A Computational Framework for Theory Building in Psychology

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under the direction of Alain Finkel and Stéphane Le Roux
ENS Paris-Saclay

1. Motivations
2. Finite automata and Communicating automata
3. Refinement & methodology
4. Application: Transactional Theory of Stress

Motivations

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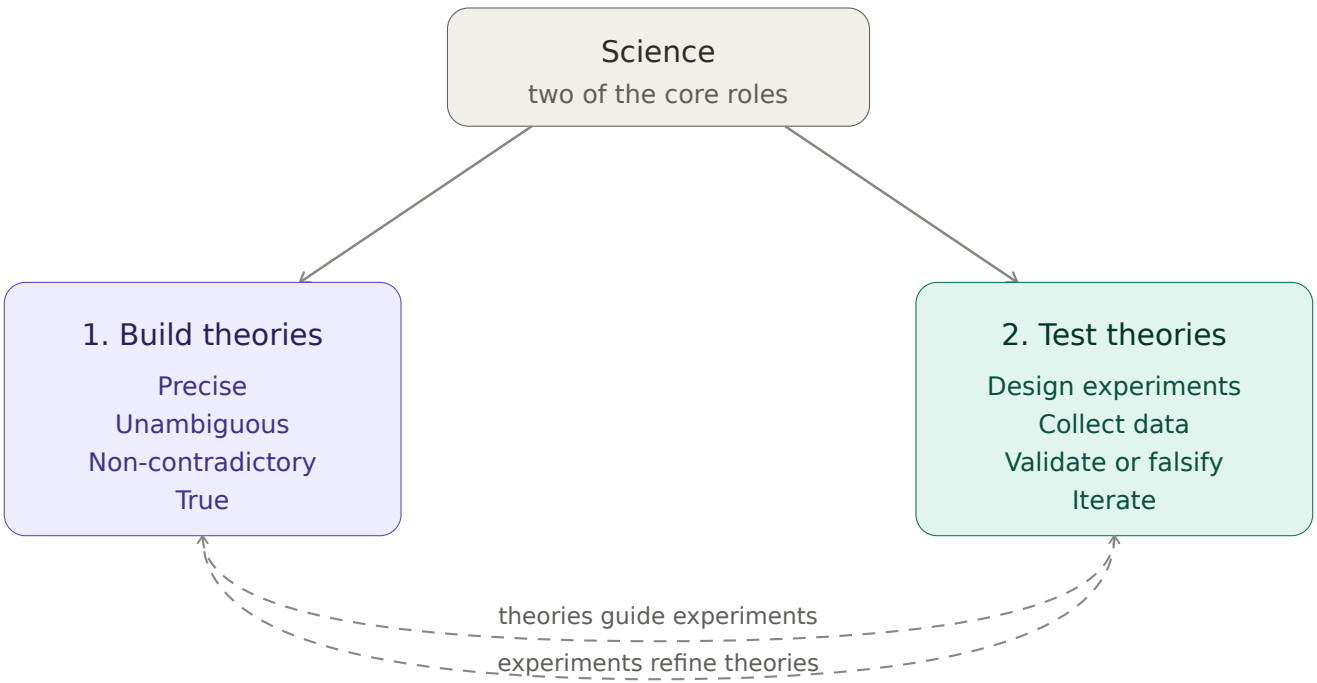
Motivations

Replicability crisis
$\rightarrow$ Half of the psychological literature does not replicate

Motivations

Two roles of science



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As a consequence:

- Call to create frameworks and methodologies for theory specification and theory building in psychology (Glockner et al., 2025; ...)

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As a consequence:

- Call to create frameworks and methodologies for theory specification and theory building in psychology (Glockner et al., 2025; ...)
- Call to specify existing psychological theories (Glockner et al.;...)

Motivations

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Can we formalize stress and coping?

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attending seminar
(rest)

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A lion enters the room.

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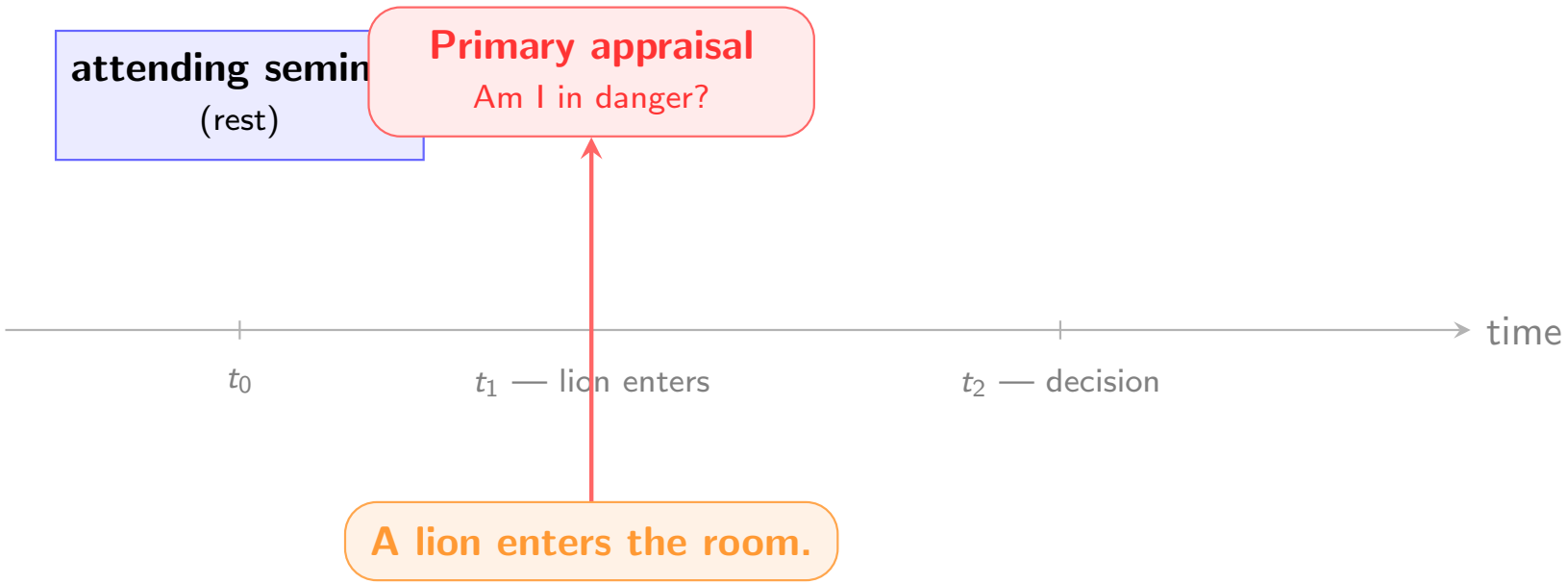

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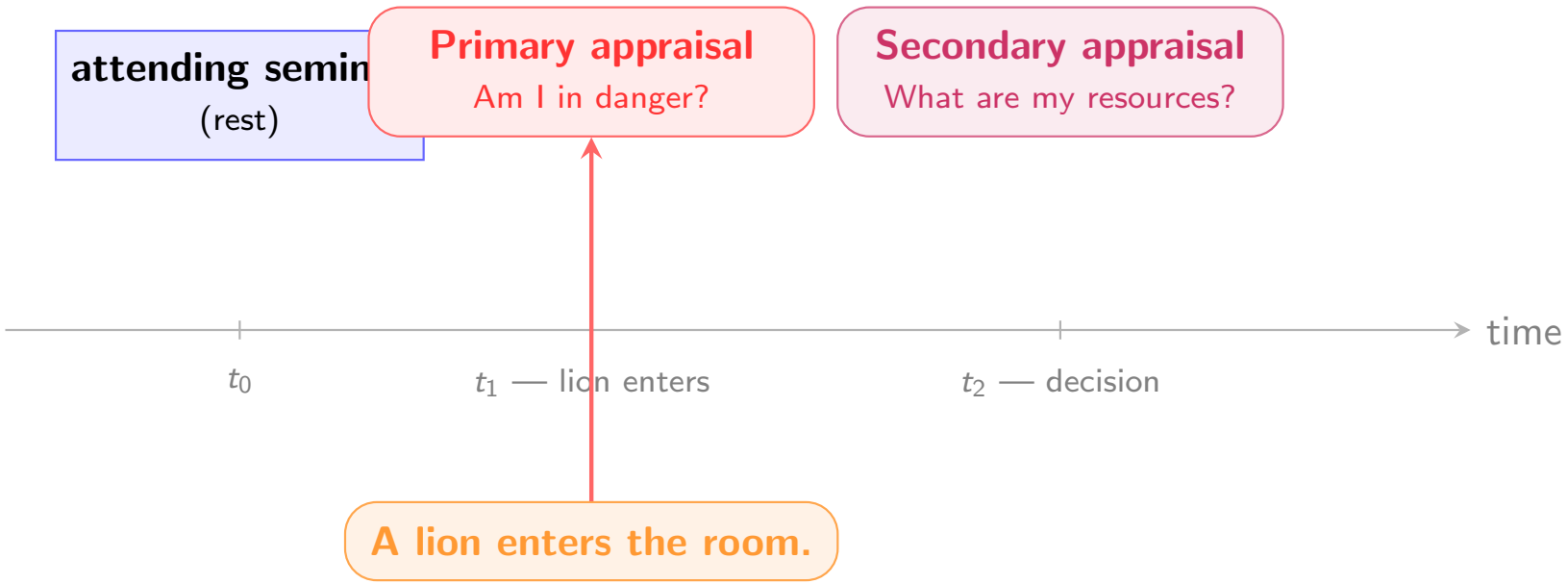

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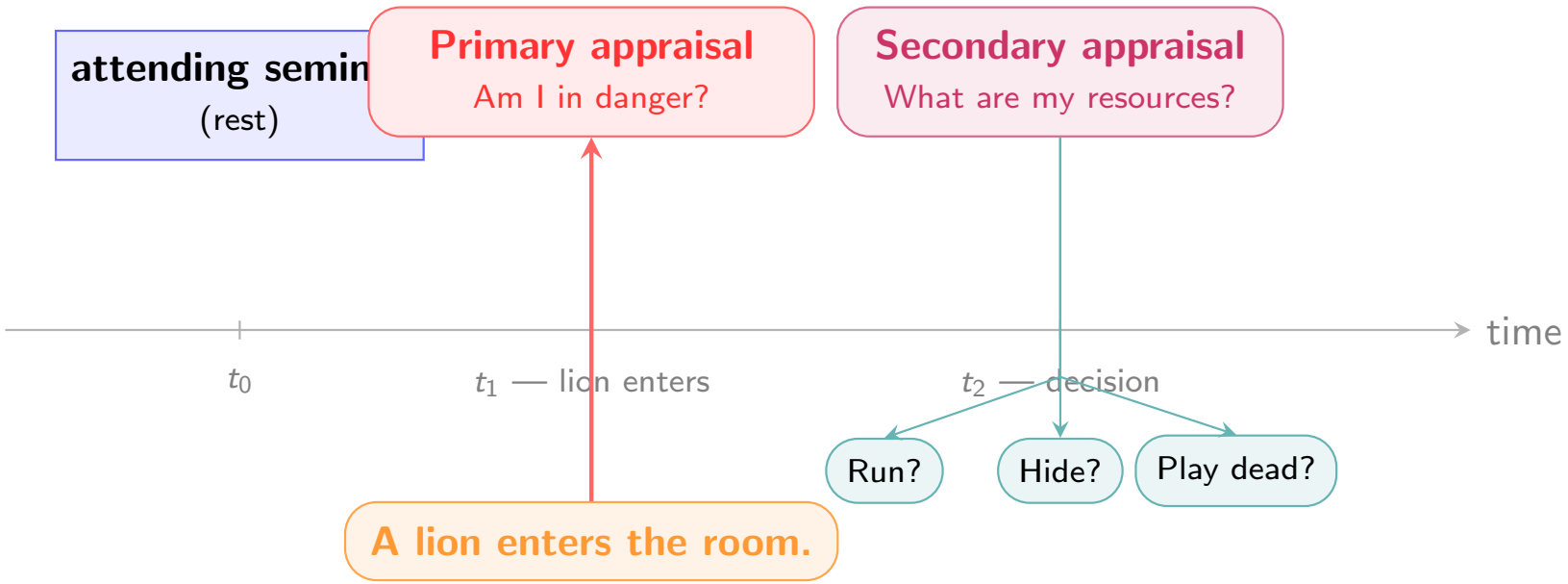

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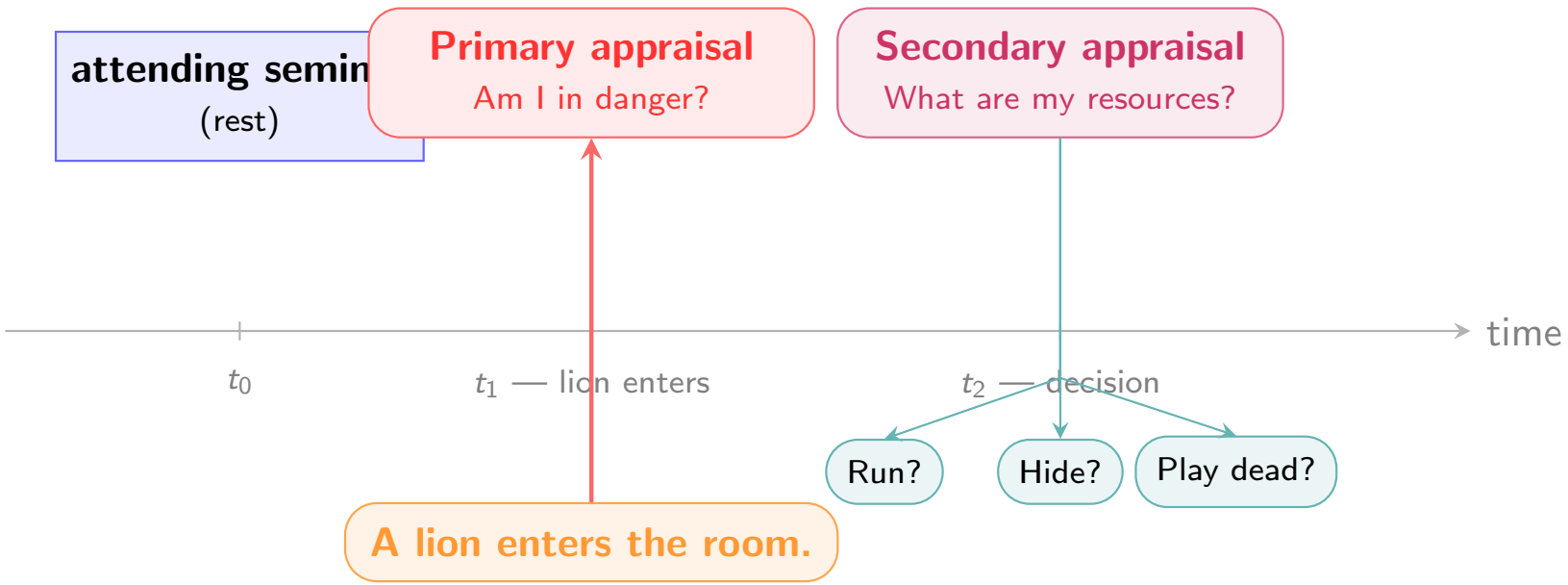

Can we formalize appraisal, stress, and coping?

Motivations

Our contributions

Methodology:
A step-by-step methodology to translate a verbal theory into a formal model, then verify faithfulness to the verbal theory.

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Framework 1 — Communicating automata:
Finite automata, synchronization, refinement, and model checking.

Application: Formal model of the Transactional Theory of Stress (Lazarus & Folkman, 1984).

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Methodology:
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Framework 1 — Communicating automata:
Finite automata, synchronization, refinement, and model checking.

Application: Formal model of the Transactional Theory of Stress (Lazarus & Folkman, 1984).

Framework 2 — Neuronal systems:
Communicating *timed* automata with tokens, refinement.

Application: Formal model of the Global Neuronal Workspace Theory (Mashour et al., 2020).

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Why this framework?

What to expect from a type of formalism?

1. Openness to all psychological theories, both cognitive and behavioral

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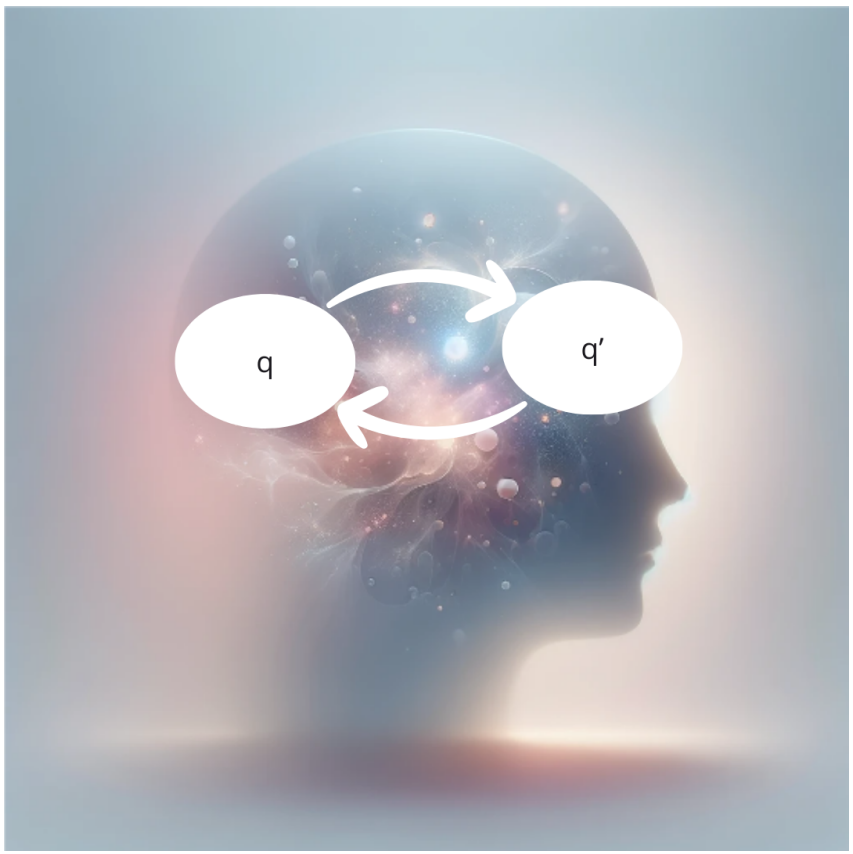
5. Possibility of step-by-step simulation
6. Formal verification of properties with the use of automatic tools
7. Formal (and automatic) comparison of models, with automatic determination of compatibility between theories

Motivations

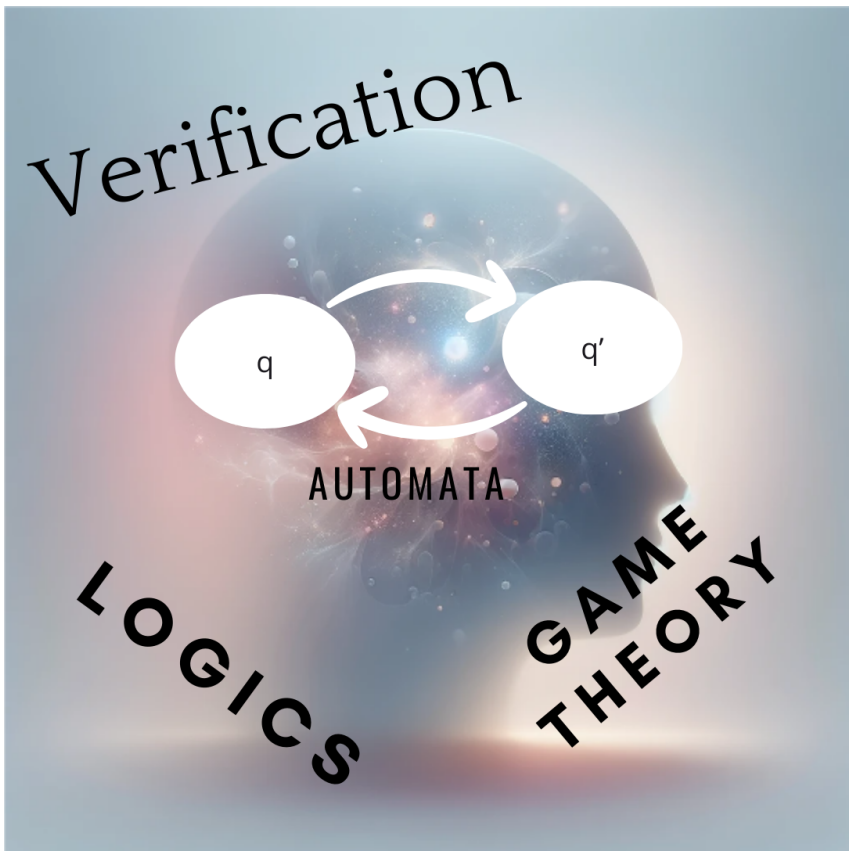
Why this framework?

- We naturally identify **states** and **transitions** in psychological theories



Motivations

- We naturally identify **states** and **transitions** in (neuro-)cognitive theories
- Theoretical CS: powerful tools to model these theories. **Finite automata & extensions!**



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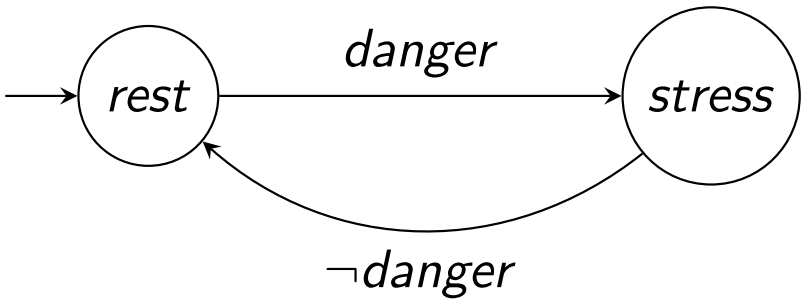


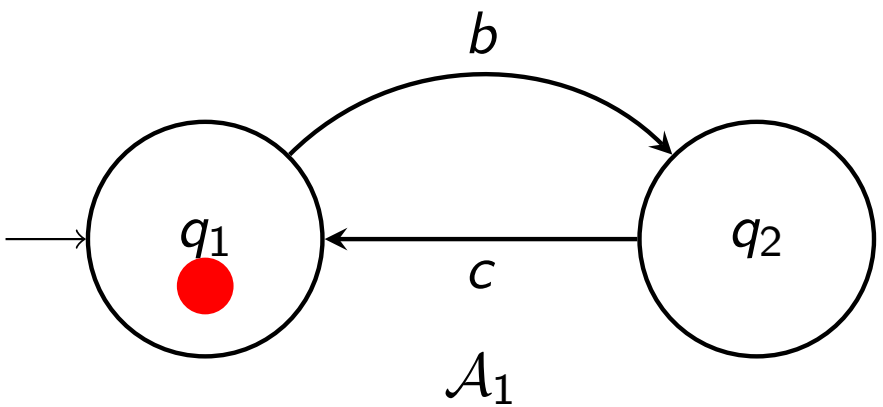
Basic understanding of stress

Finite automata and Communicating automata

Finite automata and Communicating automata

What is a finite automaton?

Example:



Finite automata and Communicating automata

What is a finite automaton?

Σ an alphabet
Q set of states
$\delta \subseteq Q \times \Sigma \times Q$ set of transitions
$I \subseteq Q$ initial states

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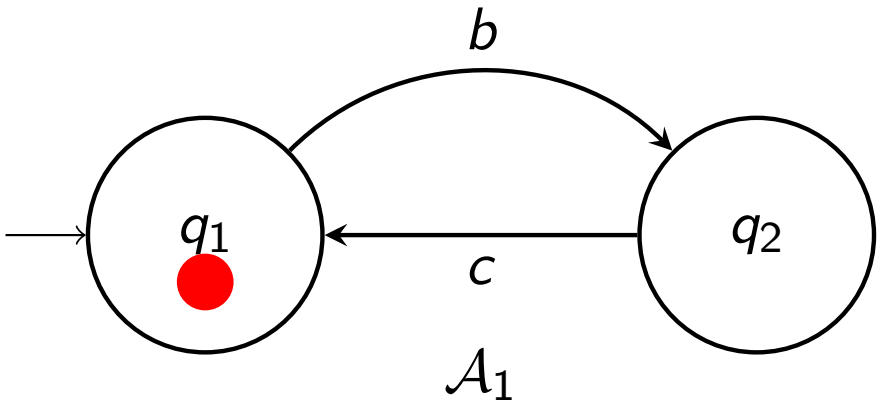

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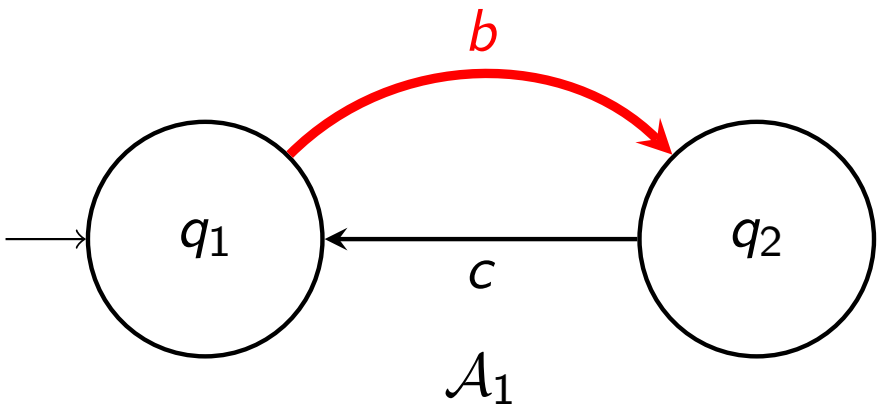

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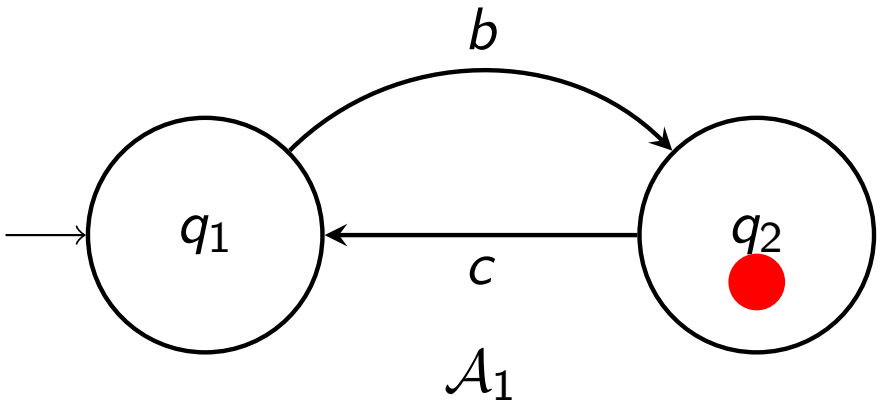
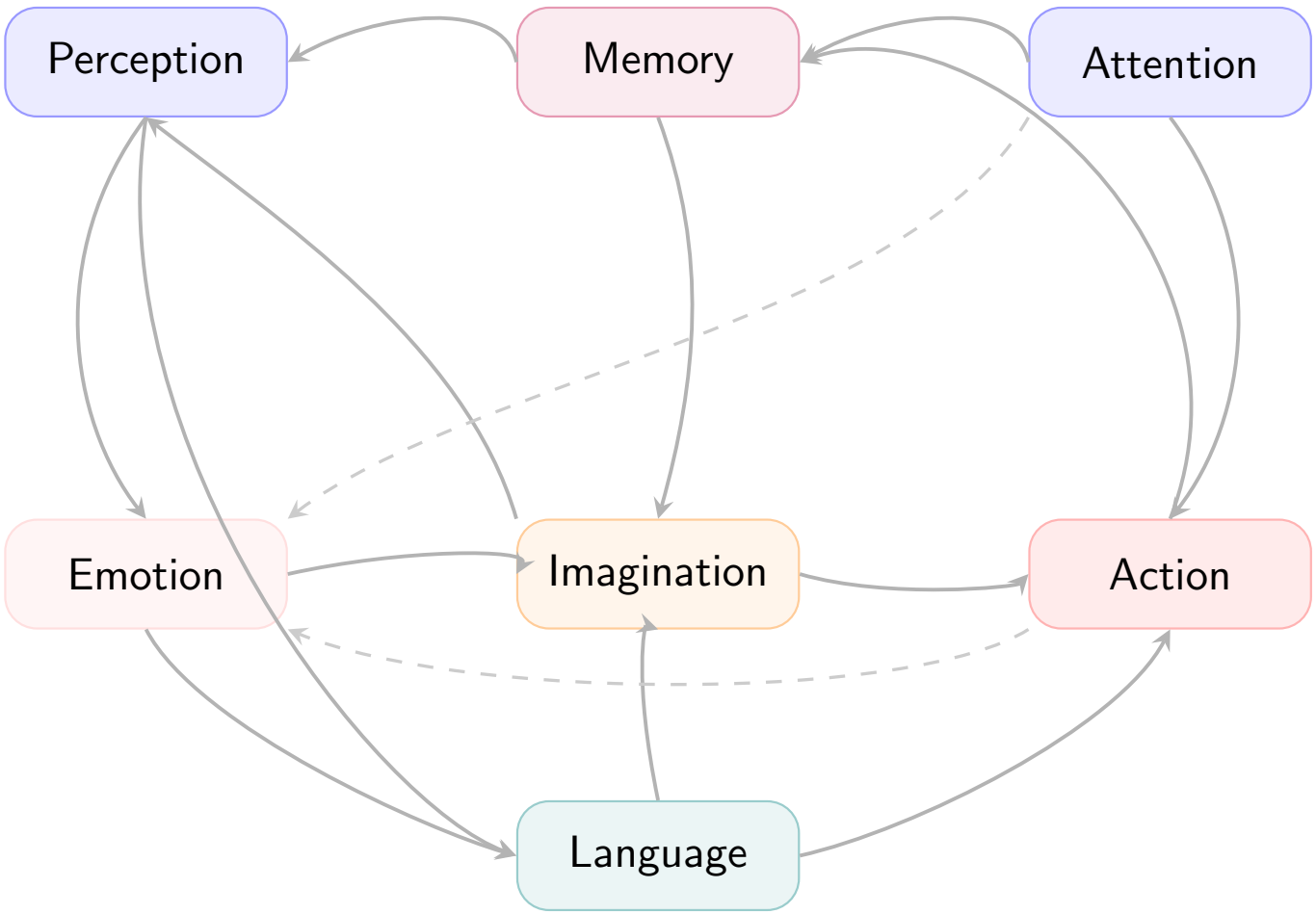


Finite automata and Communicating automata

N modules communicating $\rightarrow$ N automata.



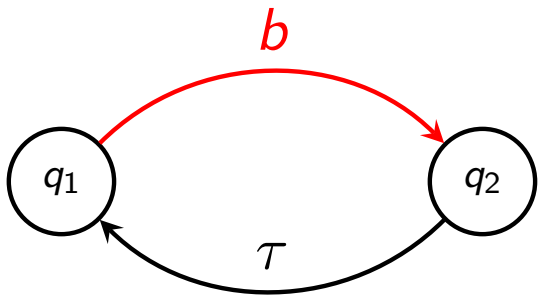
Finite automata and Communicating automata

Synchronisation via multiple "handshake" (Milner, 1989; Horn & Sangnier, 2020)

Set of automata synchronise on letters.

Example: System $(\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3)$ synchronising on letter b

Rule: all automata with letter b must synchronise simultaneously



$\mathcal{A}_1$

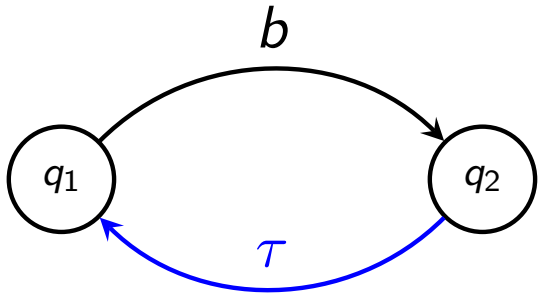
$\mathcal{A}_2$ $\mathcal{A}_3$

Finite automata and Communicating automata

Letter τ

- Meant to model imprecision: "we don't know"
- τ-transitions do **not** synchronise with other automata

τ-transition in $\mathcal{A}_1$ and
τ-transition in $\mathcal{A}_3$ happen independently!



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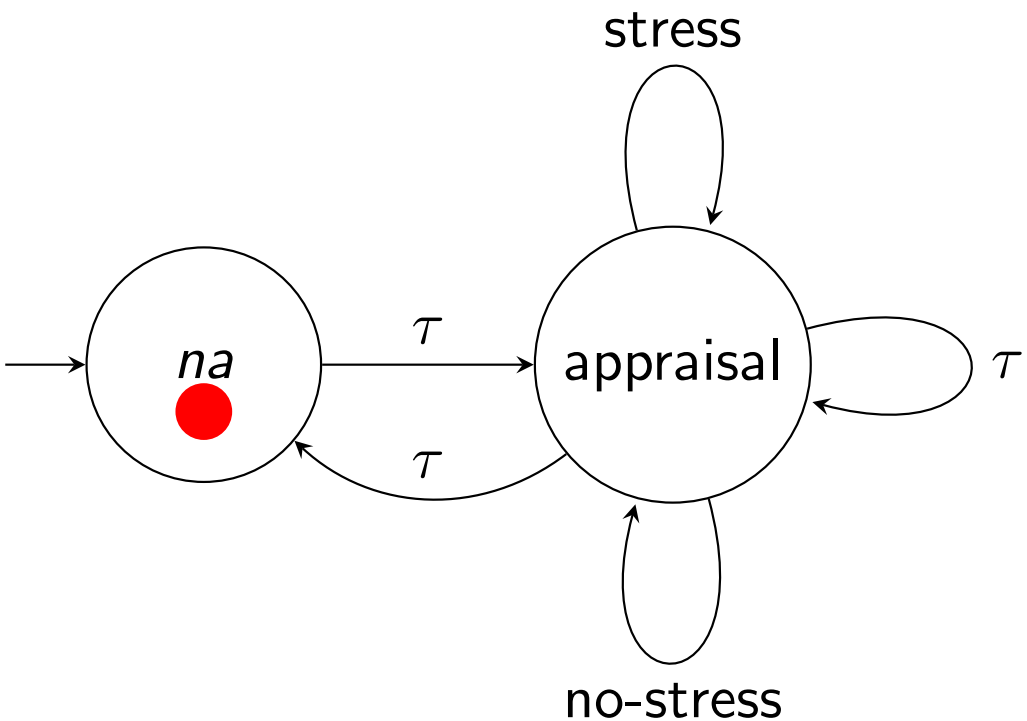

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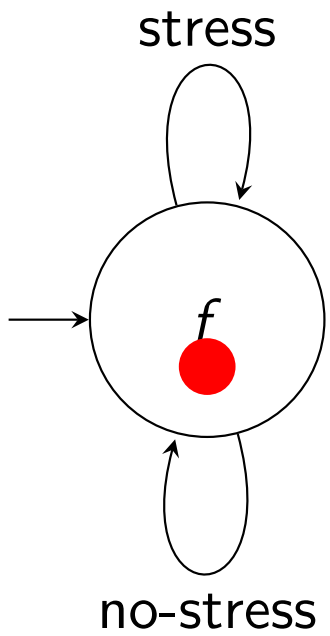
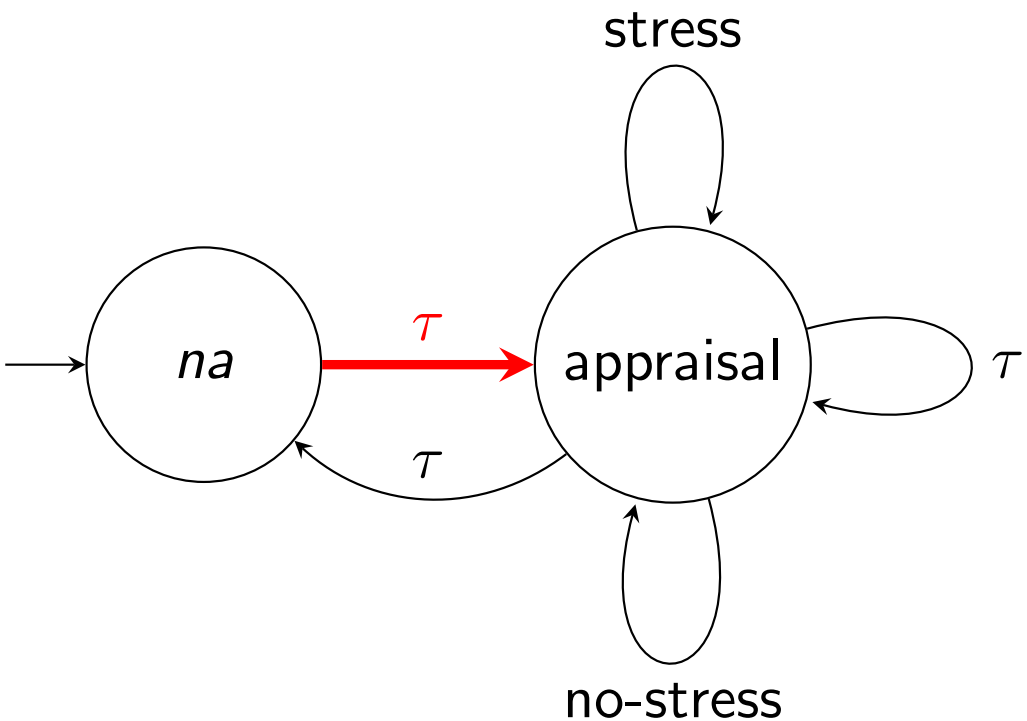


$\mathcal{A}_2$

Finite automata and Communicating automata



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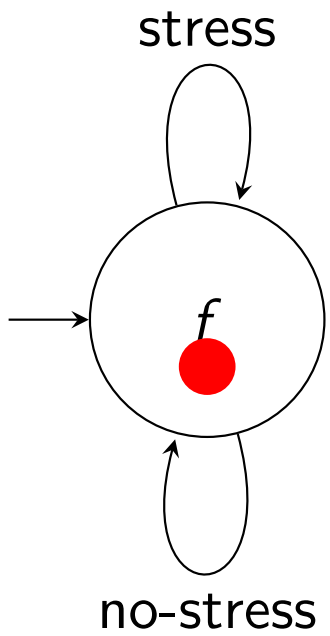

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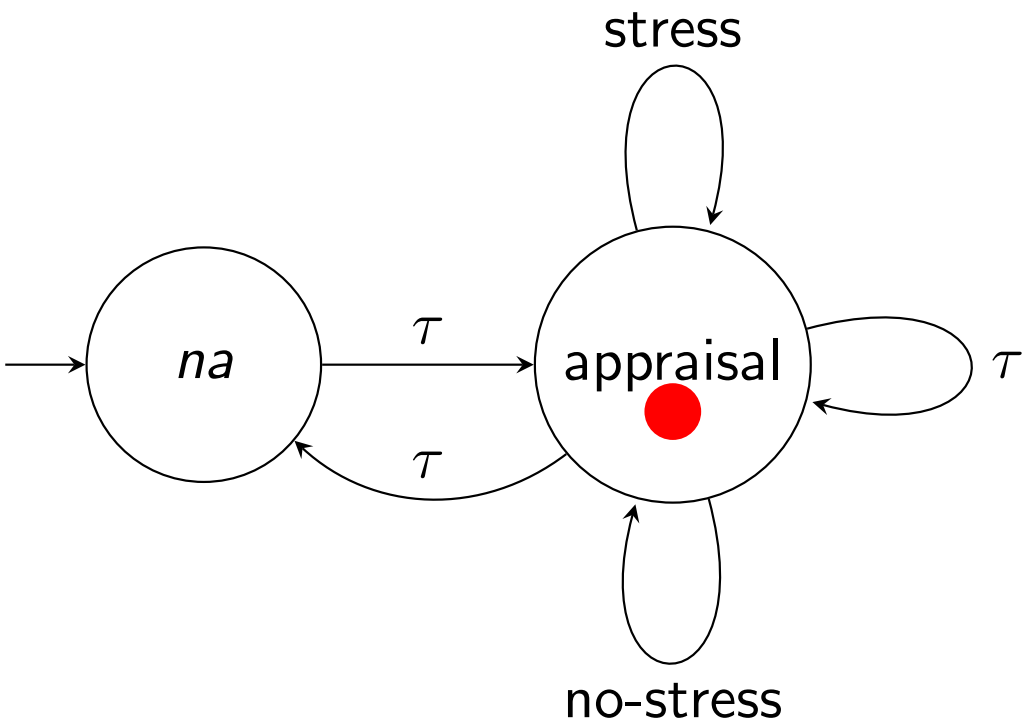

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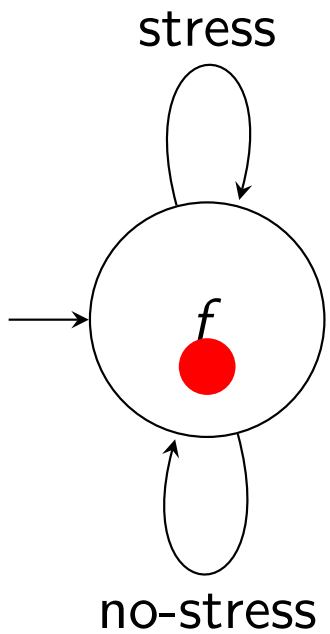

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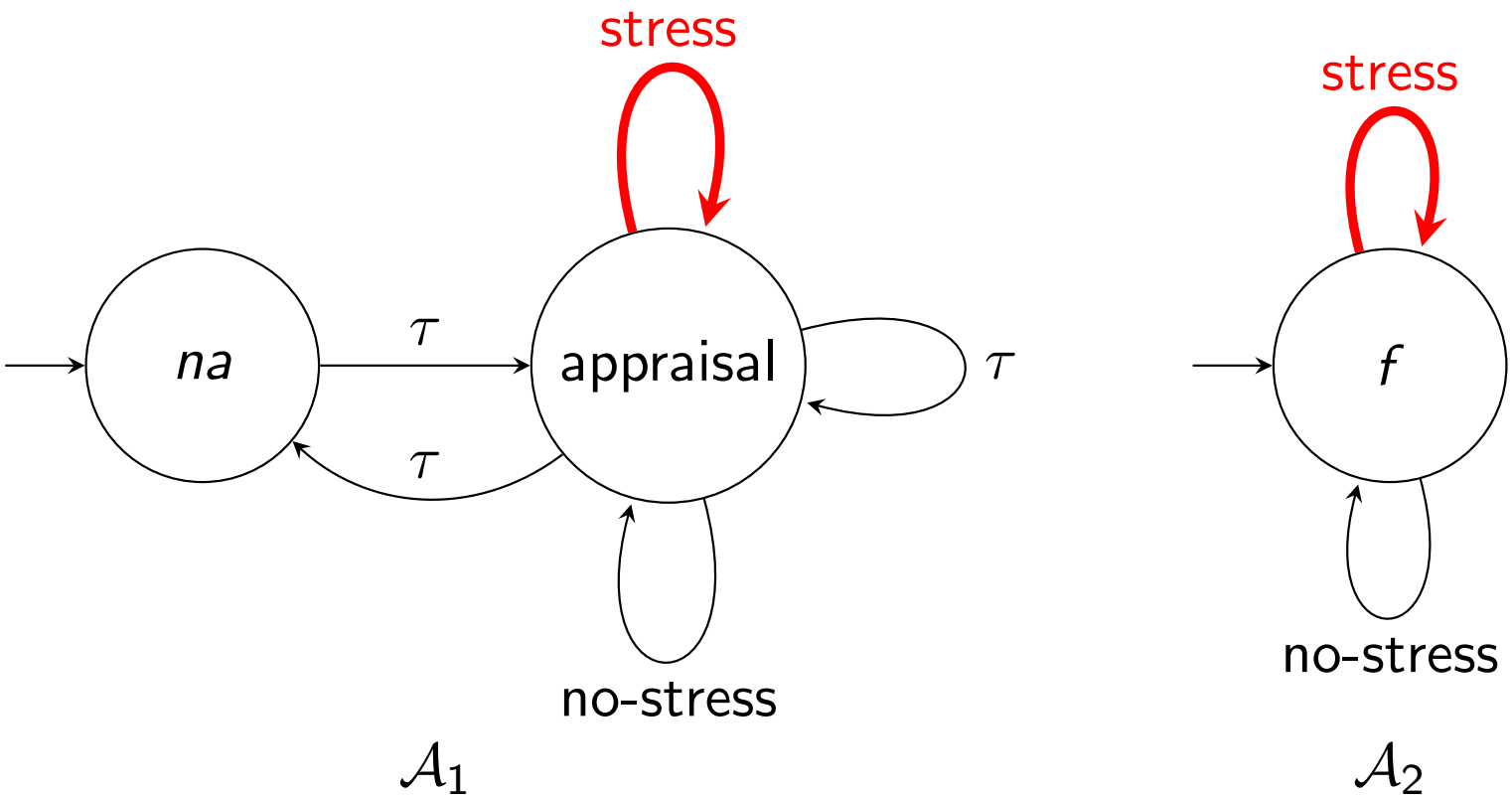

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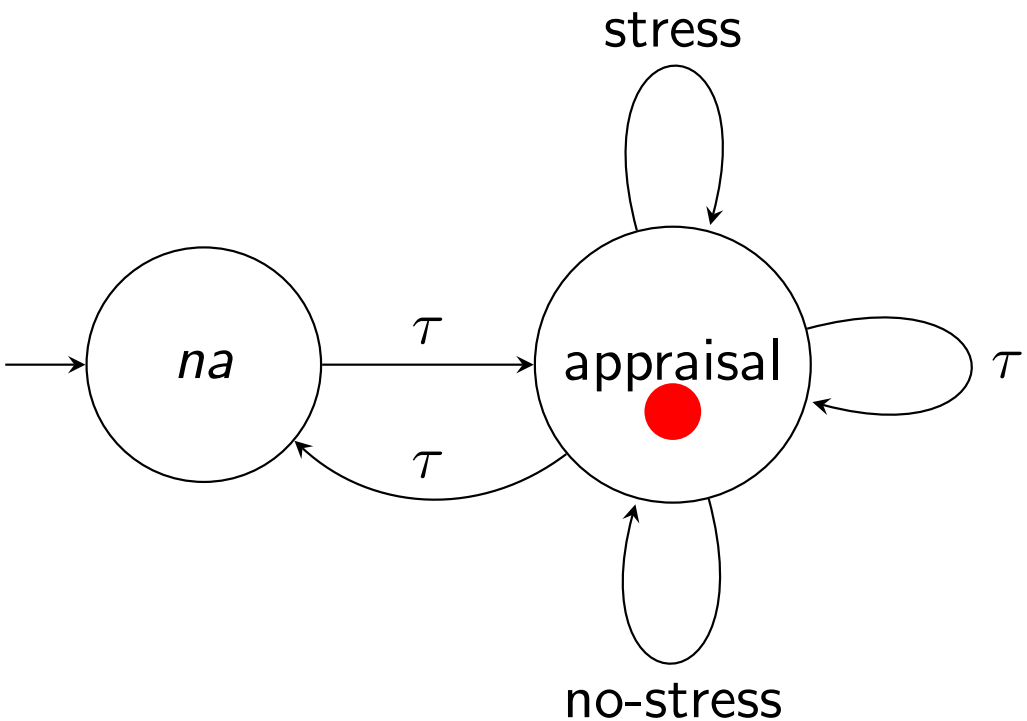

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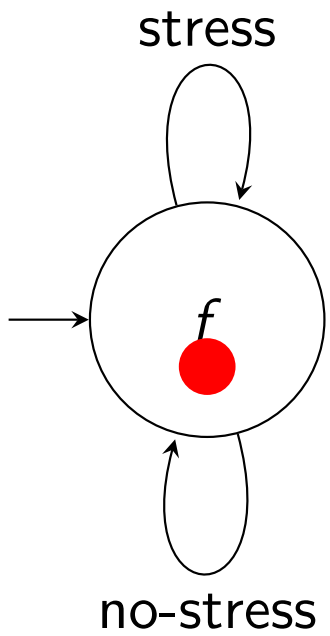


$\mathcal{A}_2$

Refinement & methodology

Refinement & methodology

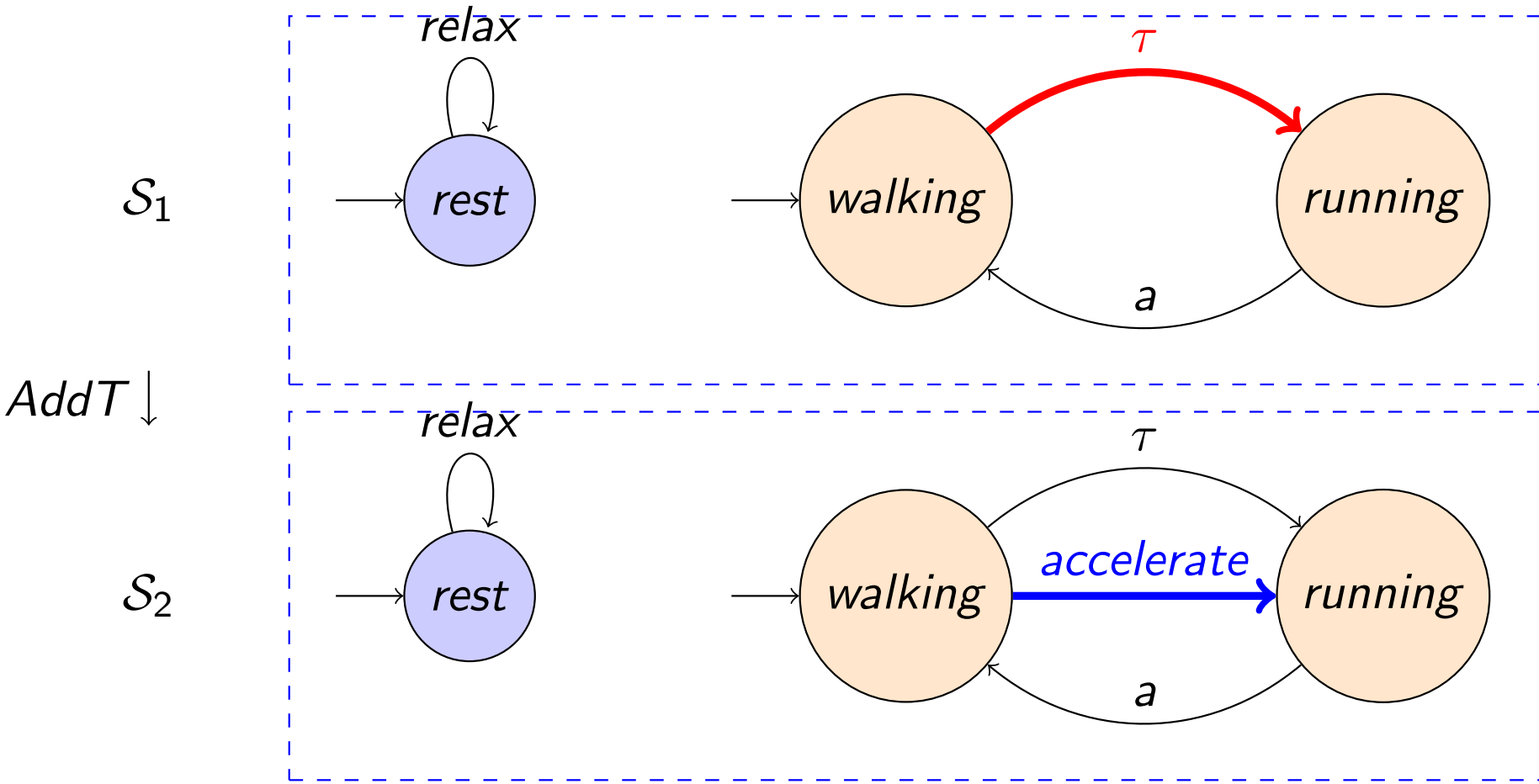
- Refinement operations to develop a theory step by step

Operations:

- Adding / removing a transition
- Splitting a state
- Making an initial state non initial
- Adding a basic automaton
- Uniting automata
- ...

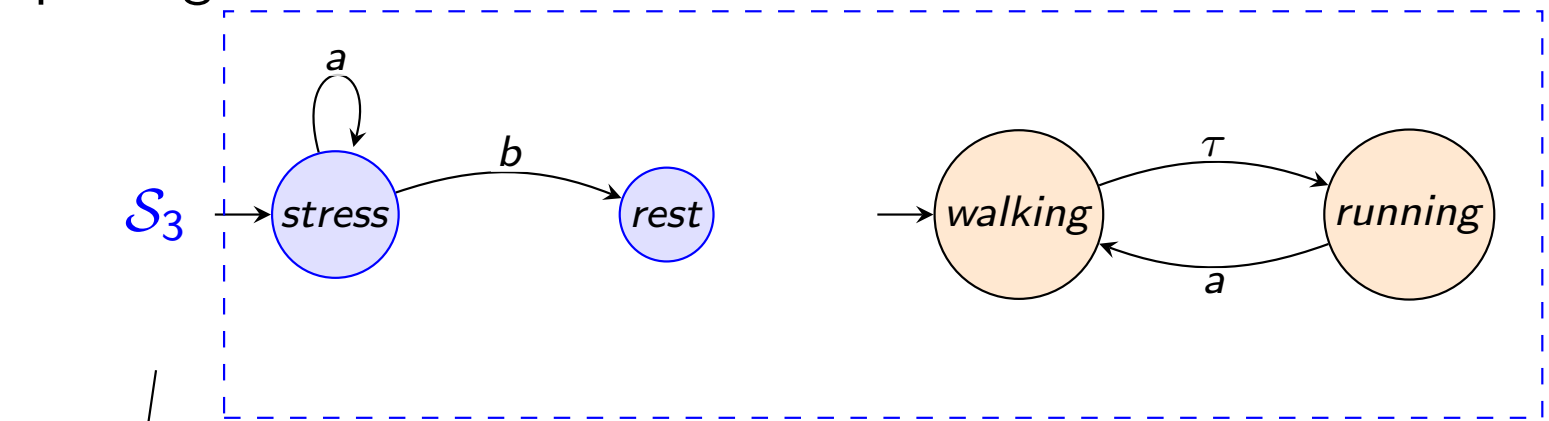
Refinement & methodology

Adding a transition

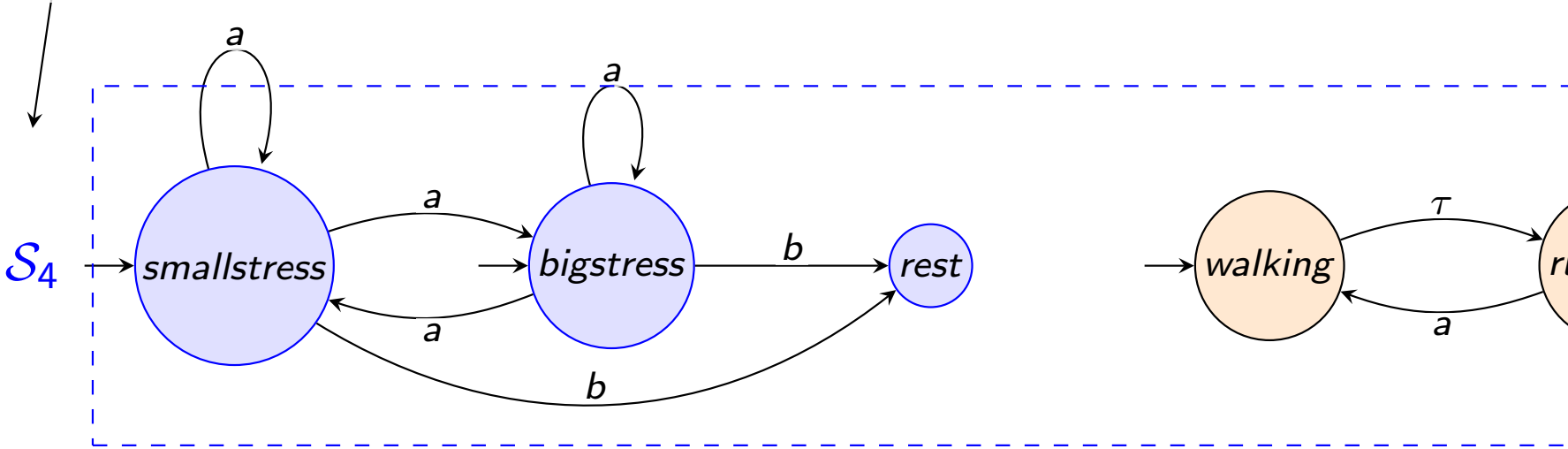


Refinement & methodology

Splitting a state



SplitS



Refinement & methodology

Proposition. The refinement operations allow us to create *any* system from a trivial system.

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Theorem. There exists a (non-trivial) relation $\mathcal{R}$ such that if $\mathcal{S}'$ is a refinement of $\mathcal{S}$, then for all runs w' of $\mathcal{S}'$, there exists a run w of $\mathcal{S}$ such that $w \mathcal{R} w'$.

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Interpretation: Refinement amounts to constraining. When refining, **no new behaviors appear**.

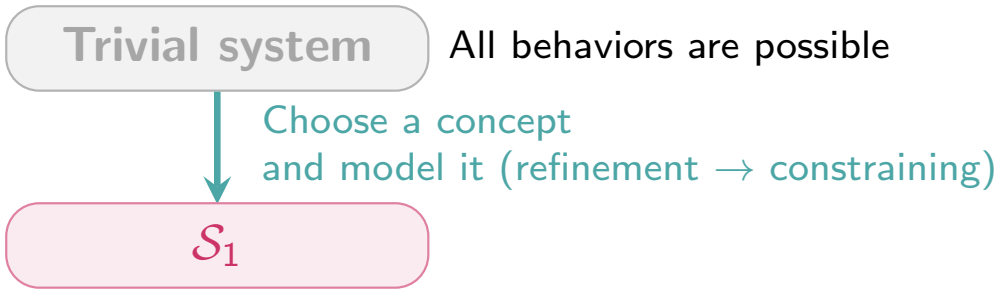
Refinement & methodology

General methodology

Trivial system All behaviors are possible

Refinement & methodology

General methodology



Refinement & methodology

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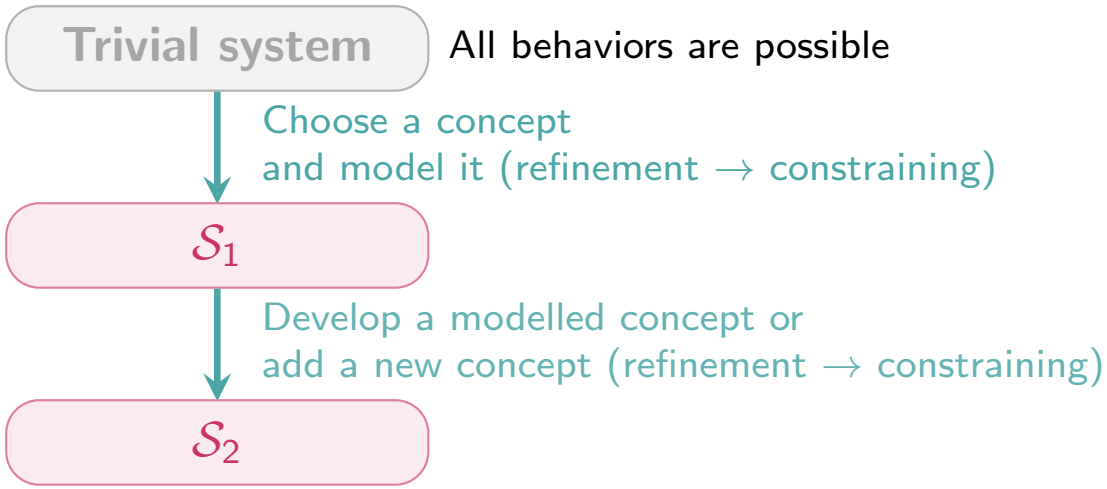

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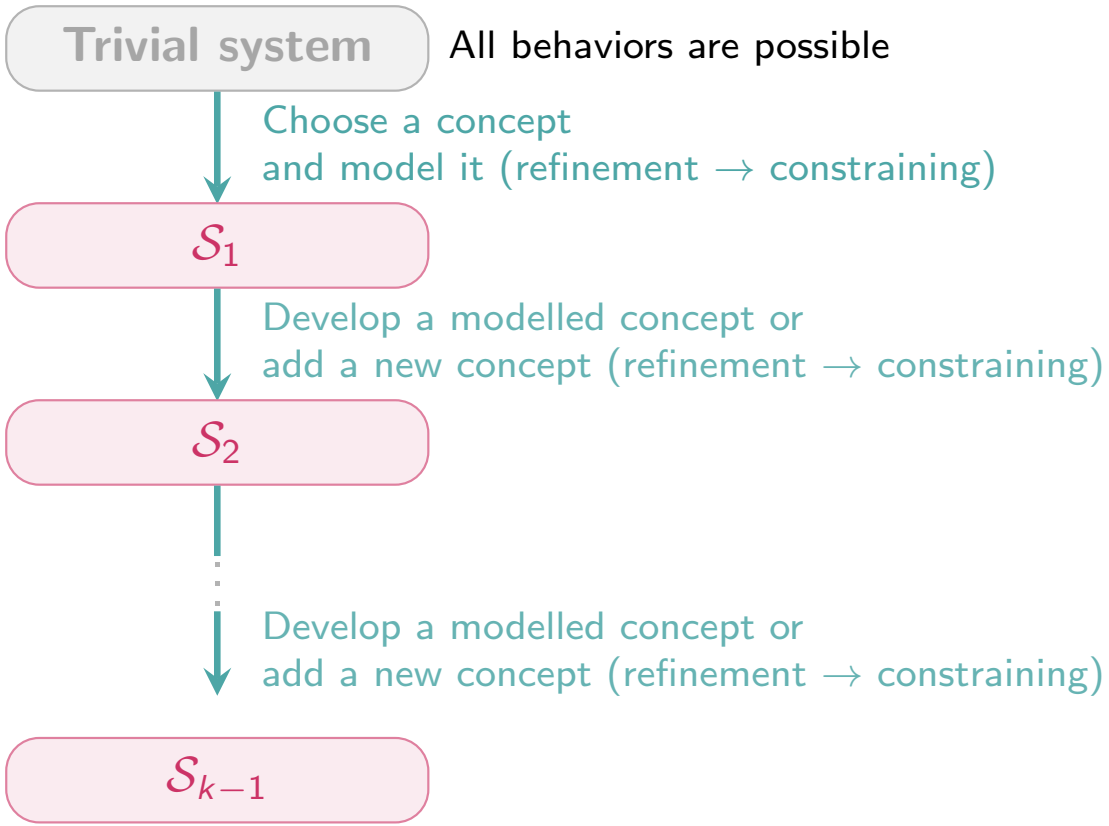

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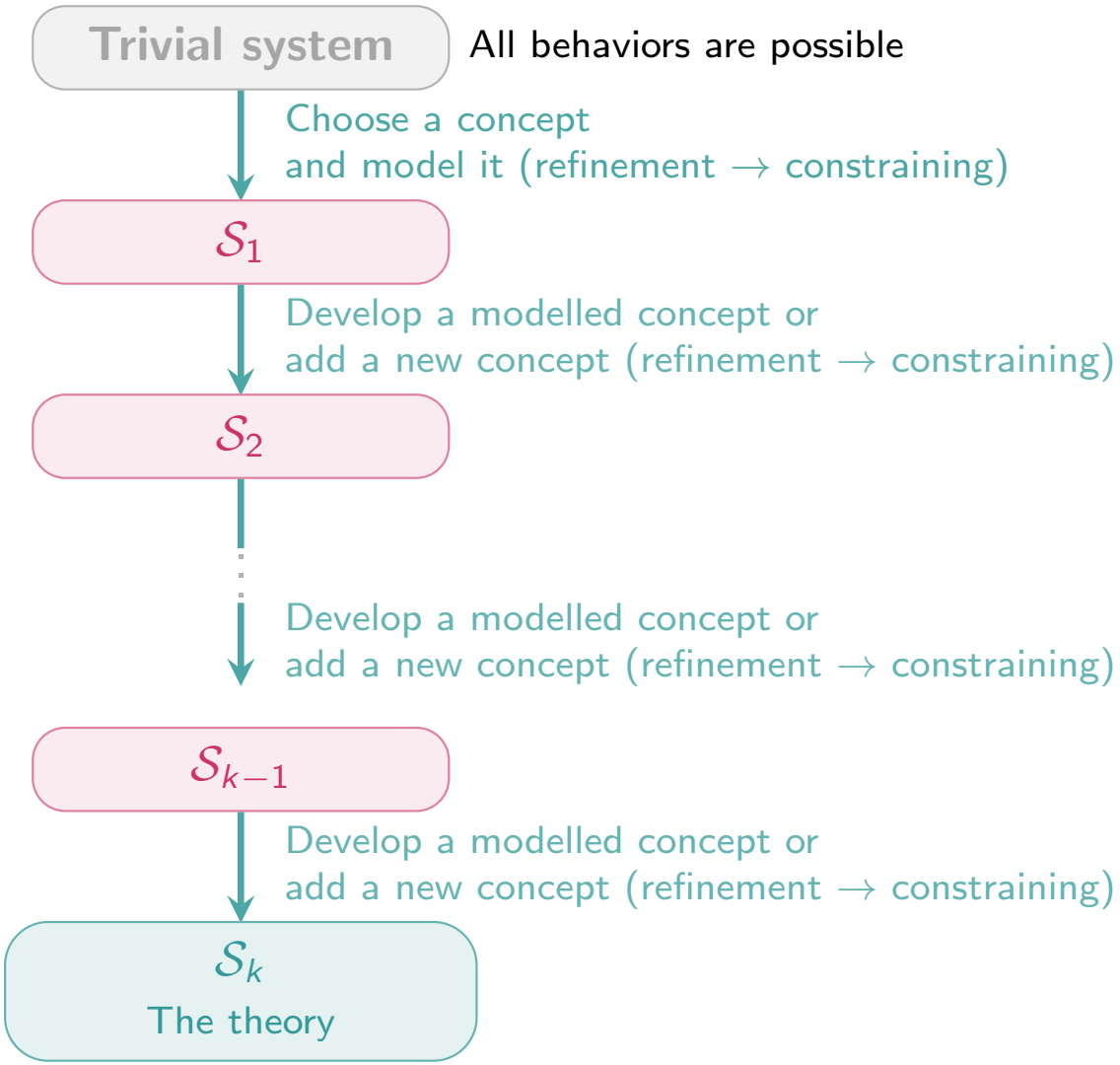

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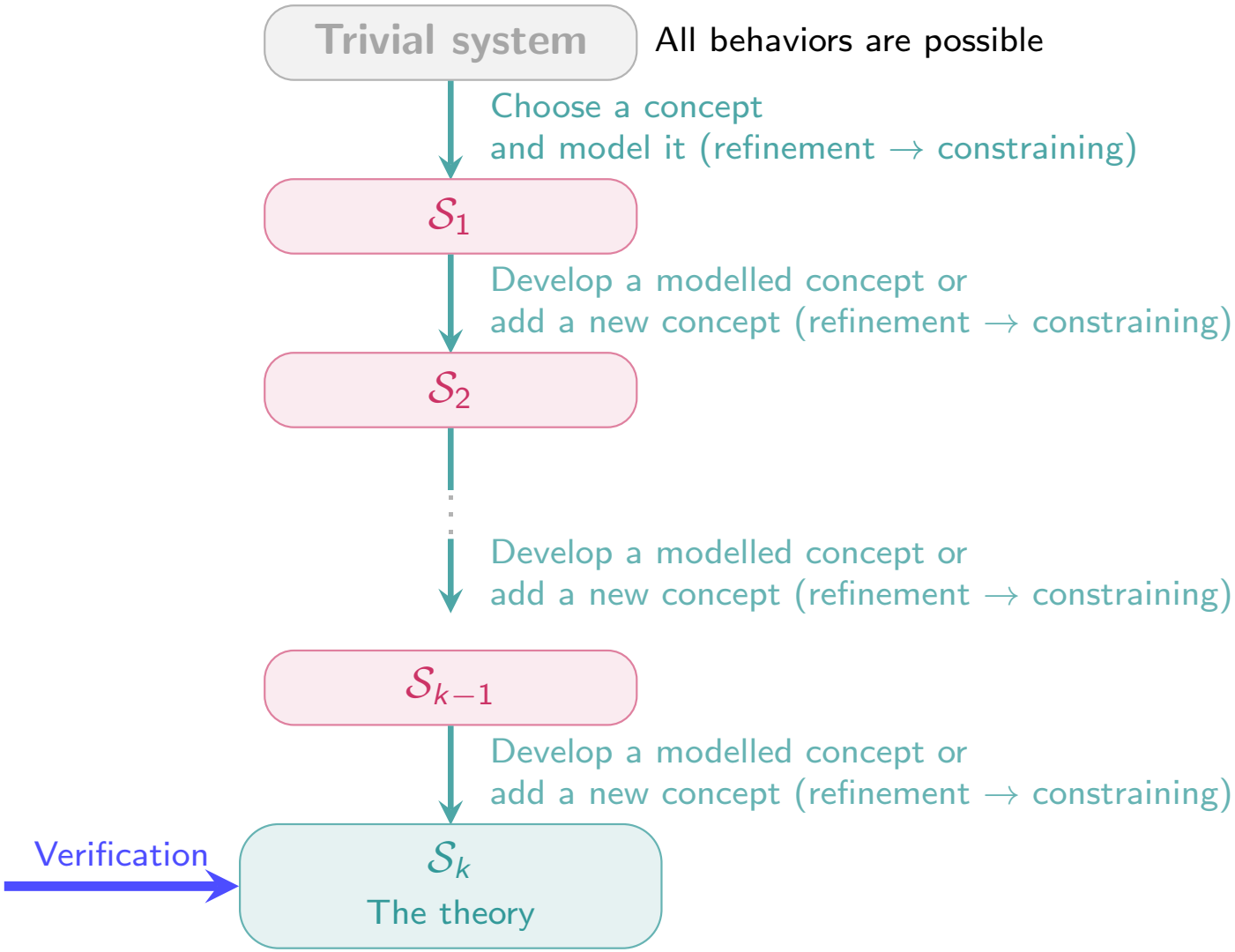
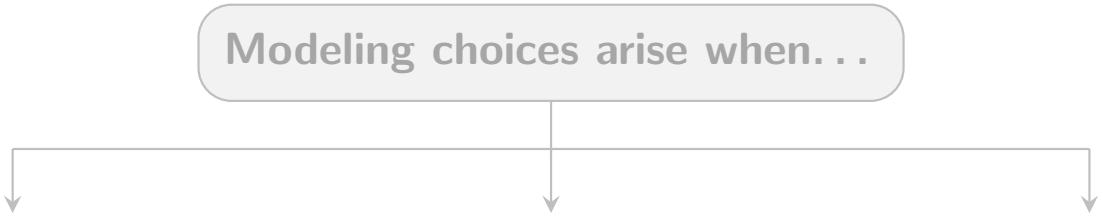


Refinement & methodology

Modeling choices arise when. . .

Refinement & methodology



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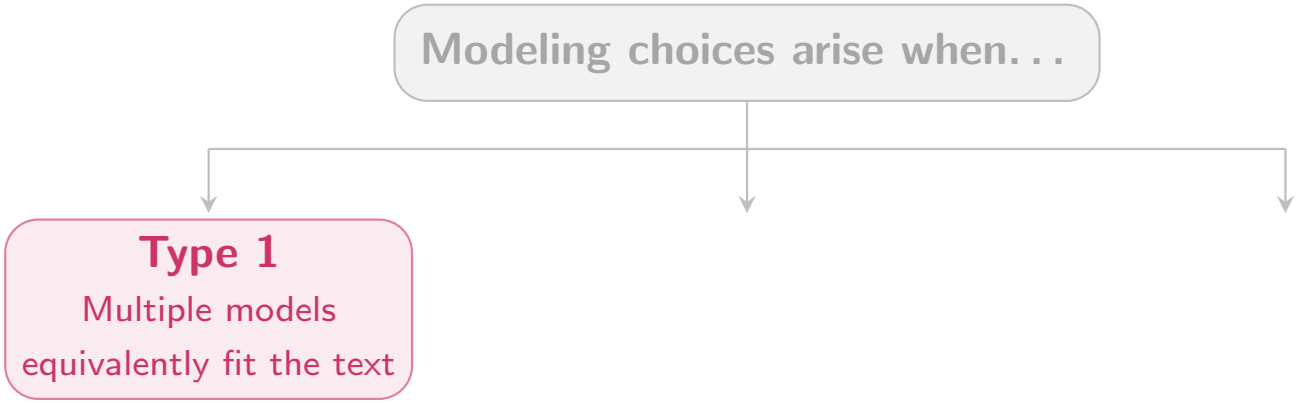

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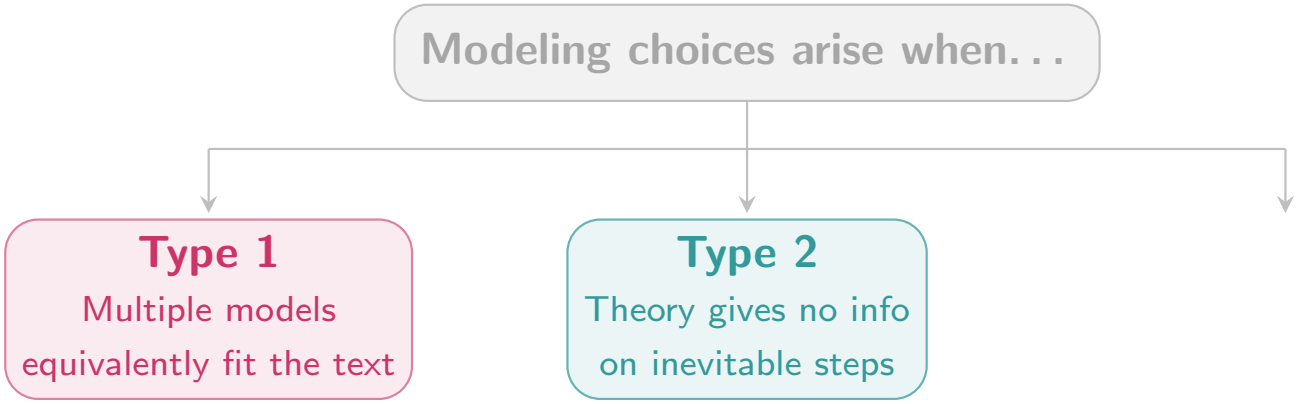

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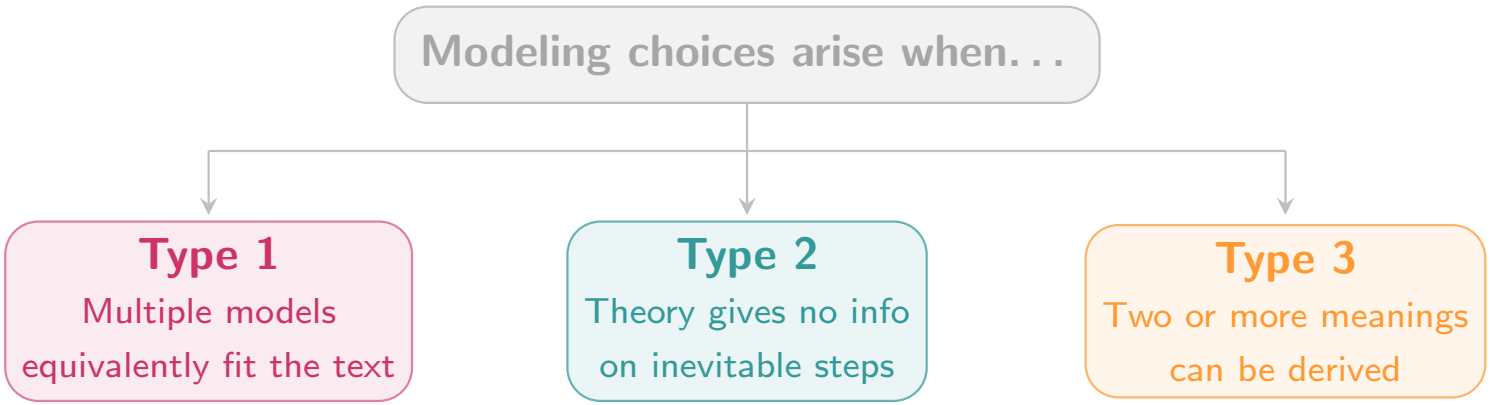

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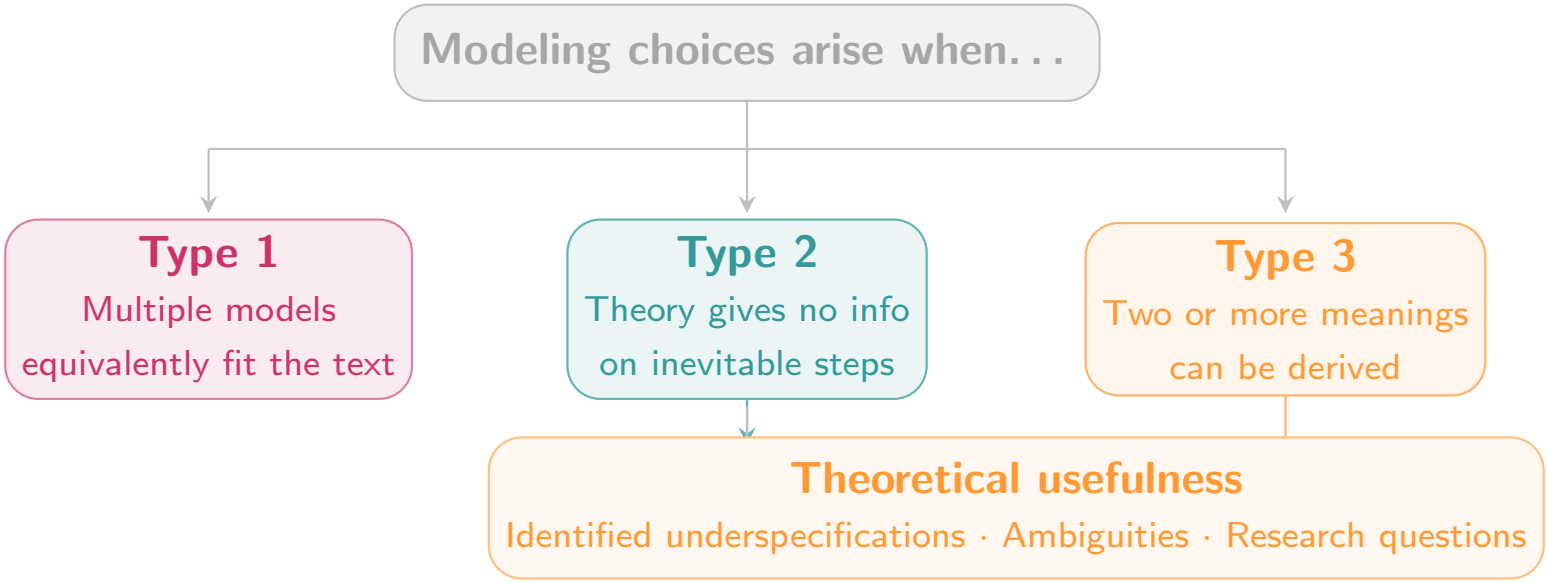

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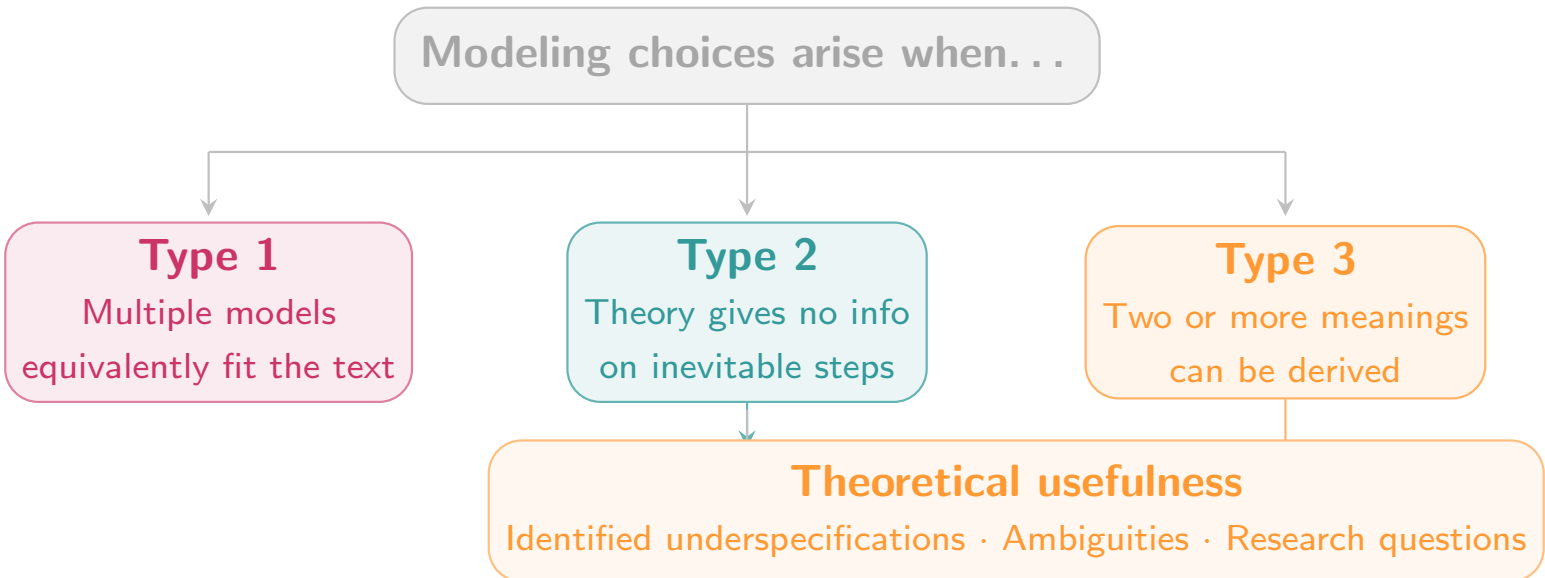

Principles for modeling choices

Equivalent options?
Choose the easier to understand

Local concept? → model as a state
Shared concept? → model as a letter

No set rules — these are guiding principles

Application: Transactional Theory of Stress

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Lazarus & Folkman, 1984

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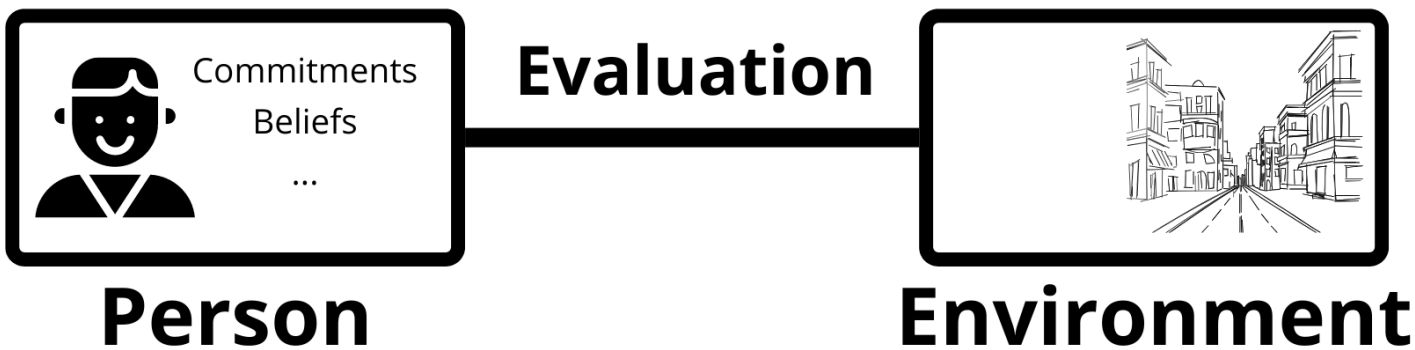
Person

Environment

Application: Transactional Theory of Stress

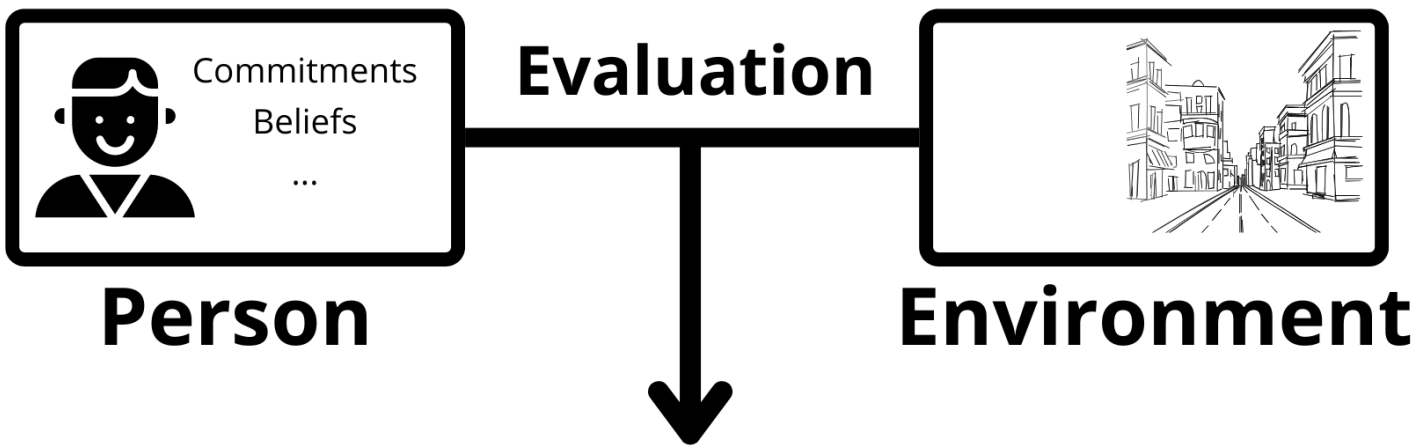
Lazarus & Folkman, 1984



Application: Transactional Theory of Stress

Lazarus & Folkman, 1984

Appraisal= Evaluation

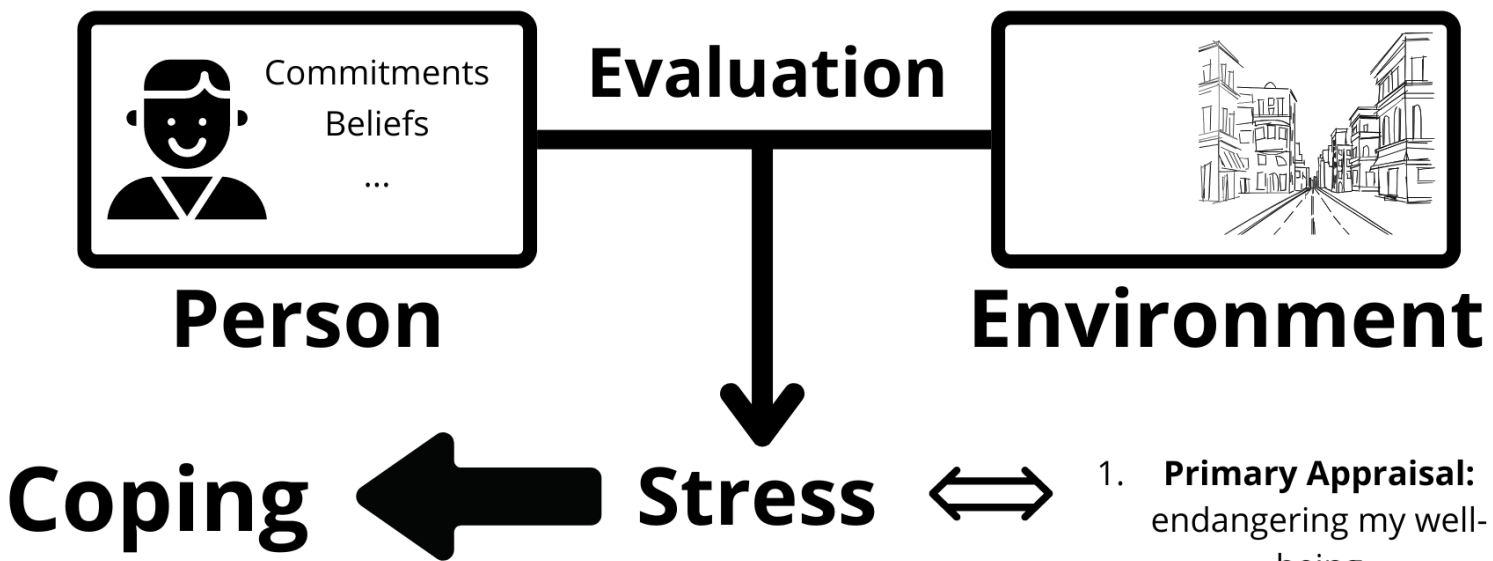


1. **Primary Appraisal:** endangering my well-being
2. **Secondary Appraisal:** taxing/exceeding my resources

Application: Transactional Theory of Stress

Lazarus & Folkman, 1984

Appraisal= Evaluation



1. **Primary Appraisal:** endangering my well-being
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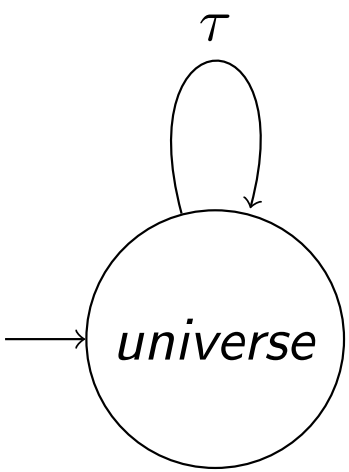
Application: Transactional Theory of Stress

Application: Transactional Theory of Stress

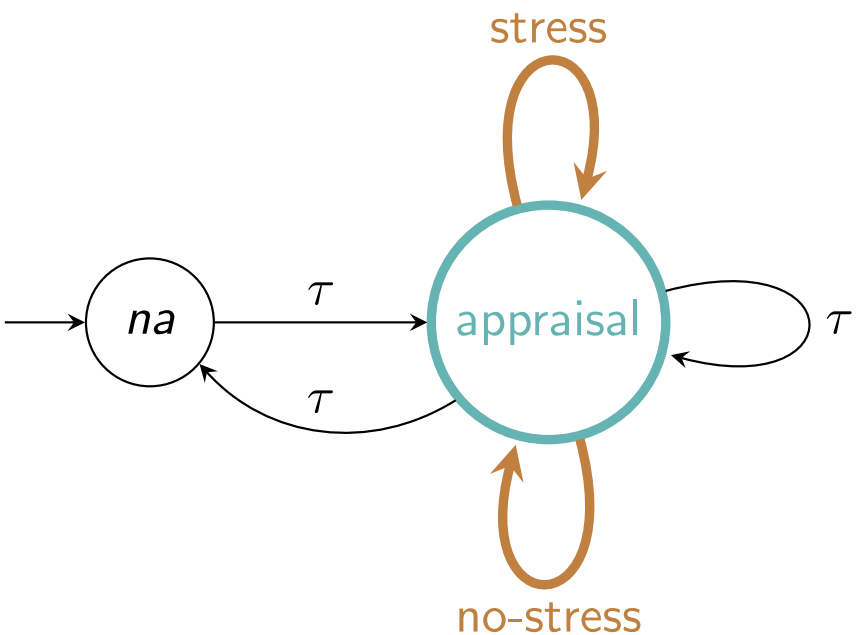
Trivial system

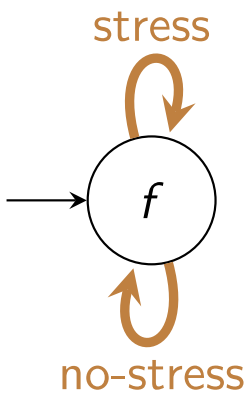


Application: Transactional Theory of Stress

Modeling appraisal: System $\mathcal{S}_1$

"Cognitive appraisal is an evaluative process that determines why and to what extent a particular transaction or series of transactions between the person and the environment is stressful." (Lazarus & Folkman, 1984)

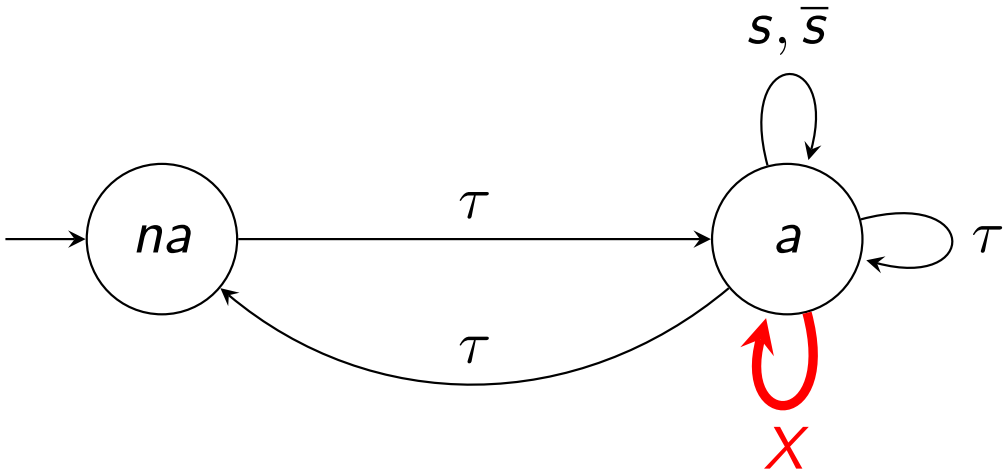




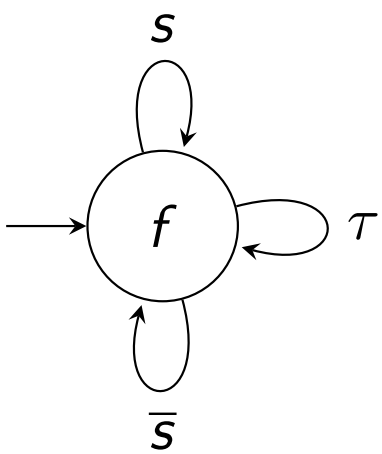
$\mathcal{A}_1$: **Cognitive Appraisal** $\mathcal{A}_2$: **Evaluation of stress**

Application: Transactional Theory of Stress

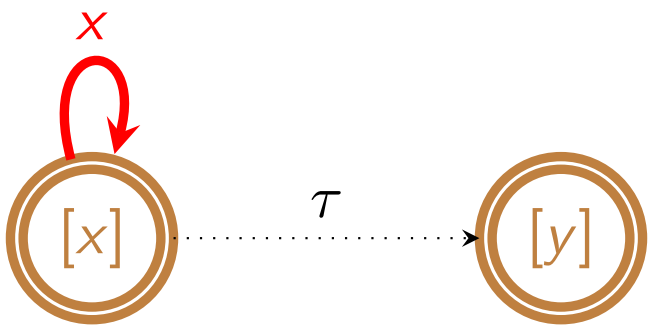
Adding the environment: Refining $\mathcal{S}_1$ into $\mathcal{S}_2$



$\mathcal{A}_1$ **Appraisal**



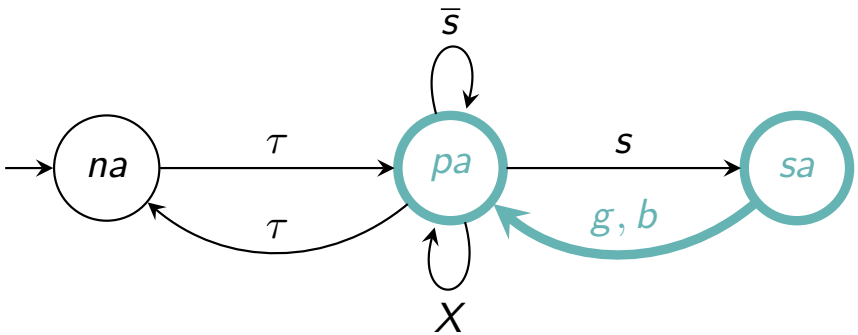
$\mathcal{A}_2$ **Evaluation of stress**



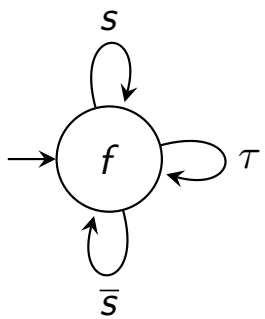
$\mathcal{A}_3$ **Environment**

Application: Transactional Theory of Stress

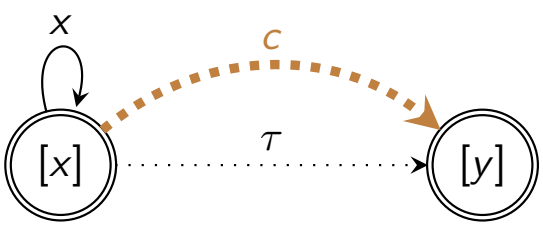
Adding primary appraisal, secondary appraisal and coping: refining $\mathcal{S}_2$ into $\mathcal{S}_3$



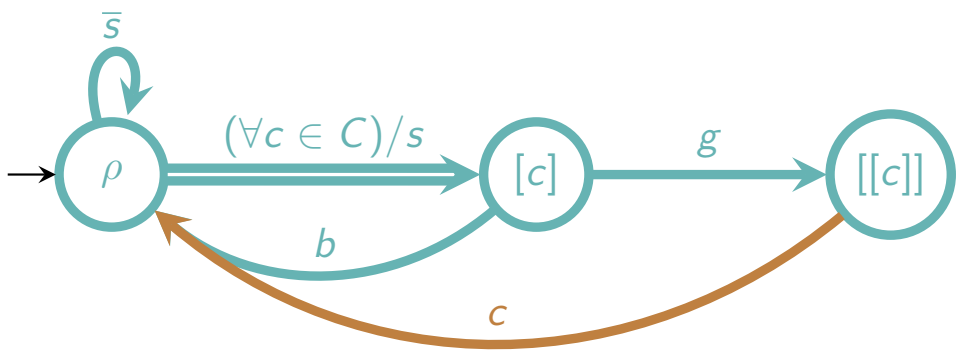
$\mathcal{A}_1$: Appraisal



$\mathcal{A}_2$: Calculating stress



$\mathcal{A}_3$: Environment

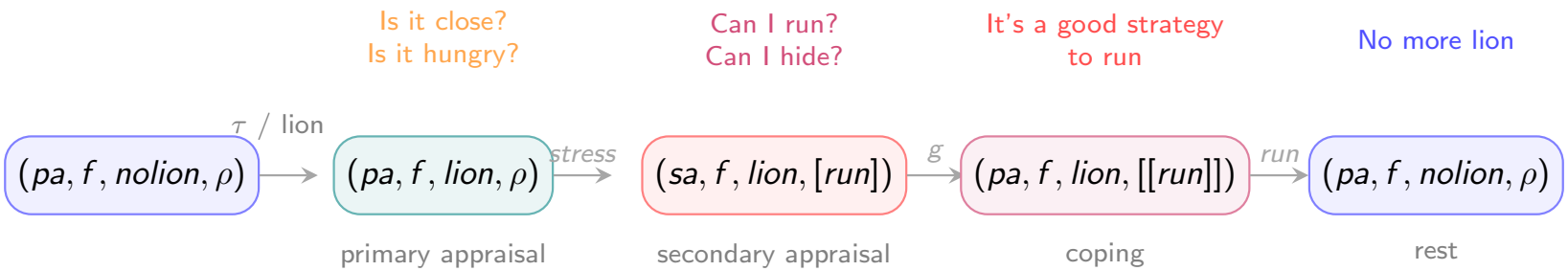


$\mathcal{A}_4$: Secondary appraisal and coping

Application: Transactional Theory of Stress

A run of the system

Scenario: A lion enters the room during the seminar.



Application: Transactional Theory of Stress

Adding more modules

- M_1: Imagining a course of actions and its results
- M_2: Memorising coping strategies
- M_3: Decision-making theories
- M_4: Calculating the stress level based on the goals, values and beliefs of the individual

...

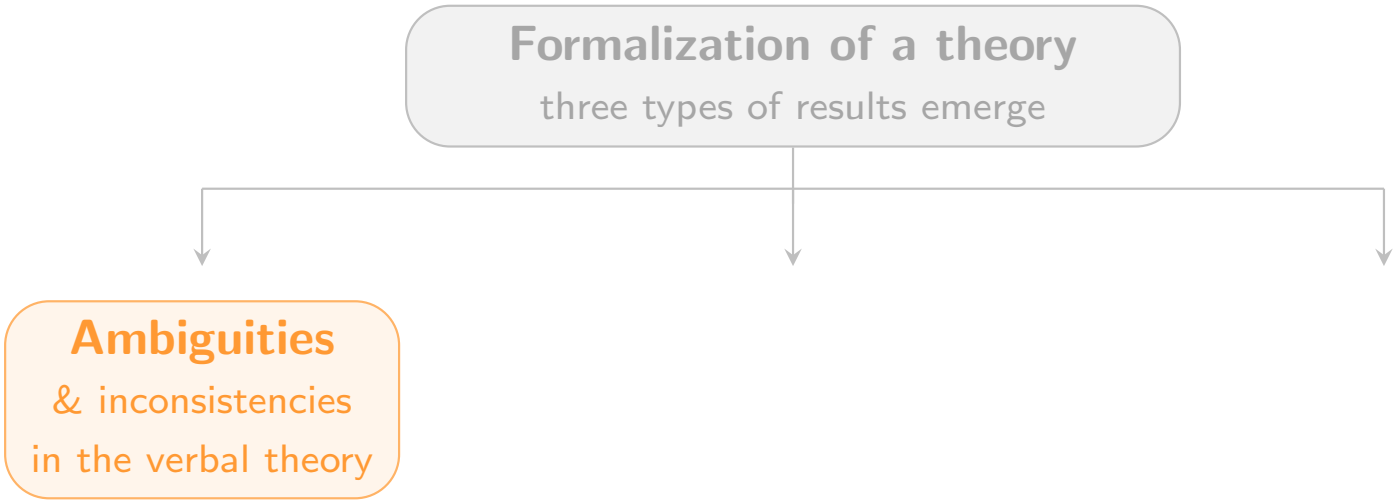
- Any **compatible** cognitive theory can be plugged in as a new module!

Application: Transactional Theory of Stress

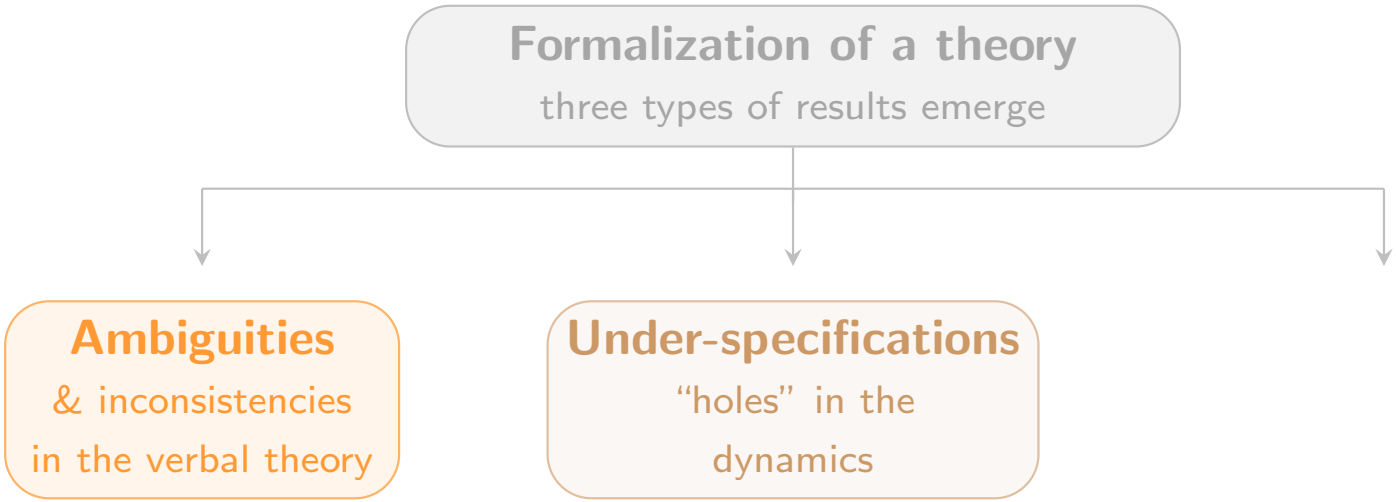
Formalization of a theory

three types of results emerge

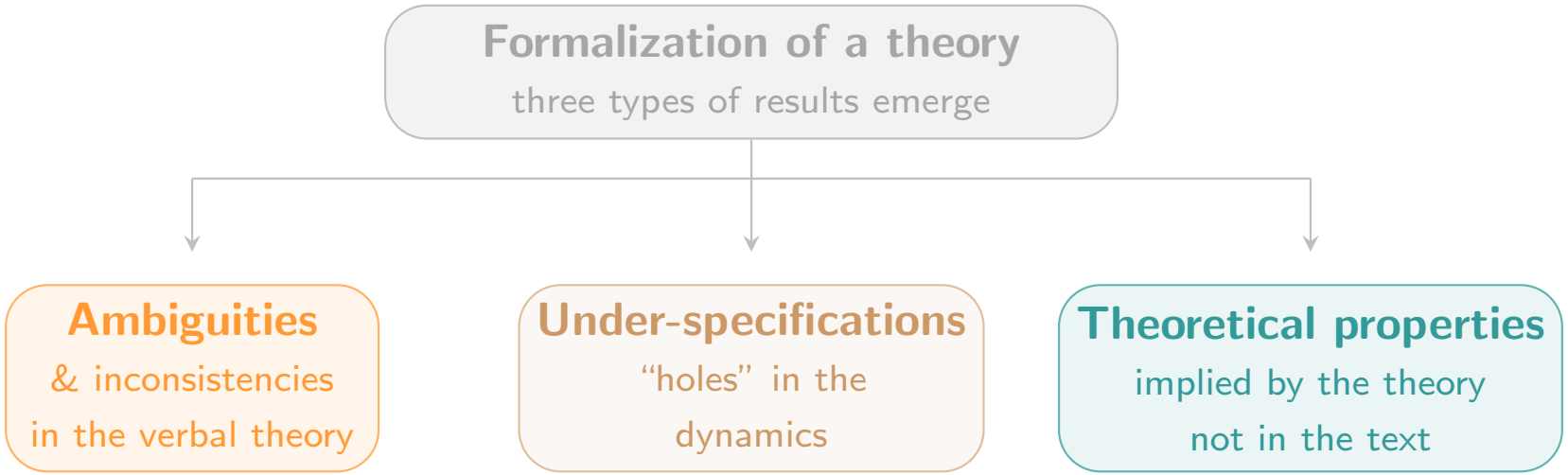
Application: Transactional Theory of Stress



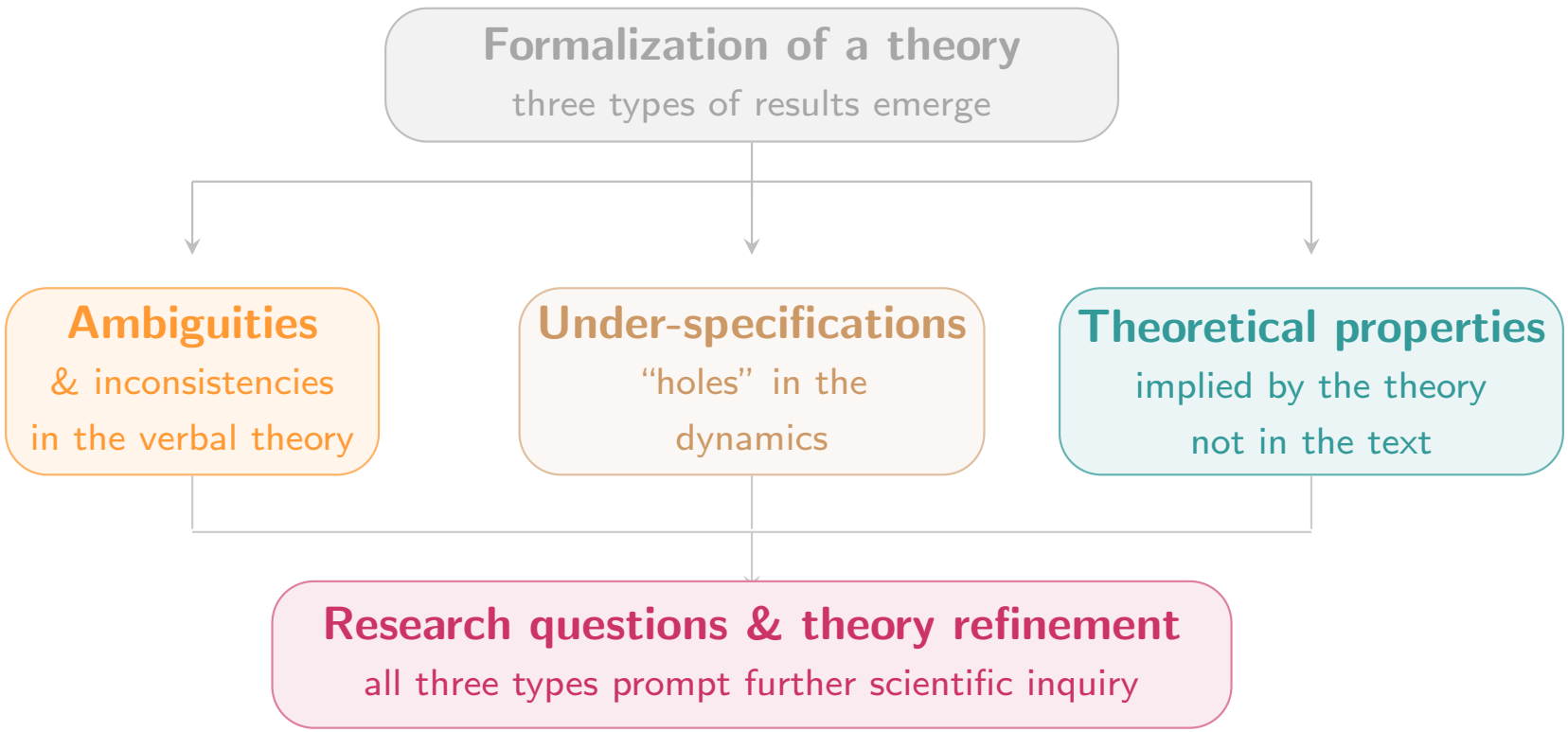
Application: Transactional Theory of Stress



Application: Transactional Theory of Stress



Application: Transactional Theory of Stress



Ambiguities

- Ambiguity in the definition of stress
- Order between primary and secondary appraisal
- What is the meaning of "continuous appraisal" ?

Under-specifications

- What happens outside of waking life?
- How is a coping strategy evaluated? Is an outcome imagined? Several? For how long? ...

Formalizing the Global Neuronal Workspace Theory

With communicating timed automata

Results of formalizing the GNW Theory (Mashour et al., 2020 · Dehaene & Naccache, 2001)

Ambiguities

Conscious threshold
During ignition, broadcast, or reception?

Threshold conditions
Attention + strength: sufficient?

Under-specifications

Exit from consciousness
When does it end?

Content transitions
One conscious state → next?

Ignition–broadcast delay
How long between them?

Minimum conscious time
Duration lower bound?

New property found

Double ignition

Attentional selection enters consciousness → GNW activates all object features

Ignition = sudden, exclusive activation, others inhibited

↓

Together imply:
2 ignitions per stimulus
"Preconscious" = features

Testable prediction ↗

Conclusion & Perspectives

Results:

- A frameworks to model psychological theories
- A methodology to translate verbal theories into formal models
- A formal model of the Transactional Theory of Stress
- Systematization of: detection of ambiguities, underspecifications, and new research questions
- Mathematical properties: completeness, refinement amounts to constraining.

Conclusion & Perspectives

Perspectives

- Add probabilities and build a methodology for generating predictions (work in progress)
- Create a **merging operator** to combine different theories
- Formally compare different theories
- Create a cognitive architecture by merging compatible theories
- Develop a **graphical interface** for modeling and model checking (UPPAAL / TCHECKER)

Conclusion & Perspectives

Also

Training sessions: building formal models with the framework
June 12th at ENS Paris-Saclay
June 16th (zoom)
One further date in July. Please send me an email if interested.

I am currently looking for a post-doctoral position

Conclusion & Perspectives

Group sessions!

Group 1: Room 2E34 / How do LLMs change research work in psychology? Give concrete examples.
Group 2: Room 2E35 / How can we use an LLM to study human cognition?
Group 3: Room 2X42 / Propose a psychological study that uses an LLM.
Group 4: Room 2X47 / Can we build a formal theory of a model from psychology? What are the obstacles?
Group 5: Room 2Z41 / How does formalizing a psychological model help us better study human behavior?

Conclusion & Perspectives

[1] Mashour, G. A., et al. (2020). Conscious processing and the global neuronal workspace Theory. *Neuron*, 105(5), 776–798.
[2] Lazarus, R. S., & Folkman, S. (1984). *Stress, Appraisal, and Coping*. Springer.
[3] Dehaene, S., & Changeux, J.-P. (2011). Experimental and theoretical approaches to conscious processing. *Neuron*, 70(2), 200–227.
[4] Meehl, P. E. (1978). Theoretical risks and tabular asterisks. *Journal of Consulting and Clinical Psychology*, 46(4), 806.
[5] Robinaugh, D. J., et al. (2021). Invisible hands and fine calipers: A call to use formal theory as a toolkit for theory construction.
[6] Alur, R., & Dill, D. L. (1994). A theory of timed automata. *Theoretical Computer Science*, 126(2), 183–235.
[7] Horn, F., & Sangnier, A. (2020). Deciding the existence of minority terms. *LICS*.