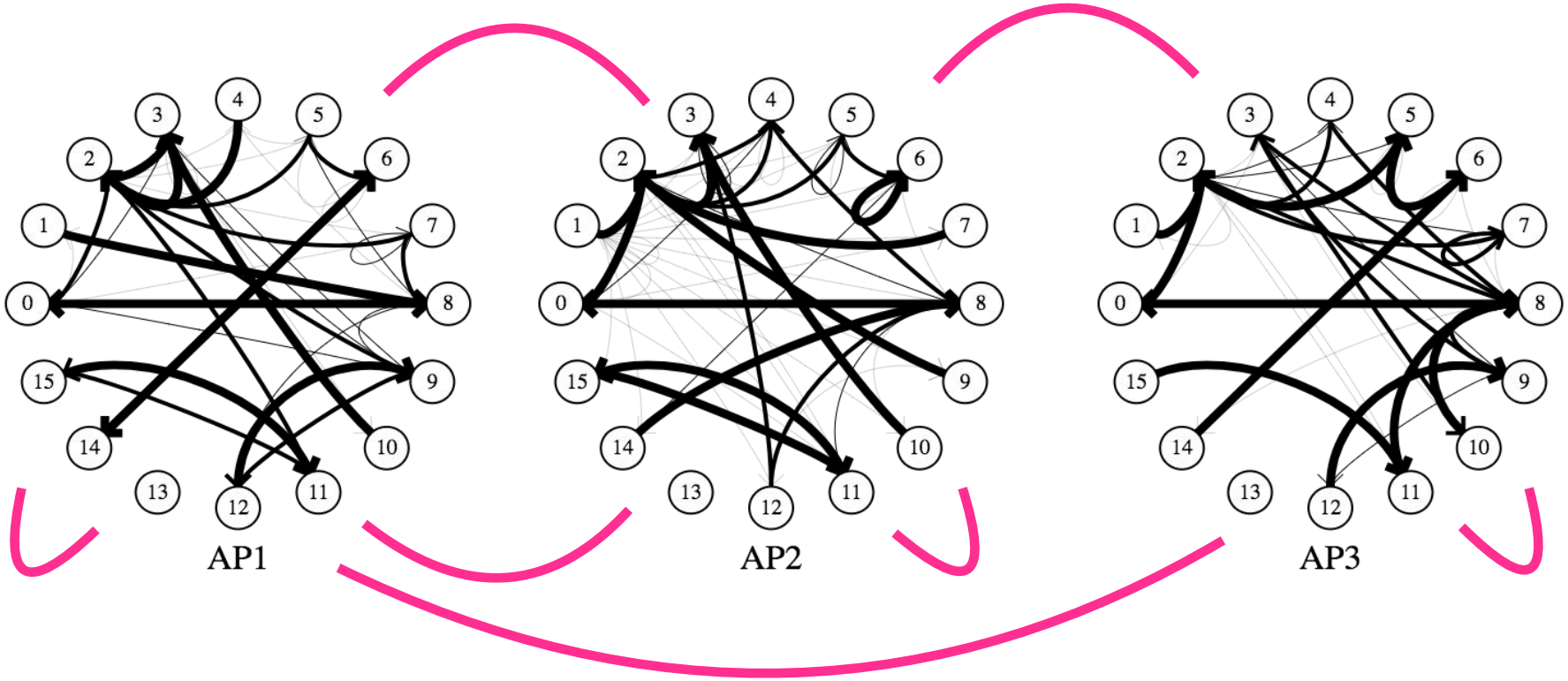
AppTracker1 State Diagram

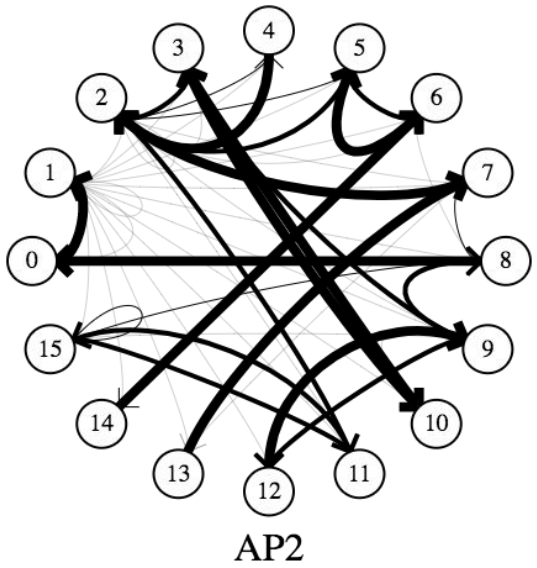


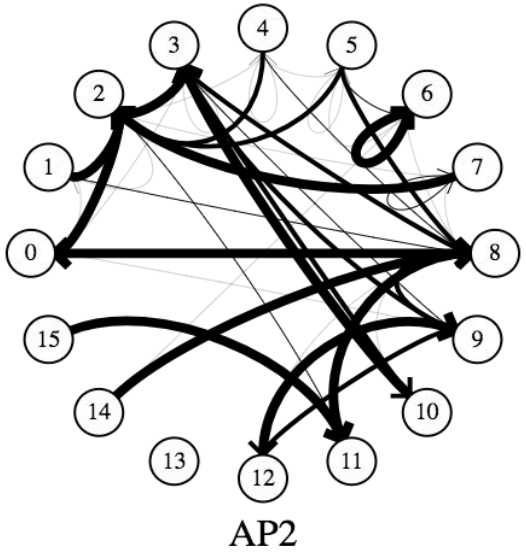
16 observable states

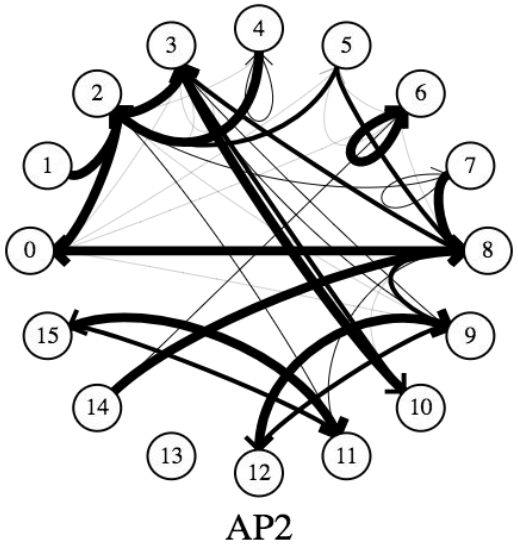
Example: 3 activity patterns



Example: AP2 in *different* months

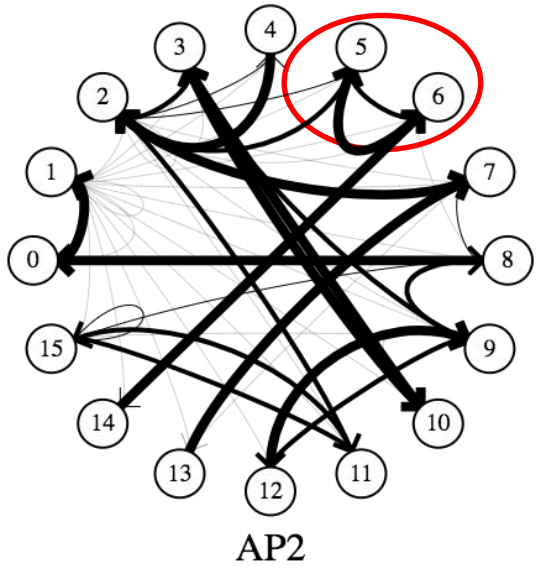


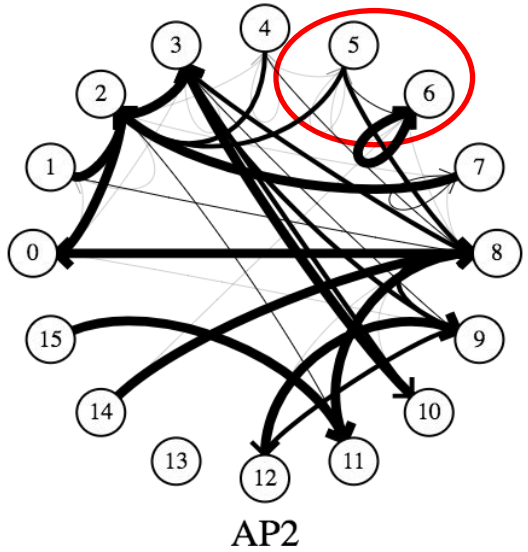


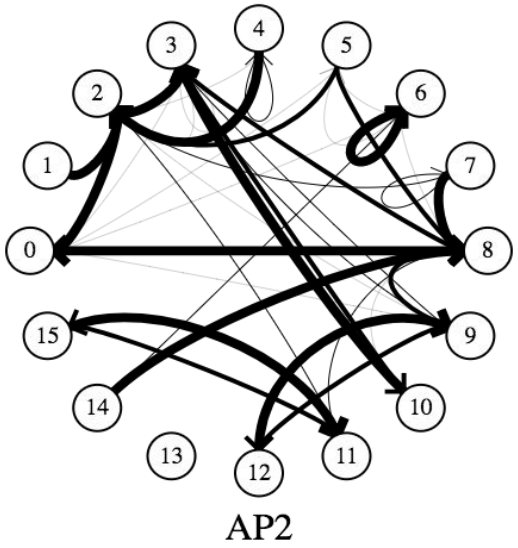


first month **second month** **third month**

K=3: AP2 in *different* months







first month **second month** **third month**

Probabilistic model checking results

Prop.	Time interval	OverallUsage		Last7Days		SelectPeriod		Stats		AppsInPeriod	
		AP1	AP2	AP1	AP2	AP1	AP2	AP1	AP2	AP1	AP2
VisitProbInit	[0,1]	0.94	0.99	0.80	0.89	0.80	0.42	0.81	0.99	0.45	0.13
	[0,7]	0.67	0.99	0.89	0.88	0.88	0.48	0.55	0.99	0.67	0.21
	[0,30]	0.59	0.99	0.91	0.92	0.90	0.56	0.46	0.98	0.76	0.29
	[30,60]	0.87	0.99	0.98	0.31	0.93	0.00	0.45	0.96	0.77	0.00
	[60,90]	0.91	0.99	0.97	0.02	0.96	0.10	0.56	0.91	0.83	0.09
VisitCountInit	[0,1]	3.54	14.58	1.63	2.24	1.92	0.72	1.74	5.77	0.95	0.28
	[0,7]	1.19	15.25	2.21	2.09	2.75	0.87	0.84	5.27	2.11	0.48
	[0,30]	0.89	15.55	2.39	2.52	2.62	1.19	0.65	4.75	1.95	0.69
	[30,60]	2.28	14.27	5.06	0.40	4.29	0.01	0.80	4.04	4.39	0.01
	[60,90]	3.00	14.73	4.48	0.02	4.61	0.10	1.28	3.63	5.64	0.82
StepCountInit	[0,1]	16.55	4.53	30.27	22.75	30.45	90.36	29.82	12.01	83.40	332.40
	[0,7]	44.55	3.63	22.14	23.24	23.27	75.96	63.24	12.58	45.55	210.12
	[0,30]	56.55	3.44	20.07	19.28	21.53	59.94	81.13	13.68	35.54	145.35
	[30,60]	23.41	2.15	9.02	137.09	18.90	5483.99	85.45	15.97	34.45	25915.18
	[60,90]	19.55	2.23	10.46	2269.78	15.49	483.09	61.19	21.01	28.65	532.74

Time interval	VisitProbInit		SessionCount		SessionLength	
	AP1	AP2	AP1	AP2	AP1	AP2
[0, 1]	0.99	0.31	10.13	0.37	3.86	130.96
[0, 7]	0.99	0.43	10.20	0.54	3.81	87.76
[0, 30]	0.99	0.38	10.82	0.47	3.51	102.07
[30, 60]	0.99	0.99	6.17	7.55	7.09	5.36
[60, 90]	0.99	0.99	5.43	7.35	8.28	5.56

Classify activity patterns

Depends on

probabilities of temporal logic properties
states involved
length of sessions

K= 2 **6** possible combinations, only **4** observed

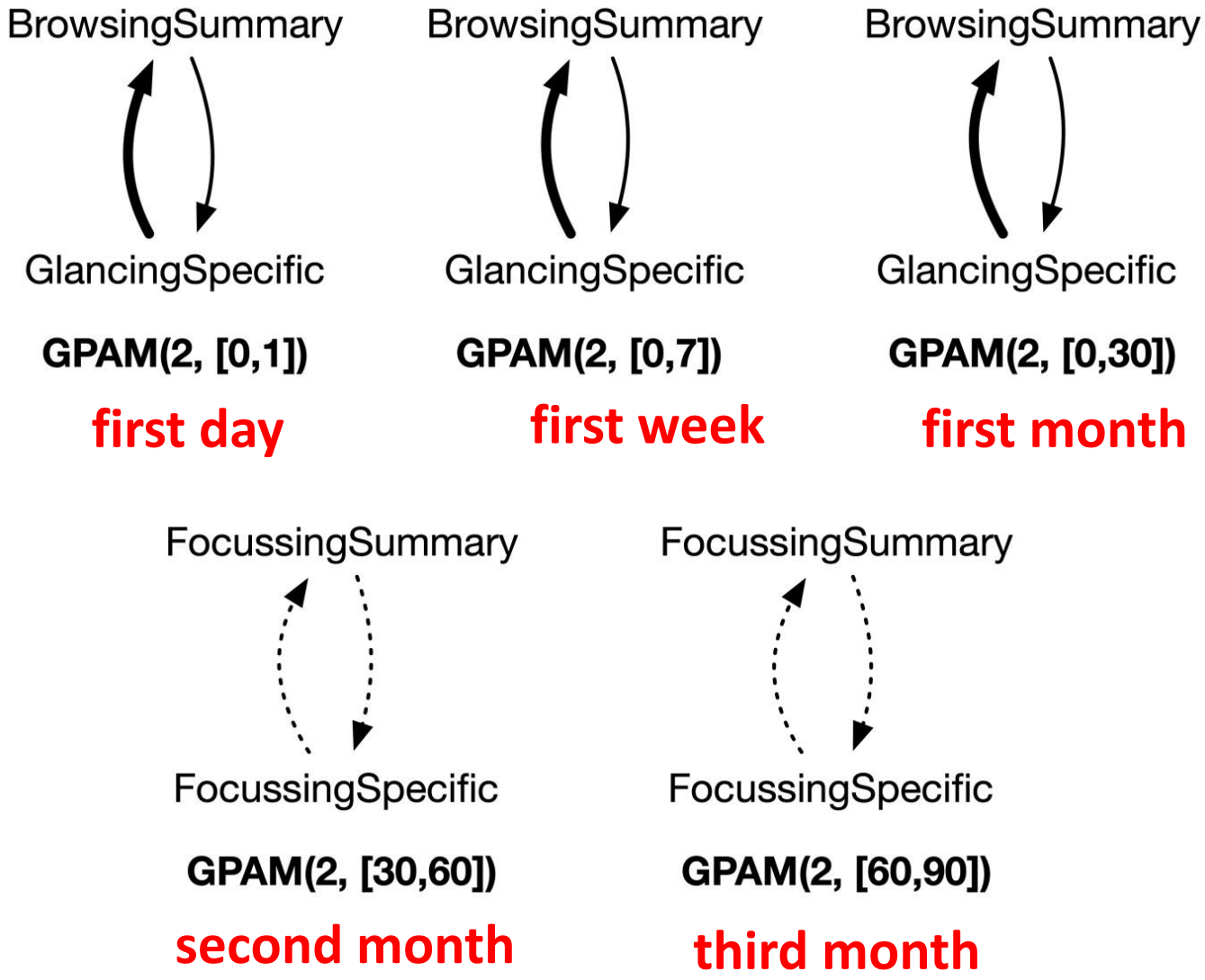
K=2: activity patterns

interval	AP1	AP2
[0, 1]	GlancingSpecific	BrowsingSummary
[0, 7]	GlancingSpecific	BrowsingSummary
[0, 30]	GlancingSpecific	BrowsingSummary
[30, 60]	FocussingSpecific	FocussingSummary
[60, 90]	FocussingSpecific	FocussingSummary

early days

experienced

K=2: probability to change activity pattern

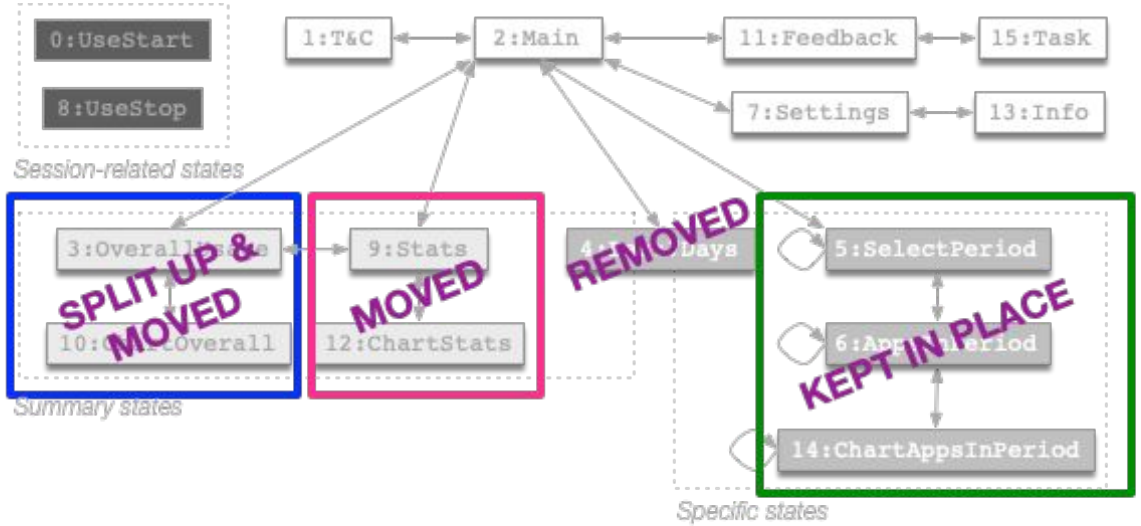


Summarising ..

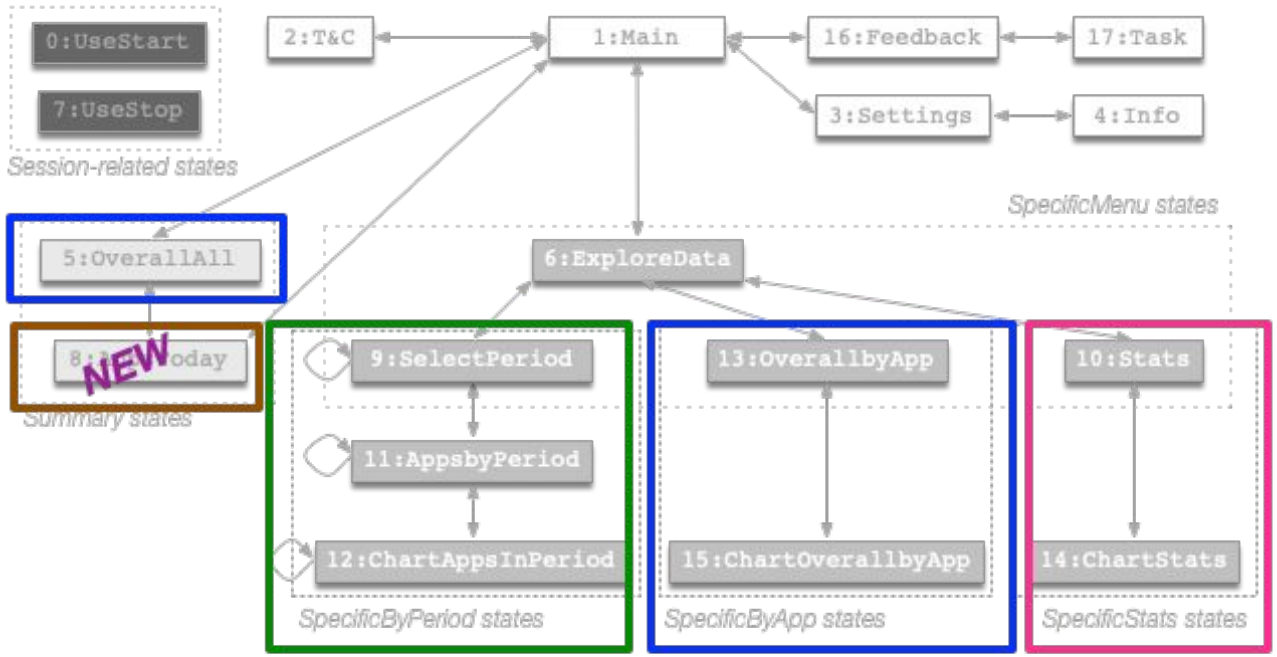
Browsing in early days usage

Focussing and **Glancing** in experienced usage

We redesigned app to support Focussing and Glancing

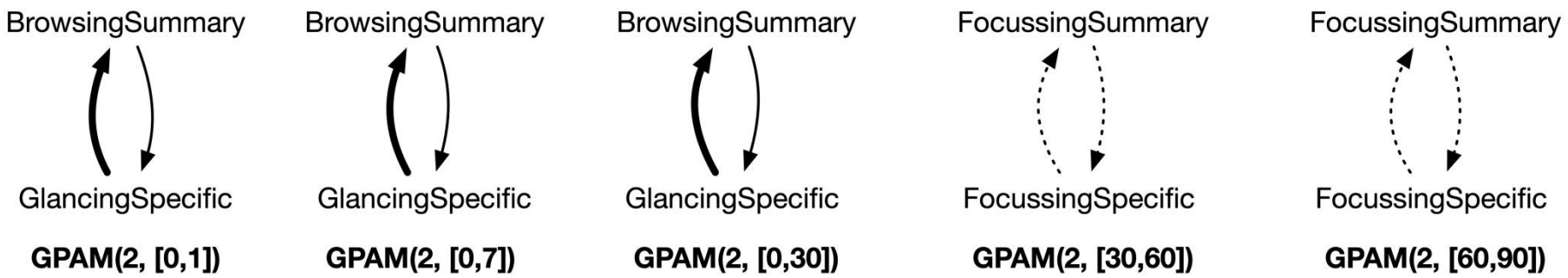


AppTracker1

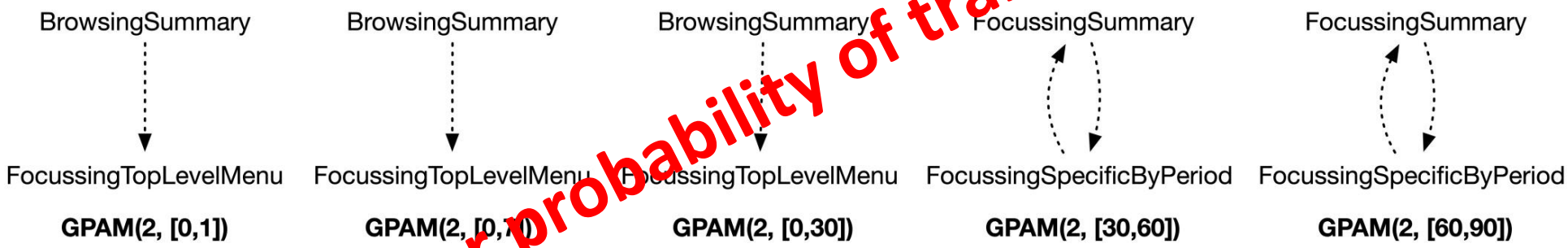


AppTracker2

K=2: probability to change activity pattern



AppTracker1



Lower probability of transition

AppTracker2

Sensitivities/ Validity

- observable states
- segmentation of the data set
- number activity patterns **K**
- inference algorithm parameters
- states for temporal property instantiation

user groups *jailbroken devices*

user groups *existing or new* can’t link installations

Novelty and what did I learn

- models of actual behaviours, not design
- unsupervised learning (ML!)
- real-world deployments: bias of existing users?
- not one monolithic “data set”, traces over time periods
- experiments take a long time - think carefully about design
- temporal logics – again
- models to inform re-design

5 examples

1. Protocol languages den. semantics, **interpreter**
2. Signalling in biochemical networks process algebra **CTMCs**, CSL
3. Domestic network management **bigraphs**, invariants, **online**
4. Mixed-reality system bigraphs, **design perspectives**
5. User interaction styles AR-HMM, DTMCs, **inferred**

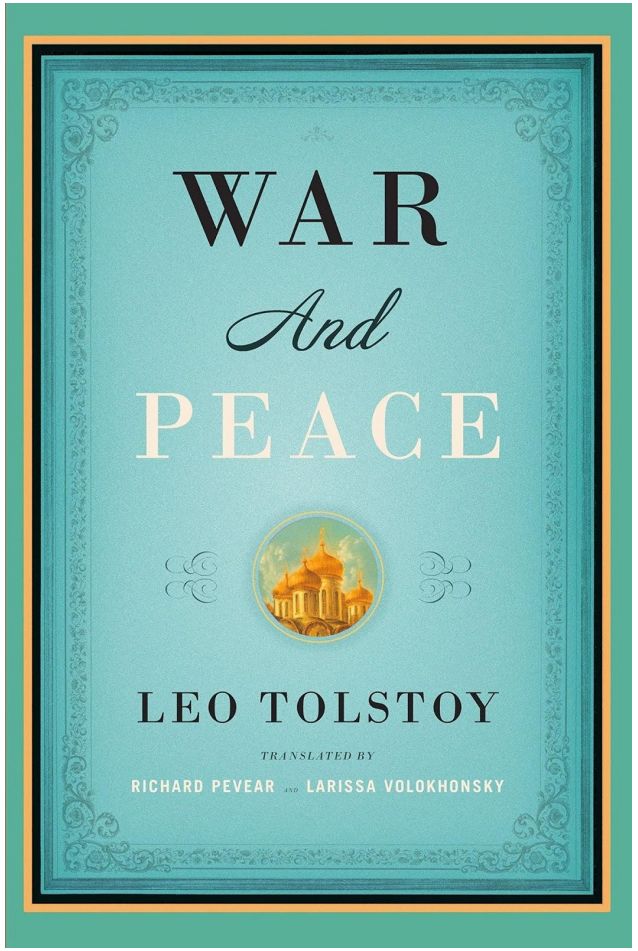
Examples I didn’t mention

BDI agents

Protocols galore

Medical devices

Service failures …



Recurring themes

- Theory is always *challenged* by applications
- More and better automated reasoning tools
- My models are *increasingly* stochastic
  online
  human in the system
  for replay/reveal behaviour in the *wild*
- Interactions and interworking issues *everywhere*
  pathways, policies, perspectives, usage styles

The future

- Models are for much more than design – online decision support

  Modelling something that *is* or what we would *like*?

- Data isn't everything, but it is something

- Models of process are informed by and with data

- Maintenance, ownership, documentation of models

- It's not always the model that matters, but the *modelling process*

Thank you

And to collaborators:

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