

Signalling to learn

**learning through sender-
receiver systems in the cell**

Ben Gaskin, University of Sydney



What is philosophical biology?

What is the relationship between biology and philosophy?

What is the proper relationship between philosophy of biology and biology?

DiFrisco argues it ought to engage with biology directly—hence why I’m here.



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[Overview Article](#)

Biology Needs Philosophy, But What Philosophy?

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Abstract

Philosophy of biology has the potential to contribute to biology by improving scientific reasoning. However, this potential is largely unrealized because of the lack of awareness by most biologists of what philosophy can offer, because of deficits of biological expertise among most philosophers, and because of adherence to disciplinary norms in philosophy that render much work in philosophy of biology irrelevant to biologists. We believe that philosophy of biology will contribute little to biology without a change of practice. We provide guidelines (“comments” *sensu* Slobodkin 1975, “commandments” *sensu* Kornberg 2000, 2003, Francis et al. 2007) for how biologists can better engage with philosophy and for how philosophers can better engage with biology so as to create a “philosophical biology” that improves our biological understanding.

Keywords: philosophy of biology, theoretical biology, cell biology, evolutionary biology, philosophical biology

Philosophy and science were once intertwined as “natural philosophy” (e.g., see Blair 2006, Grant 2007). Vestiges of this union can still be found in the journal titles *Philosophical Transactions of the Royal Society* and *Biological Reviews of the Cambridge Philosophical Society*. Although philosophy and science are now largely separate, we believe that something like “natural philosophy” can exist today and would improve the practice of science. Here, we focus on biology and philosophy of biology (POB) and how to create from them a “philosophical biology” that generates new and improved insights into nature.

In biology, there is increasing recognition of the need for guiding concepts and integrative theory (Phillips 2015, Nurse 2021, Levenstein et al. 2023, MacArthur 2023, Salguero-Gómez et al. 2024). The contribution of philosophers of biology to meeting this need could include connecting various kinds of knowledge, improving clarity of thought, and improving the formulation of biological hypotheses. Some have recently argued on these grounds that “science needs philosophy” (Laplane et al. 2019, p. 3948, Pradeu et al. 2023, Heger et al. 2024). However, the obstacles to philosophers of biology meeting the need for theory and concepts in biology are much greater than the advocates of integration suggest. Although many philosophers endorse “naturalism” (the view that science provides evidence and thus has authority over philosophy on topics of overlapping interest such as the nature of matter or evolution; see Papineau 2023), the idea that “science needs philosophy” appears to have little acceptance among biologists and other scientists.

We describe how attitudes and incentives within biology discourage engagement with conceptual and theoretical issues. We also describe why most POB is of little use to biologists due to deficits of biological knowledge on the part of the philosophers and because most work is tied to philosophical traditions that are irrelevant to biology. Philosophers of biology have tended to create a “duplicate space” of concepts that originate in biology but is too tenuously connected to biology to contribute to it. With the intention of improving the situation, we propose “comments” or metaphorical “commandments” (*sensu* Slobodkin 1975, Kornberg 2000, 2003, Francis et al. 2007, Elmer et al. 2017, Hulsén 2019,

Turner 2020, Silva et al. 2021, Lyach 2022) for biologists and for philosophers who wish to contribute to philosophical biology. In doing so, we echo Francis and colleagues (p. 217) “...our humble intention is to stimulate much needed discussion.” Hereafter, we refer to these as “suggestions.”

Why biology is not well connected to philosophy of biology

It is sensible to think that conceptual work in biology should be done by biologists. However, biology does not provide enough of this work to meet its needs (Woese 2004, Galas et al. 2008, Phillips 2015, Goldstein 2018, Nurse 2021, Levenstein et al. 2023, MacArthur 2023, Medzhitov 2026). We believe there are three reasons why this is the case.

The first is the attitude common among biologists that biology is primarily about the description and explication of facts about nature, such as how photosynthesis works. All biological investigations have a conceptual framework, but most often it is unacknowledged especially in print, as can be seen by perusal of an issue of, say, *Nature* or *Science*. This is especially true in cellular and molecular biology. Conceptual discussions in print are somewhat more common in ecology and evolutionary biology (e.g., Byrnes and Dee 2025, Nichols and Cooch 2025), but even there, conceptual discussions have often been disparaged by biologists who assert that the choice among different definitions of a concept is “arbitrary” or “semantic.” For example, Dobzhansky (1957, p. 235) writes of a controversy about the regulation of population size:

To a non-ecologist, the controversy which has made our session so lively is, I confess, somewhat bewildering. I have had a feeling for several years now that this is a controversy chiefly about words, about “semantics,” to use a fashionable word. Having tried to the best of my ability to understand the issue involved, I still continue to feel that way.

Dobzhansky later states that the controversy is not “futile” and that it stimulates “a lot of interesting research” but here

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What is learning for a single cell?

Definitions of learning

“Disciplines differ in their specific definitions of learning for pragmatic reasons, but it is possible to reconcile most of these definitions by reference to a common theoretical framework: **learning as a structured updating of system properties based on the processing of new information.**”

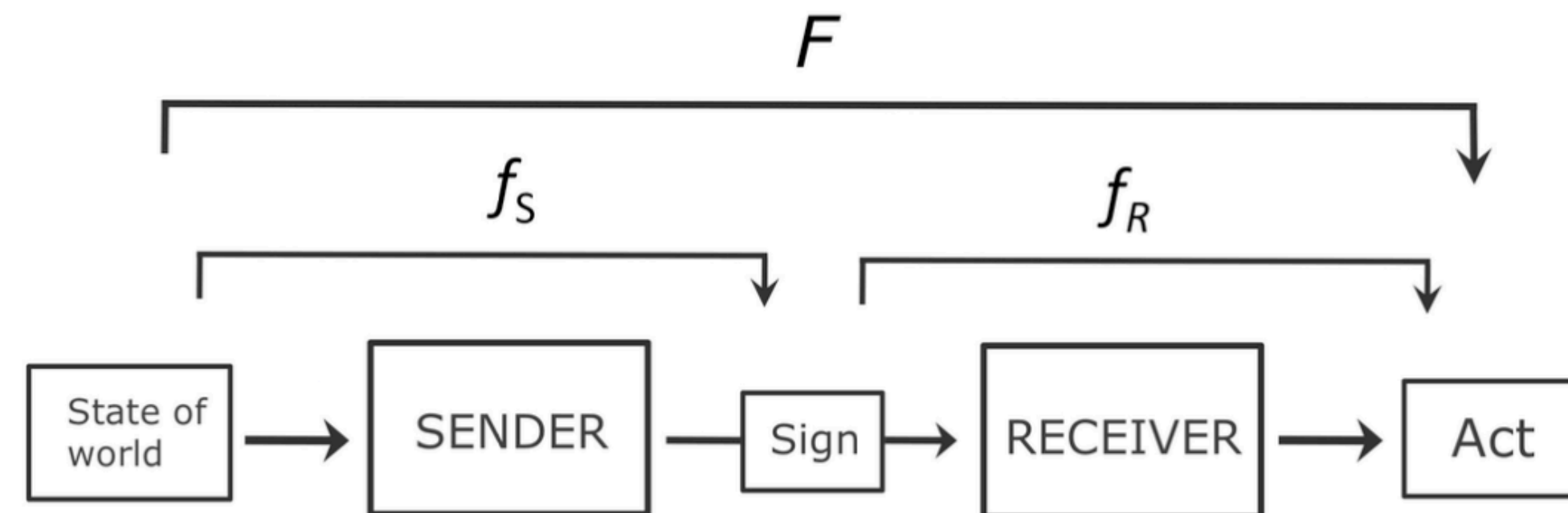
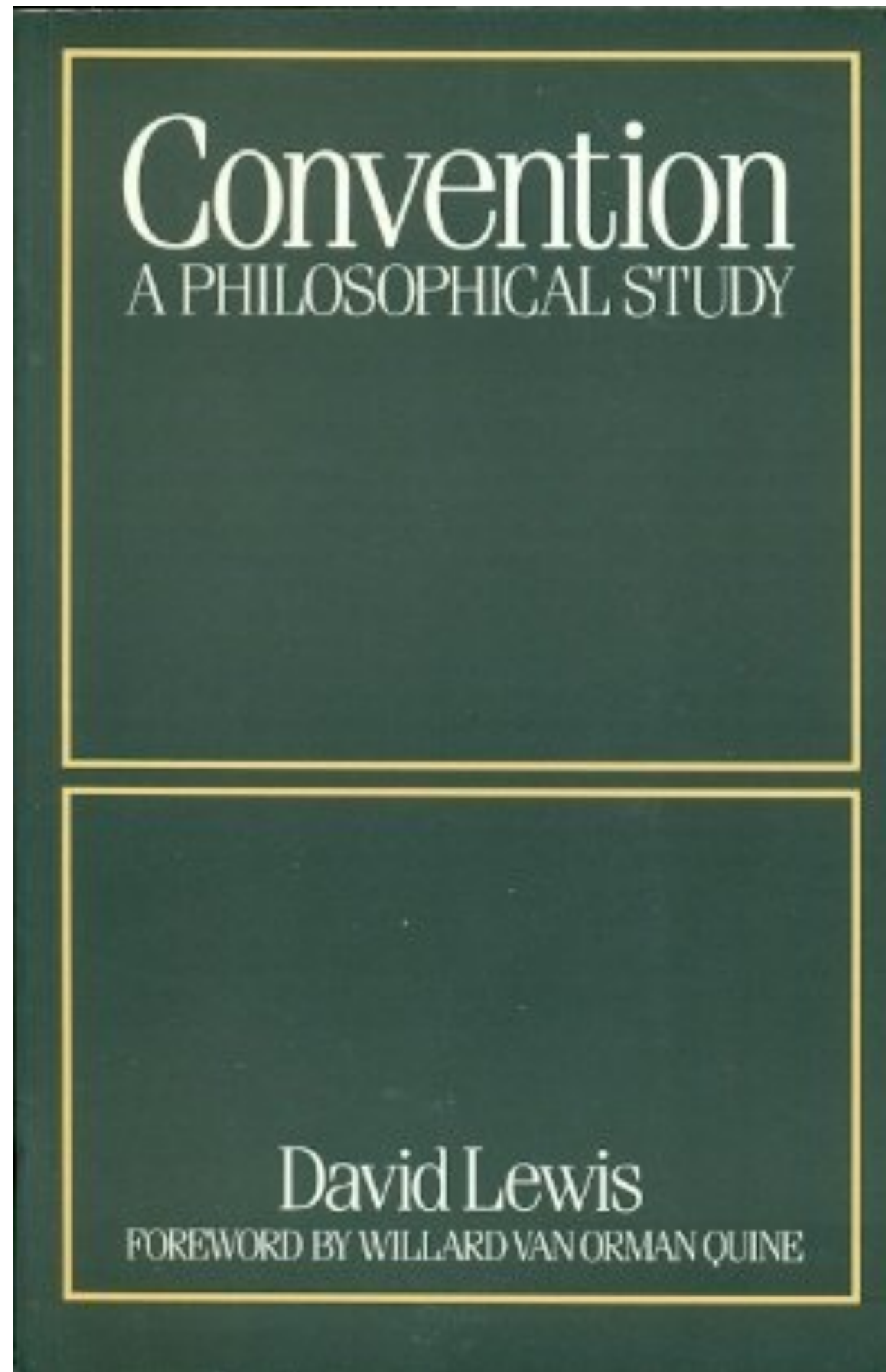
—Barron et al., 2015

Defining learning in terms of signalling topologies

Definitions should be:

- Neither overly exclusive nor inclusive
- Exclude non-learning history dependence
- See continuity with other types of learning

Signalling as a coordination problem



f_S : sender's rule, maps states of the world to signs.

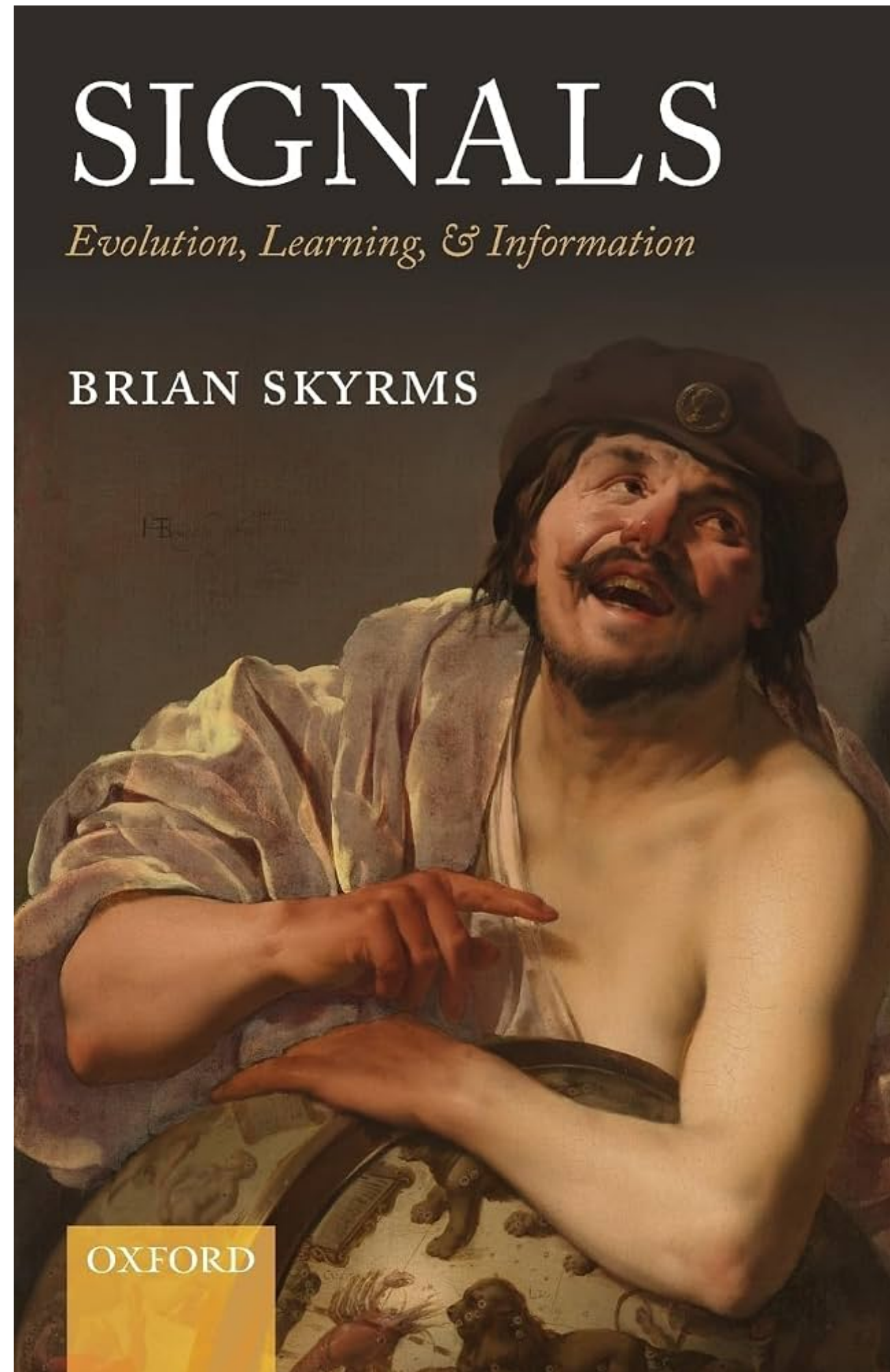
f_R : receiver's rule, maps signs to acts.

F : the resulting mapping from states to acts.

F^* : the mapping from states to acts preferred by both agents.

Godfrey-Smith, 2012

Signalling as a coordination problem



“This set-up can also be seen as a solution to a particular kind of problem of control: pairing behavior usefully with states of the world, dealing with the environmental contingency of effective action.”

—Godfrey-Smith, 2012

Skyrms describes learning to signal, but what about signalling to learn?

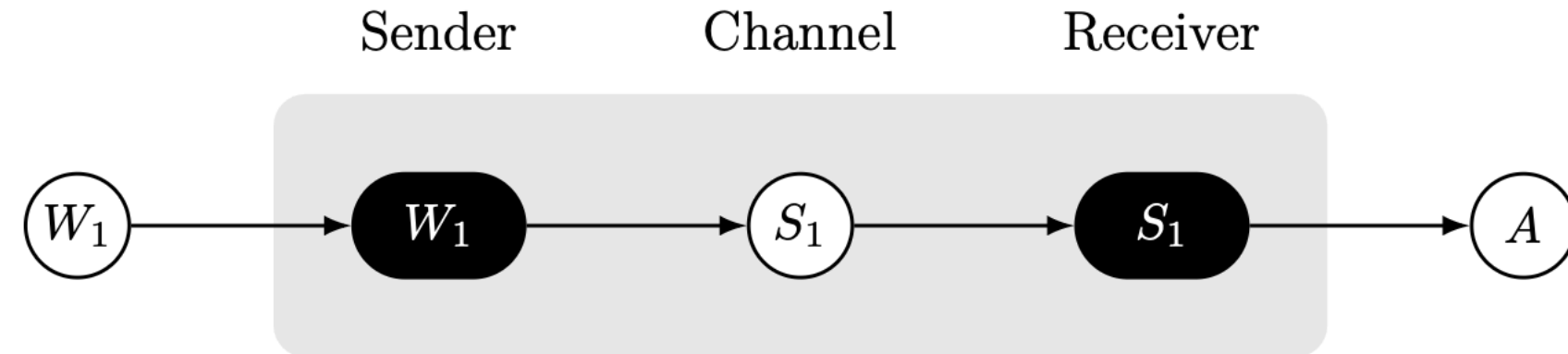
“Present selves have access to information that will be useful to the guidance of action by future selves, so present selves lay down marks that can be consulted later. Memory is sending messages over time.”

—Godfrey-Smith, 2012

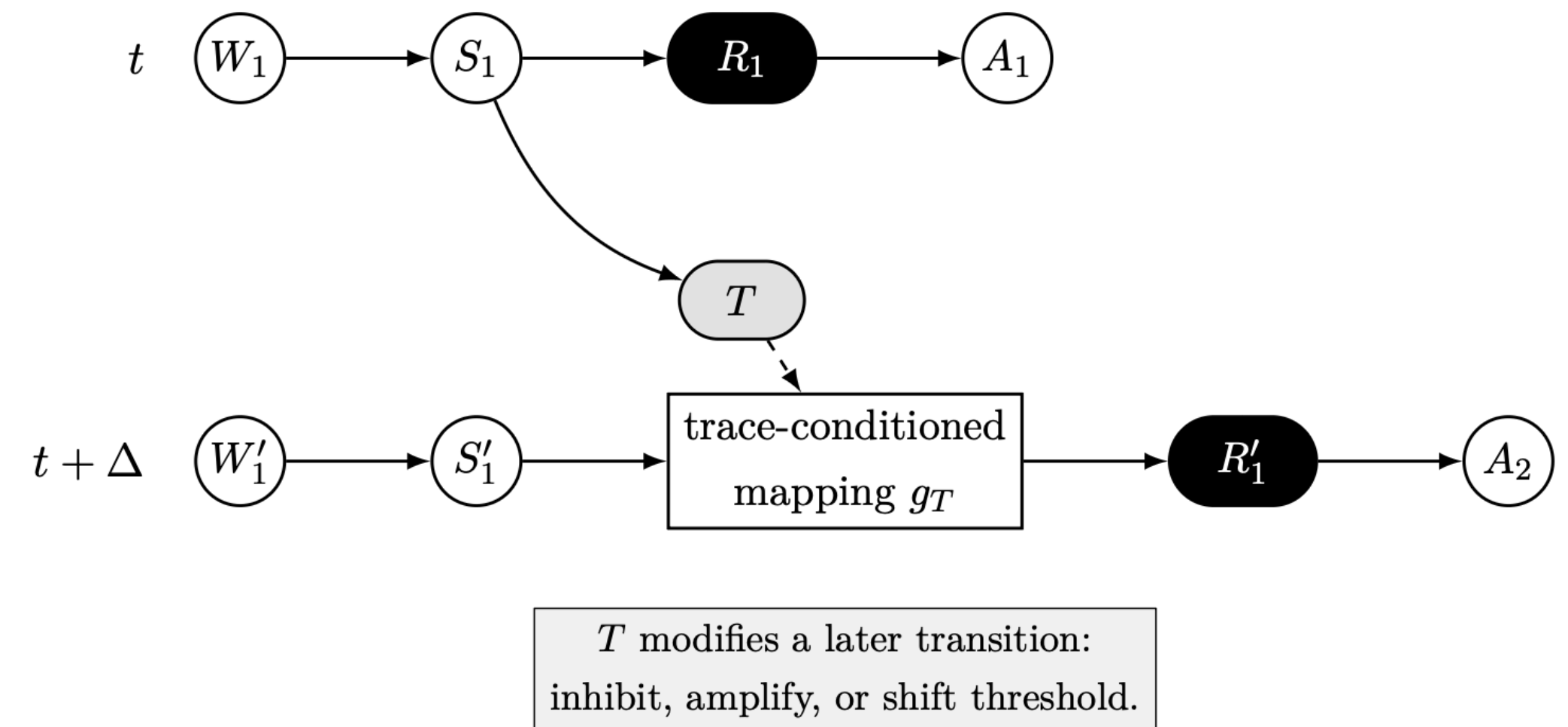
Learning as second-order signalling

Godfrey-Smith distinguishes between two orders of behavioural complexity—

First-order: behaviour is **conditional based on the environmental state**.

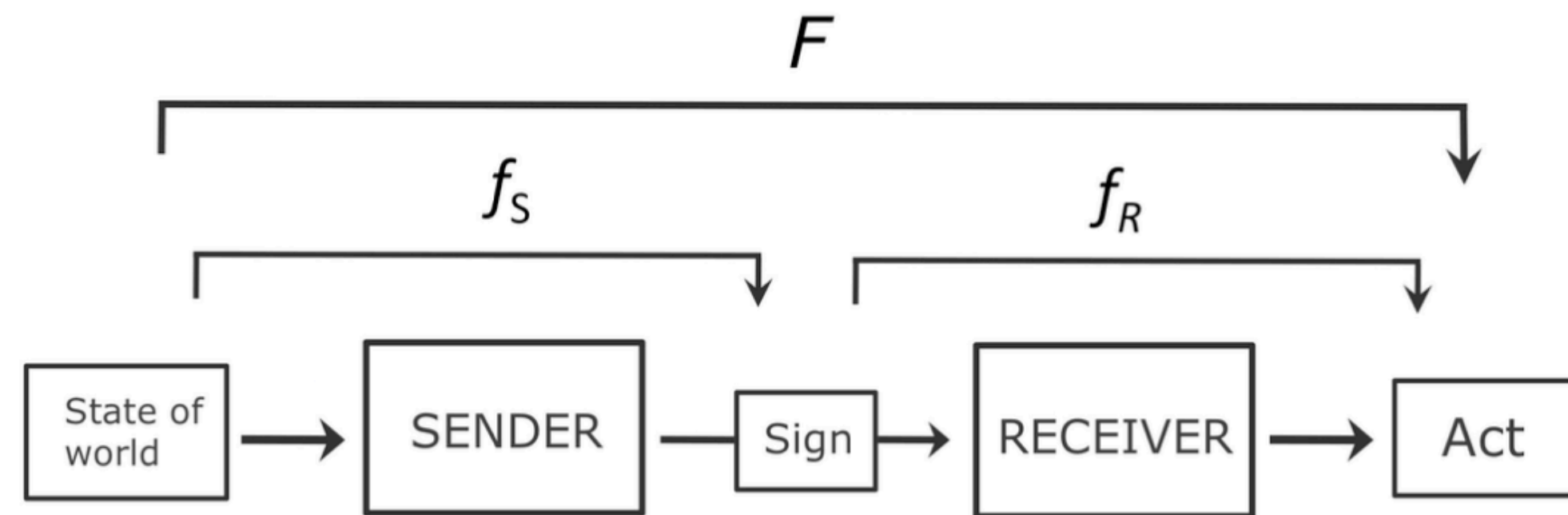


Second-order: **conditionals are themselves conditionally variable**.



Can we apply signalling games to cells?

What is the essence of a sender-receiver configuration?



f_s : sender's rule, maps states of the world to signs.

f_R : receiver's rule, maps signs to acts.

F : the resulting mapping from states to acts.

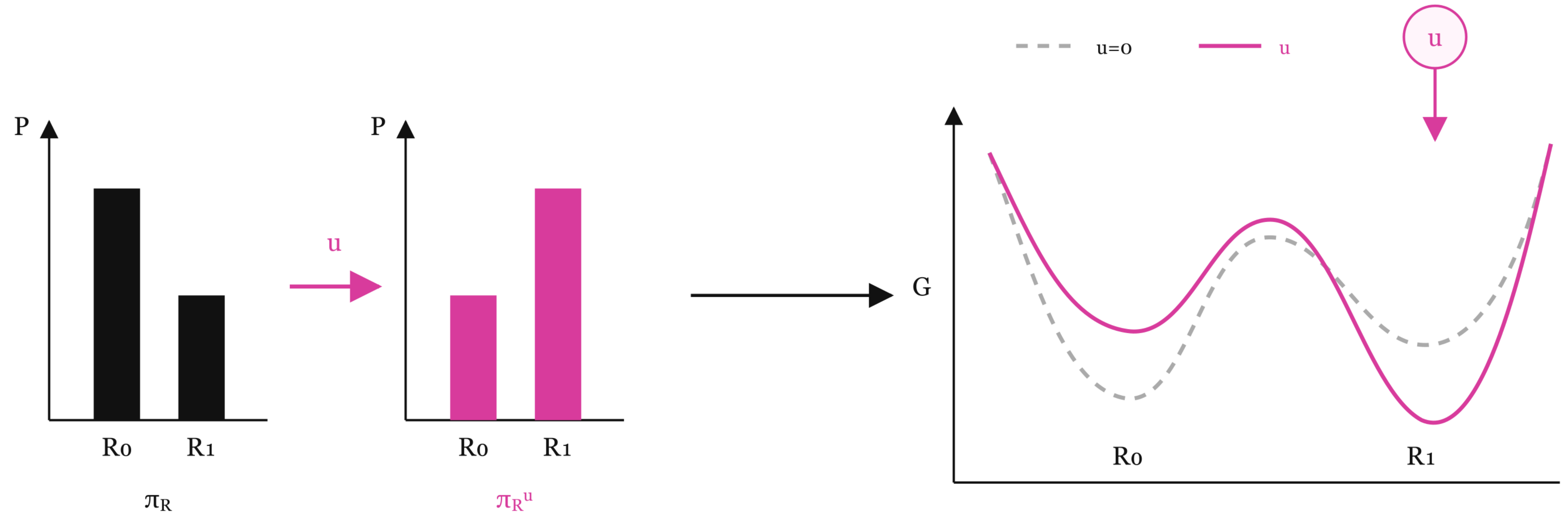
F^* : the mapping from states to acts preferred by both agents.

Godfrey-Smith, 2012

- 1. Differential susceptibility
- 2. Conditional dependence
- 3. Tuneable mappings

This structure is selected for based on the history of the system, whether by learning, evolution, or rational agents.

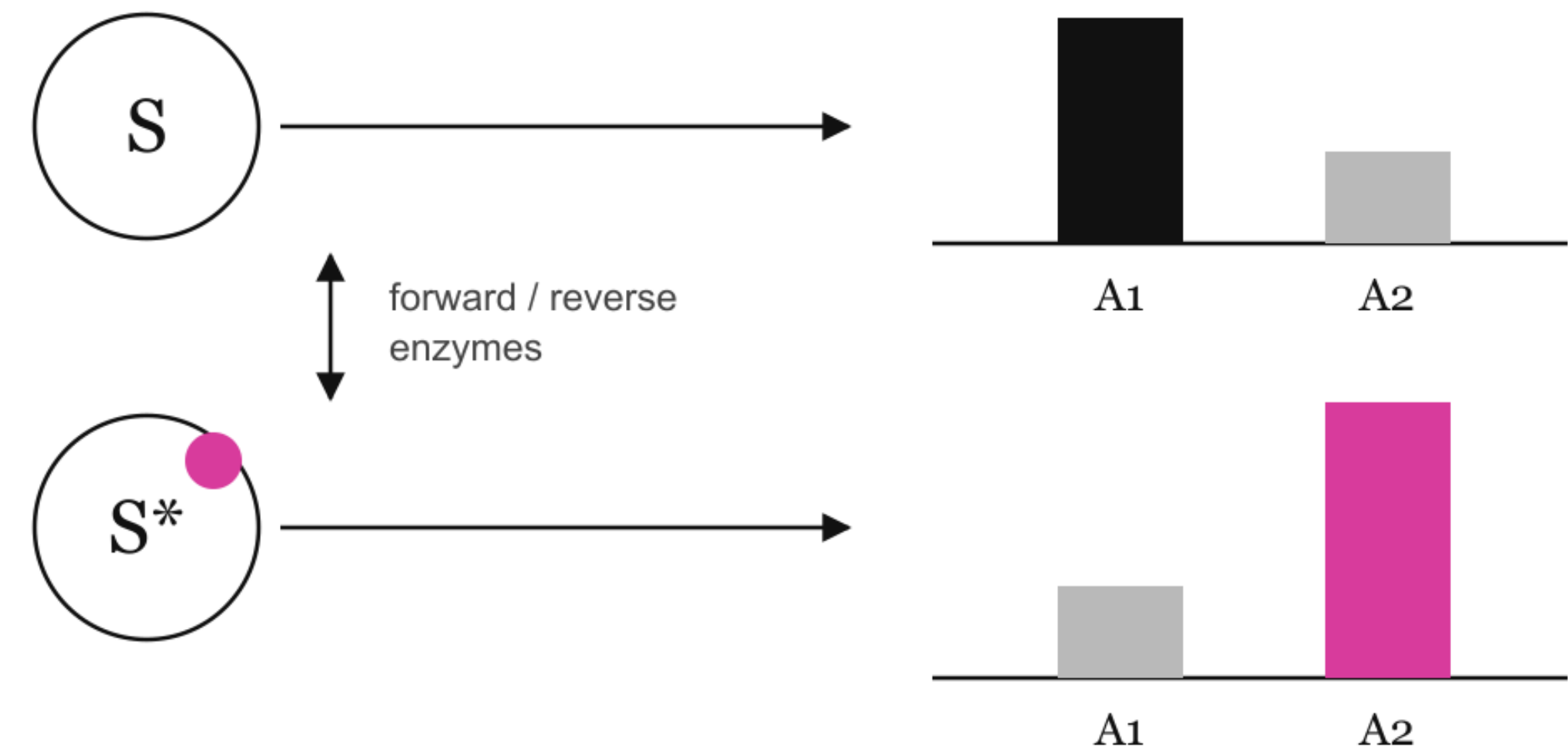
Information as a change in conditional probabilities



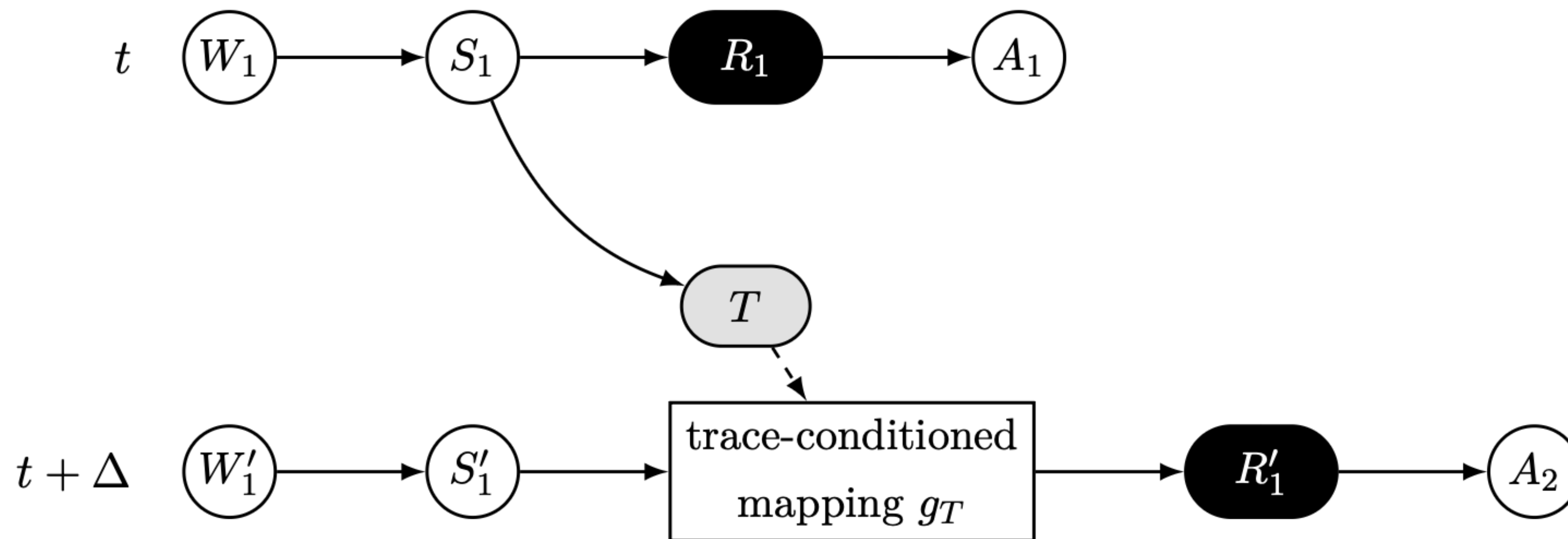
Biochemical signals modify conditional dispositions

“What has been affected ... is not necessarily what you do ... but rather what you would be ready to do if given (relevant) circumstances arose.”

—MacKay, 1969

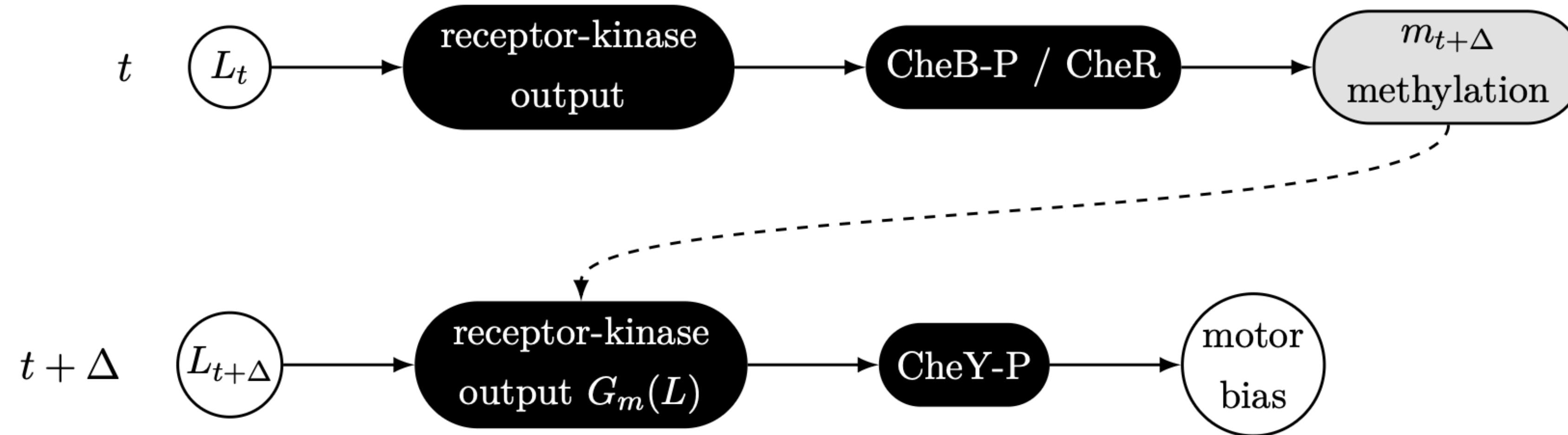


Minimal learning in E. coli chemotaxis



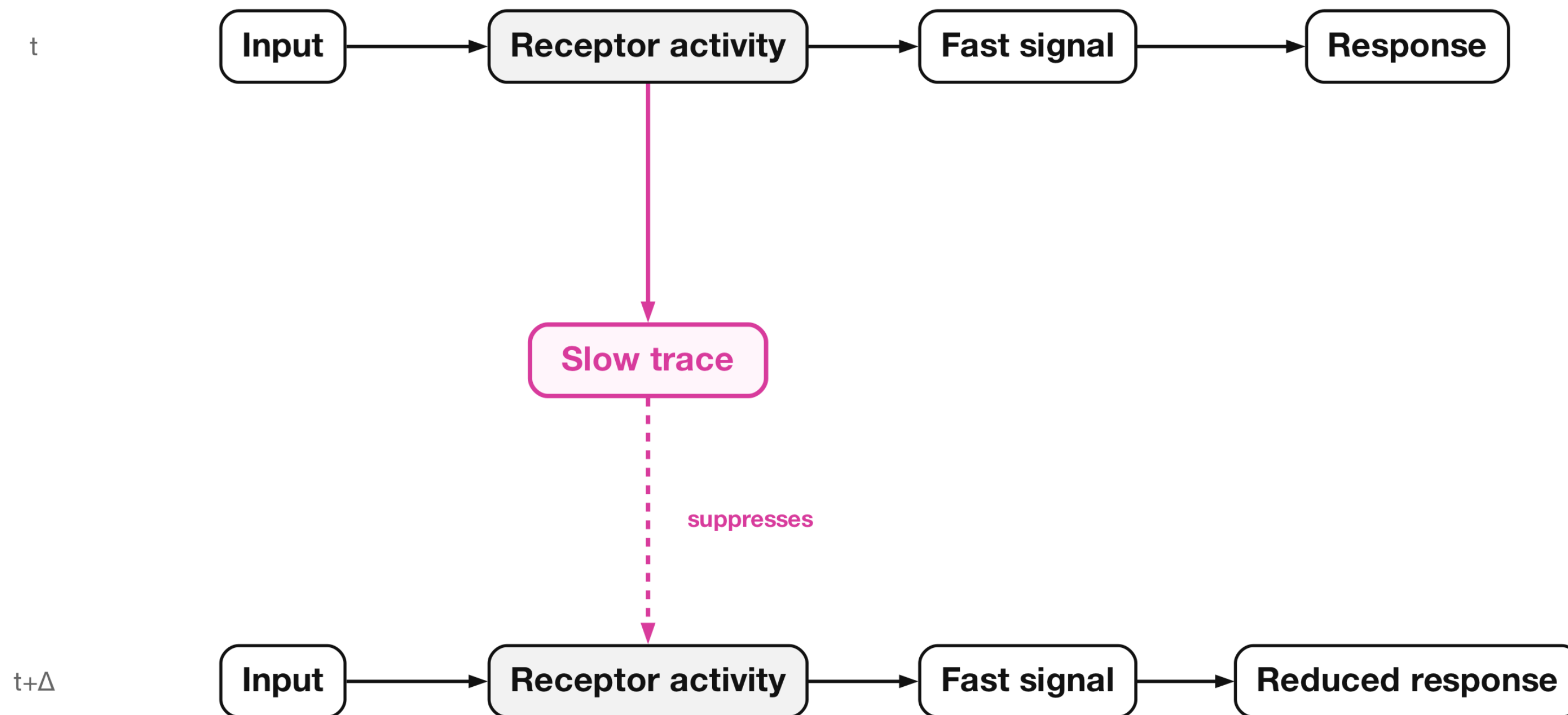
T modifies a later transition:
inhibit, amplify, or shift threshold.

Minimal learning in E. coli chemotaxis

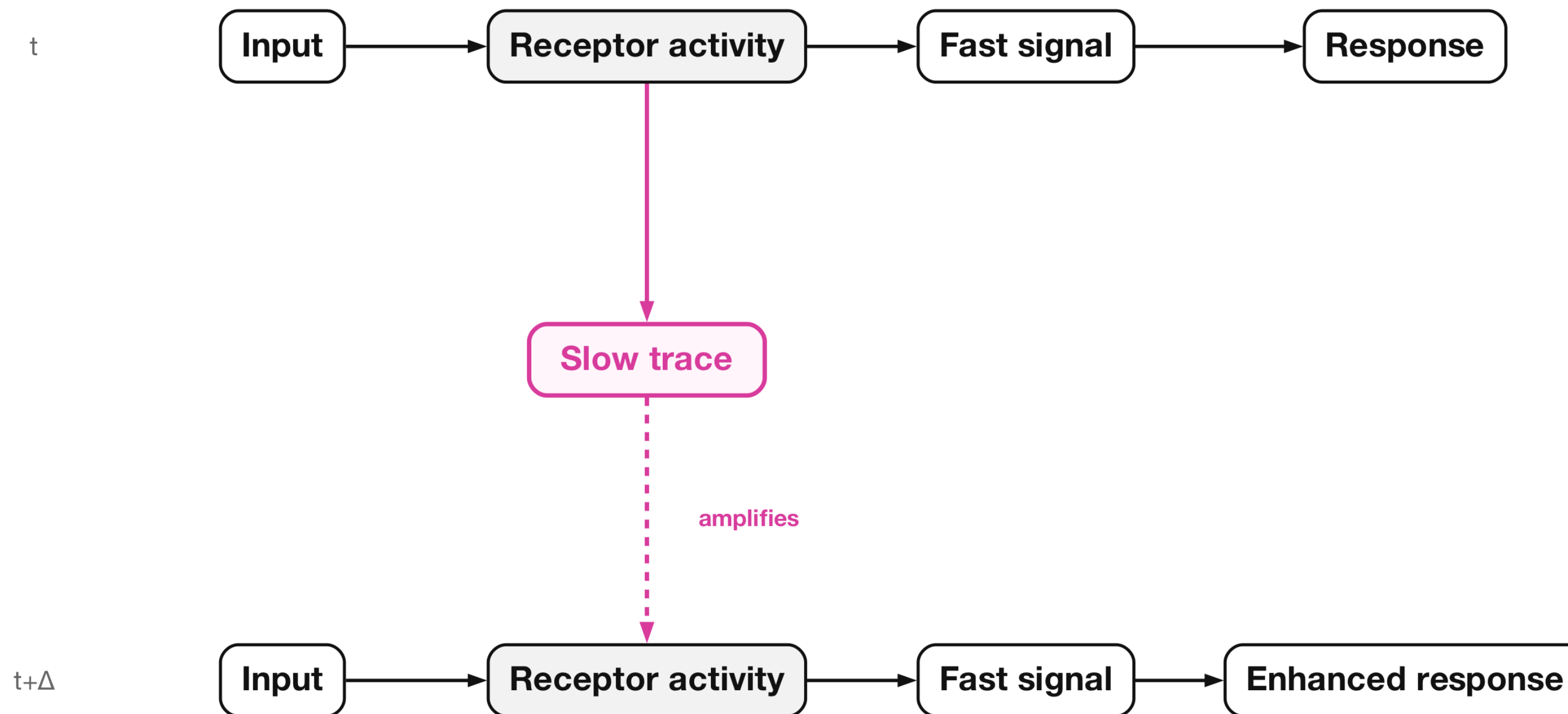


How can we define learning in these terms?

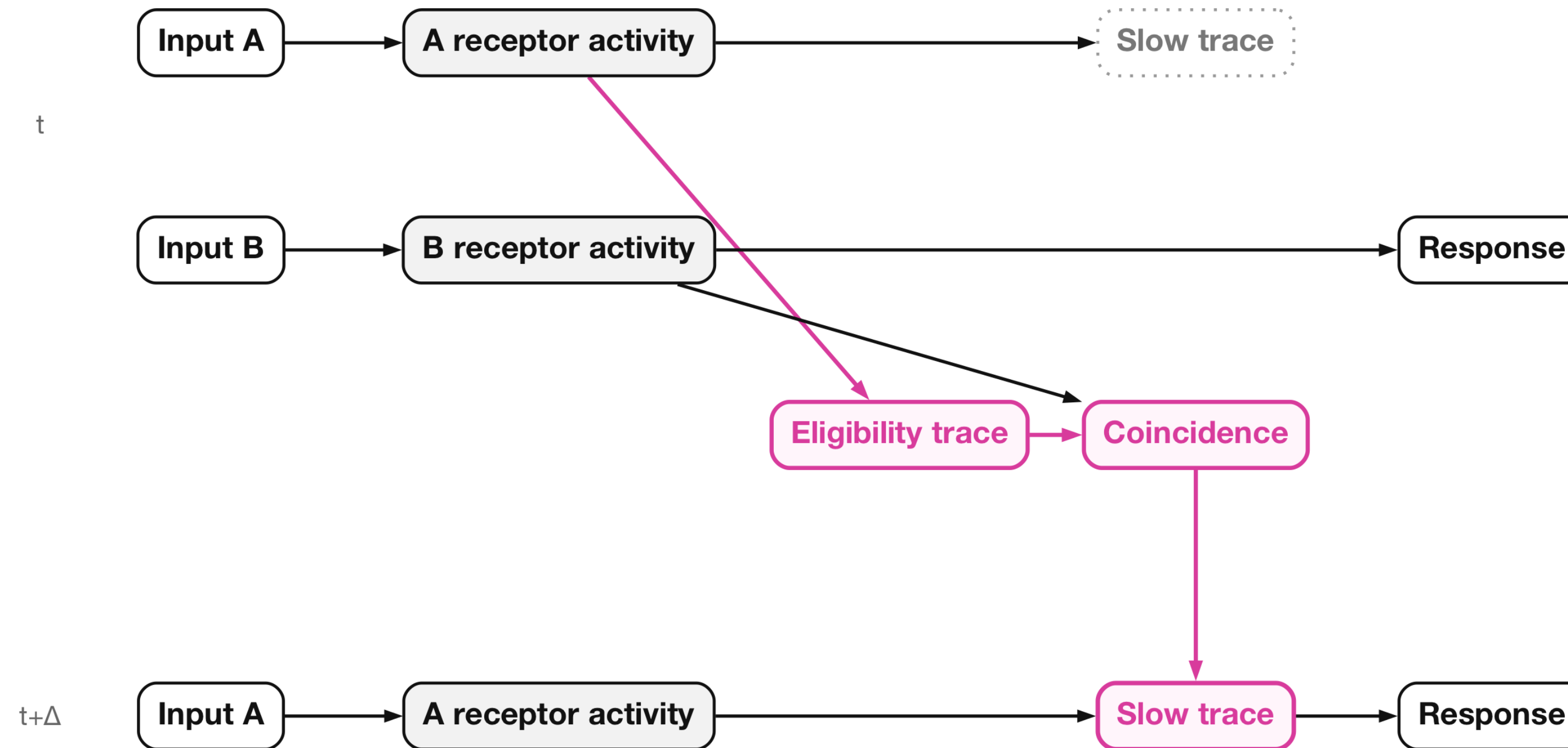
Continuity between subtypes of learning: habituation



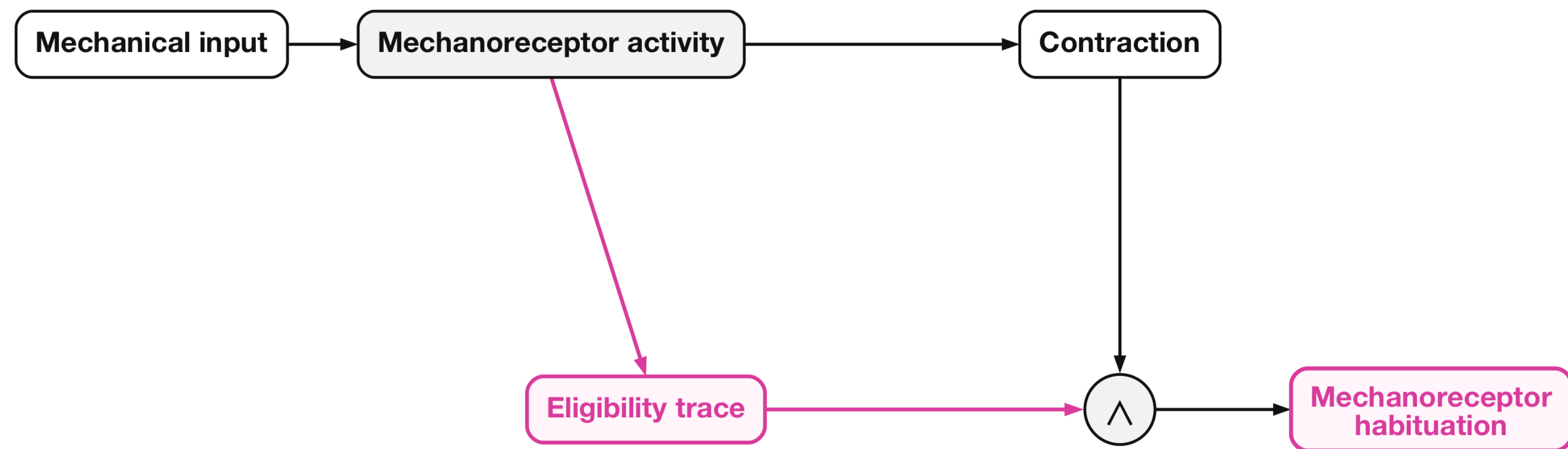
Continuity between subtypes of learning: sensitisation



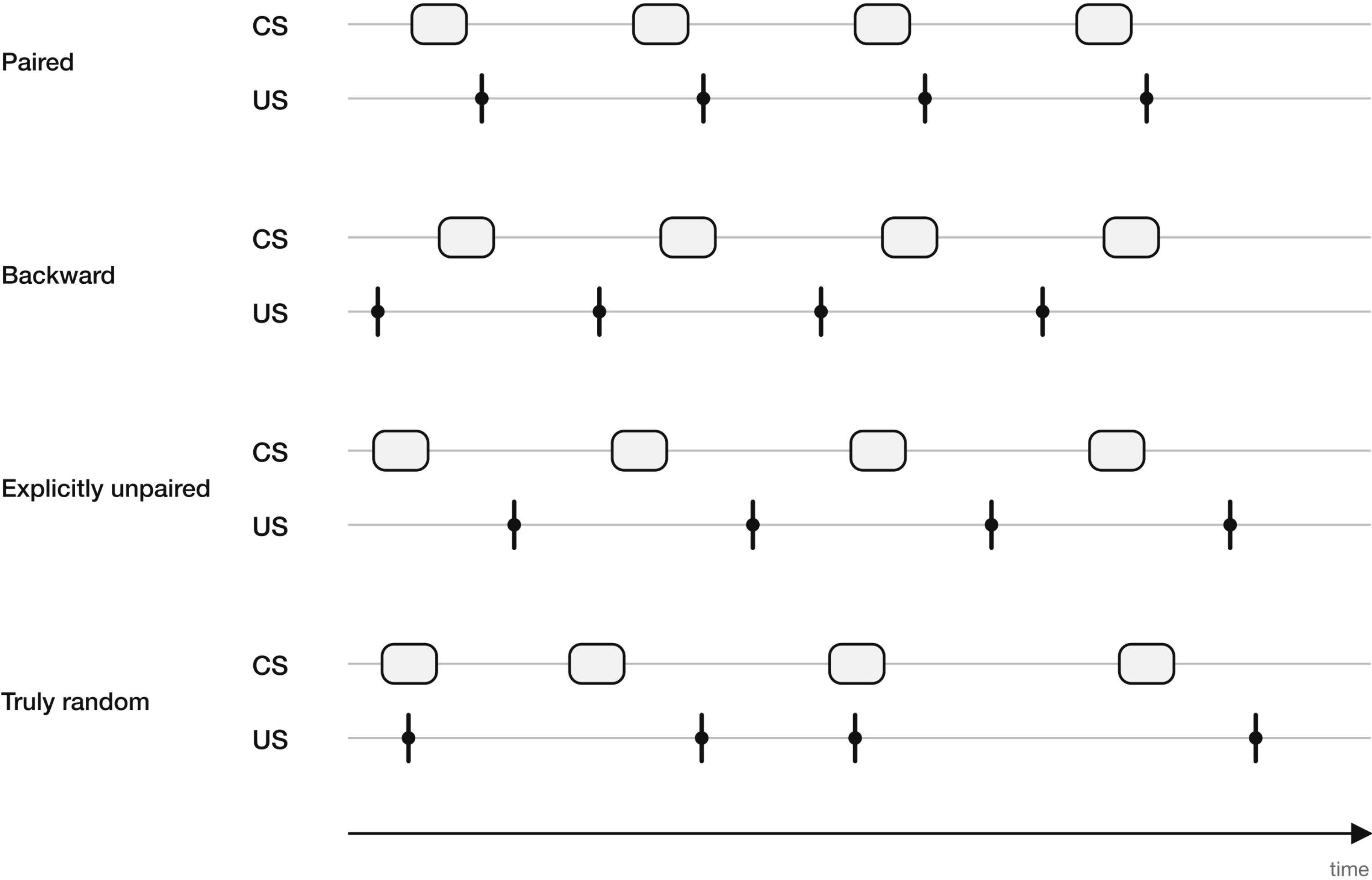
Continuity between subtypes of learning: association



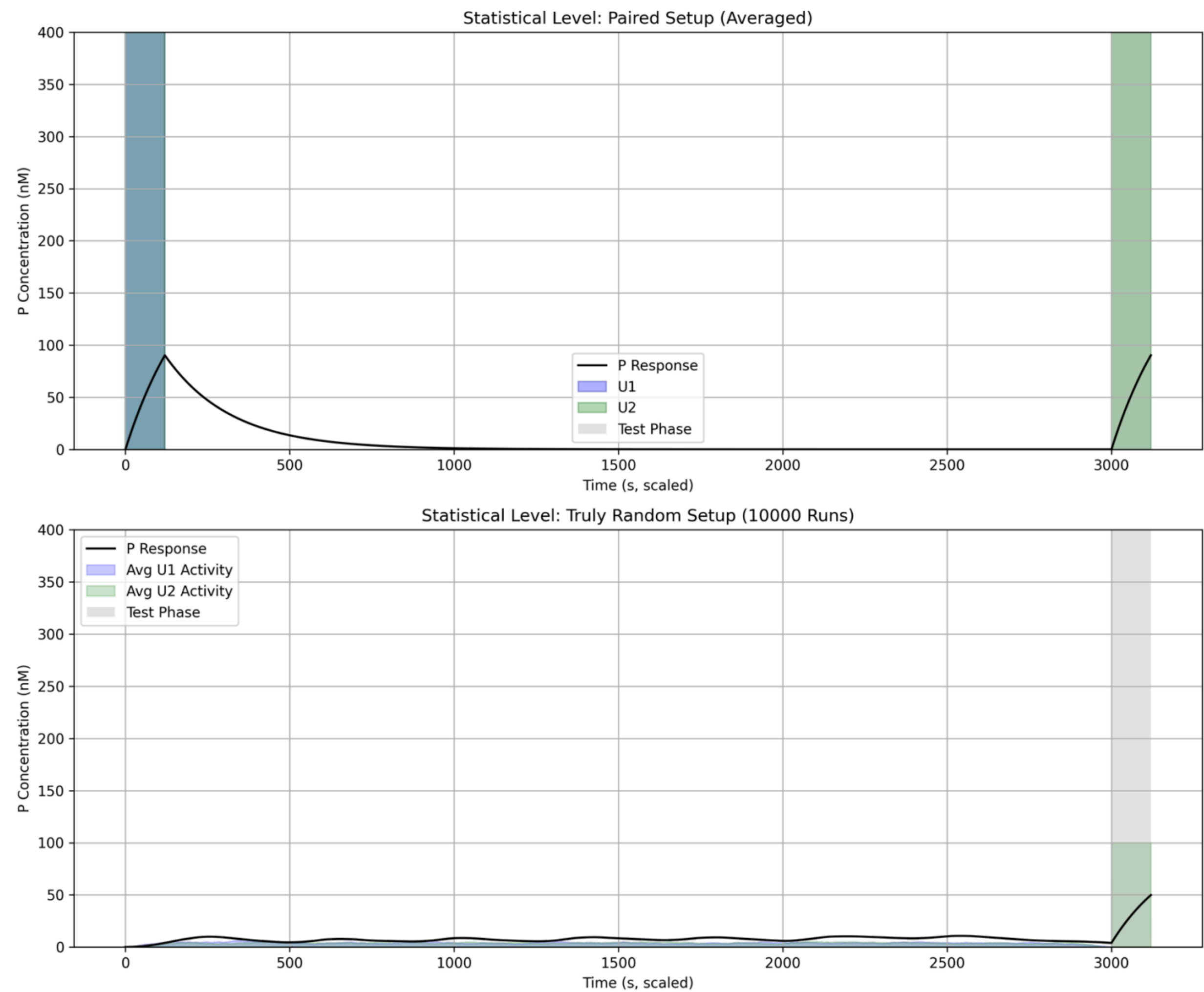
Stimulus specificity may require coincidence detection



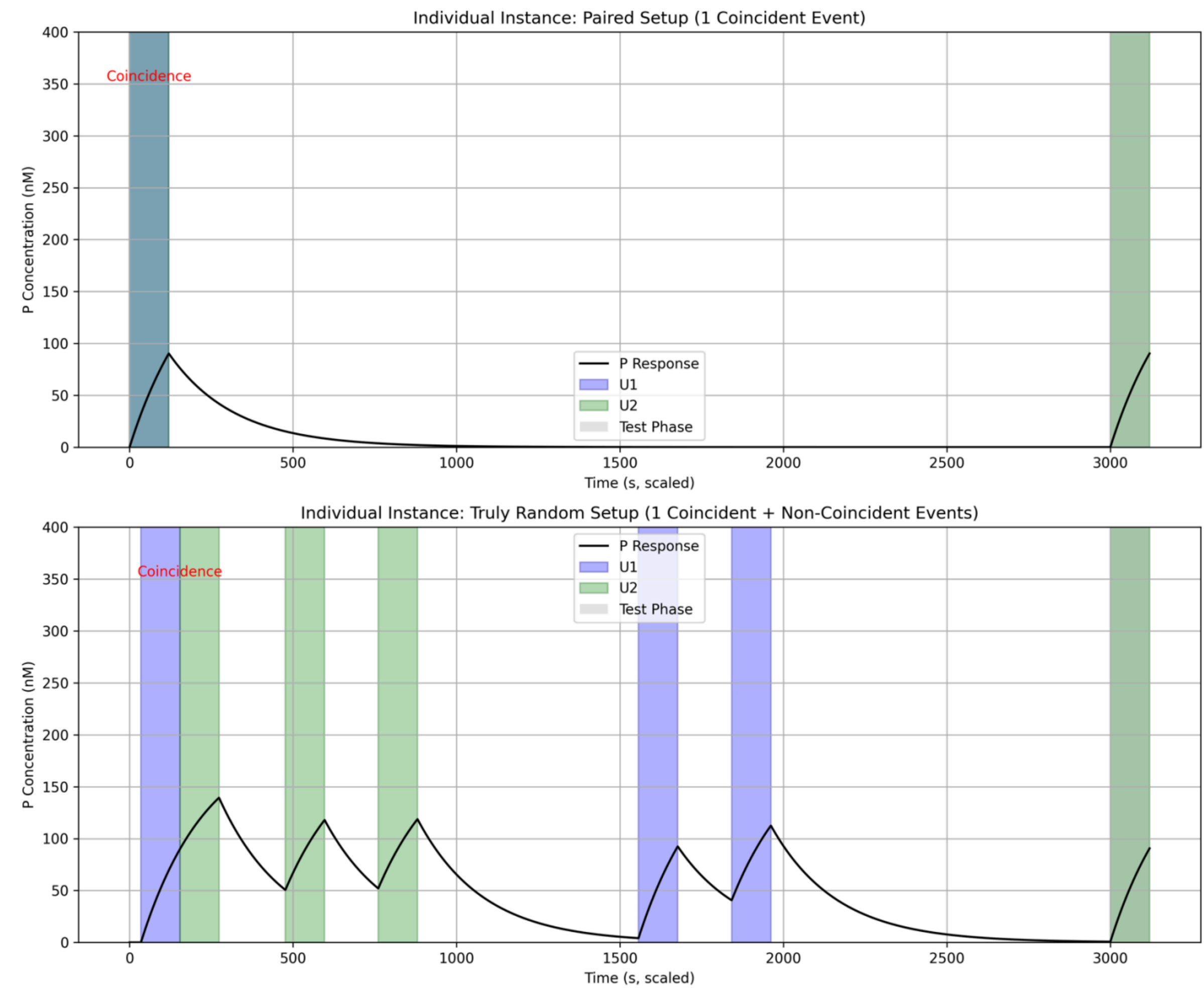
Discontinuities within subtypes: coincidence vs. contingency



Discontinuities within subtypes: coincidence vs. contingency



Discontinuities within subtypes: coincidence vs. contingency

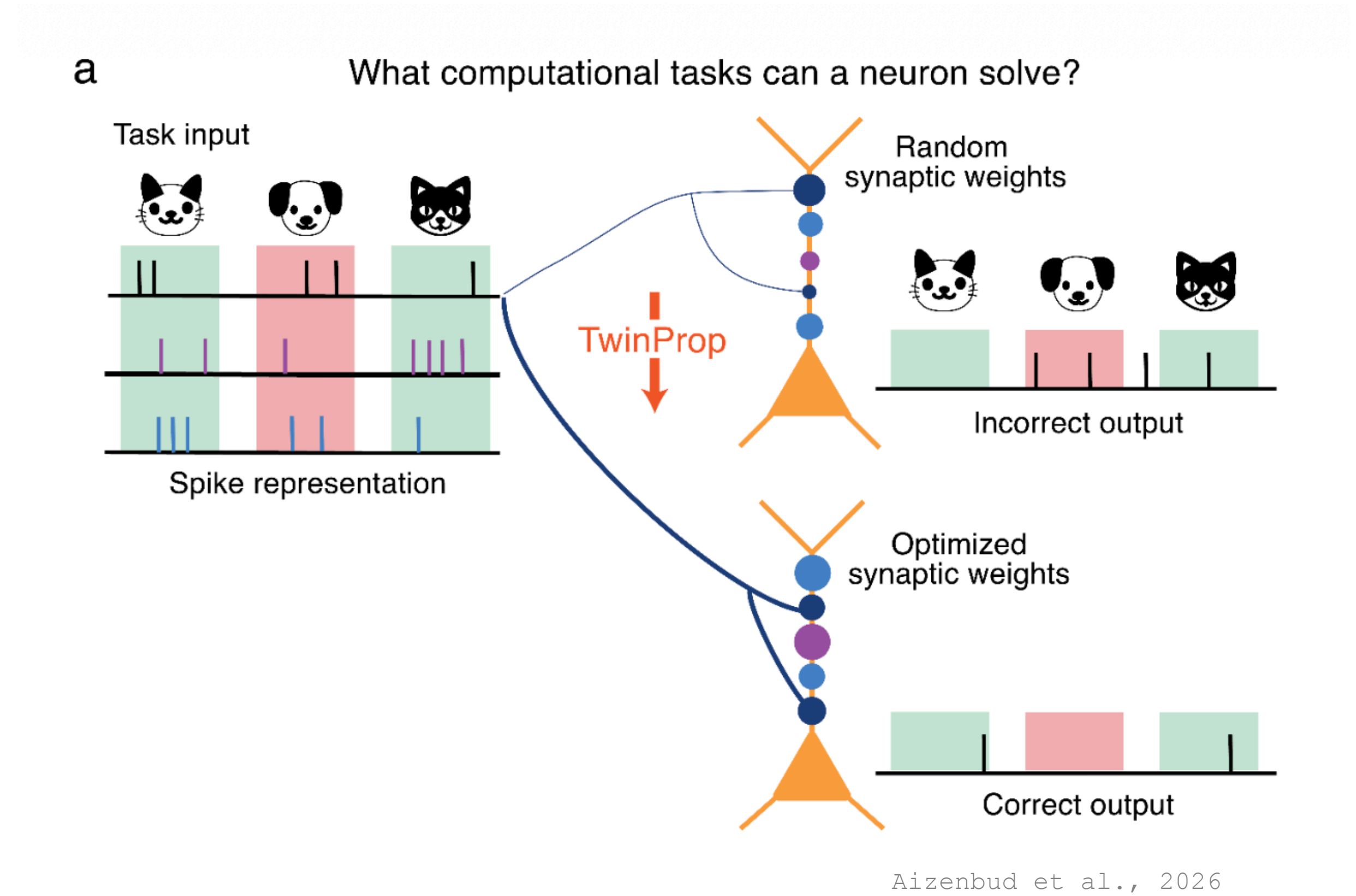
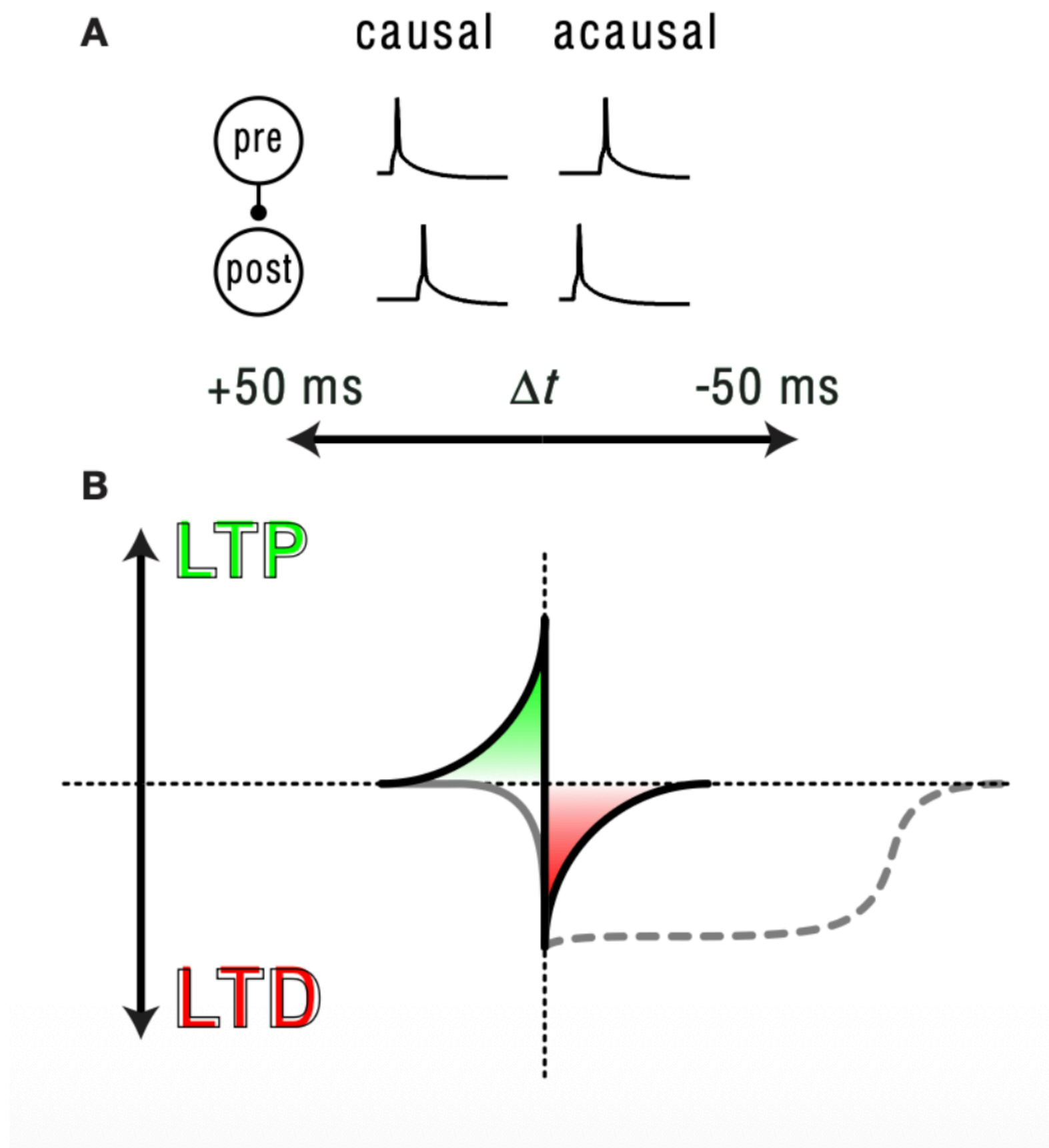


What about learning in metazoan cells?

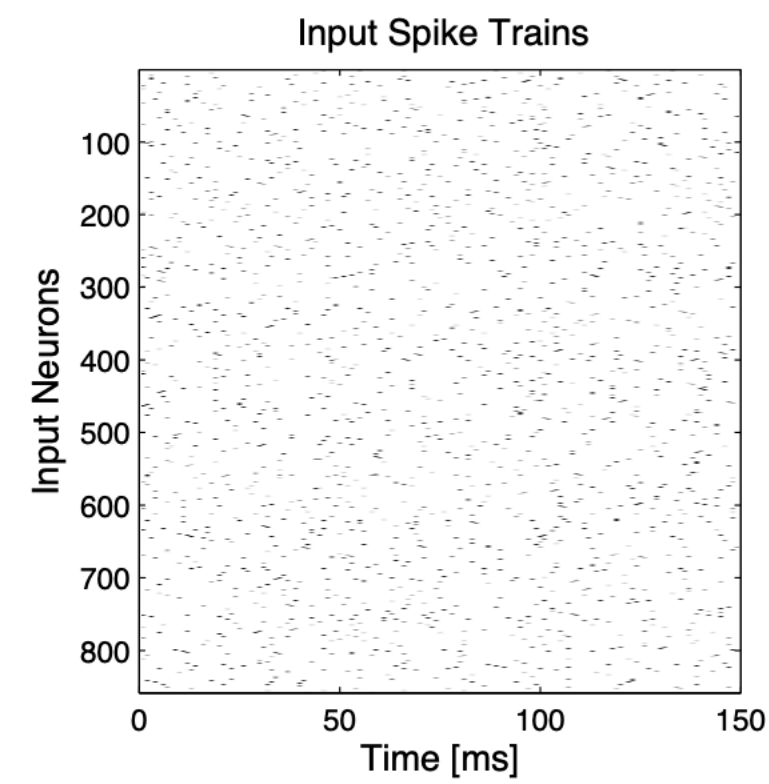
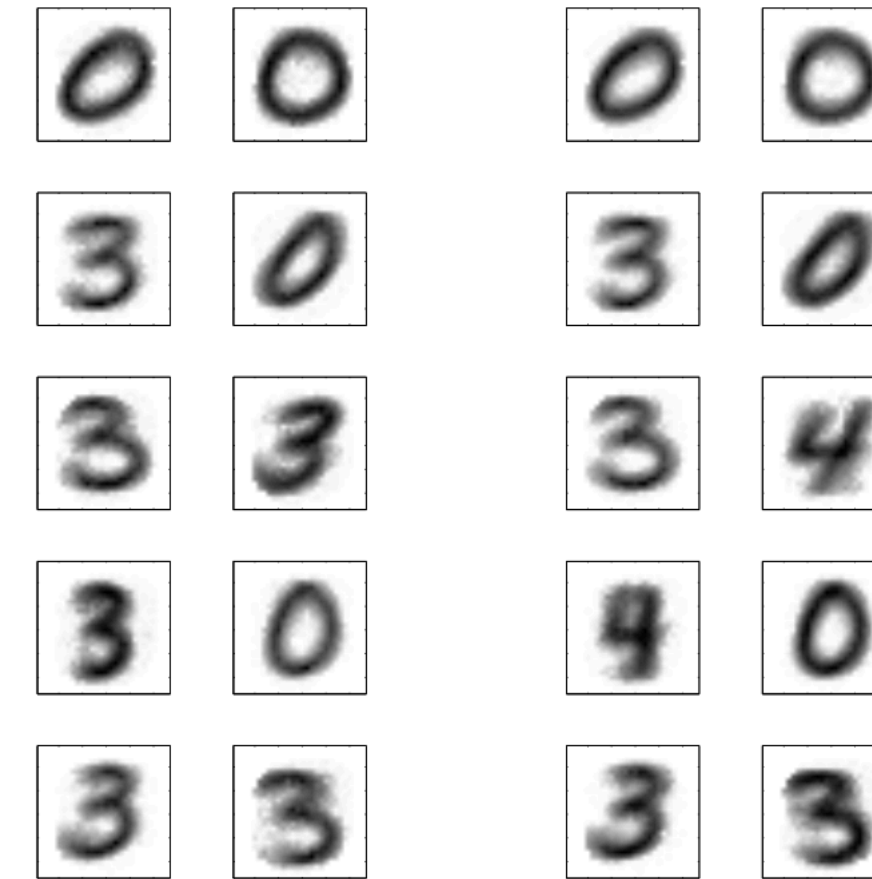
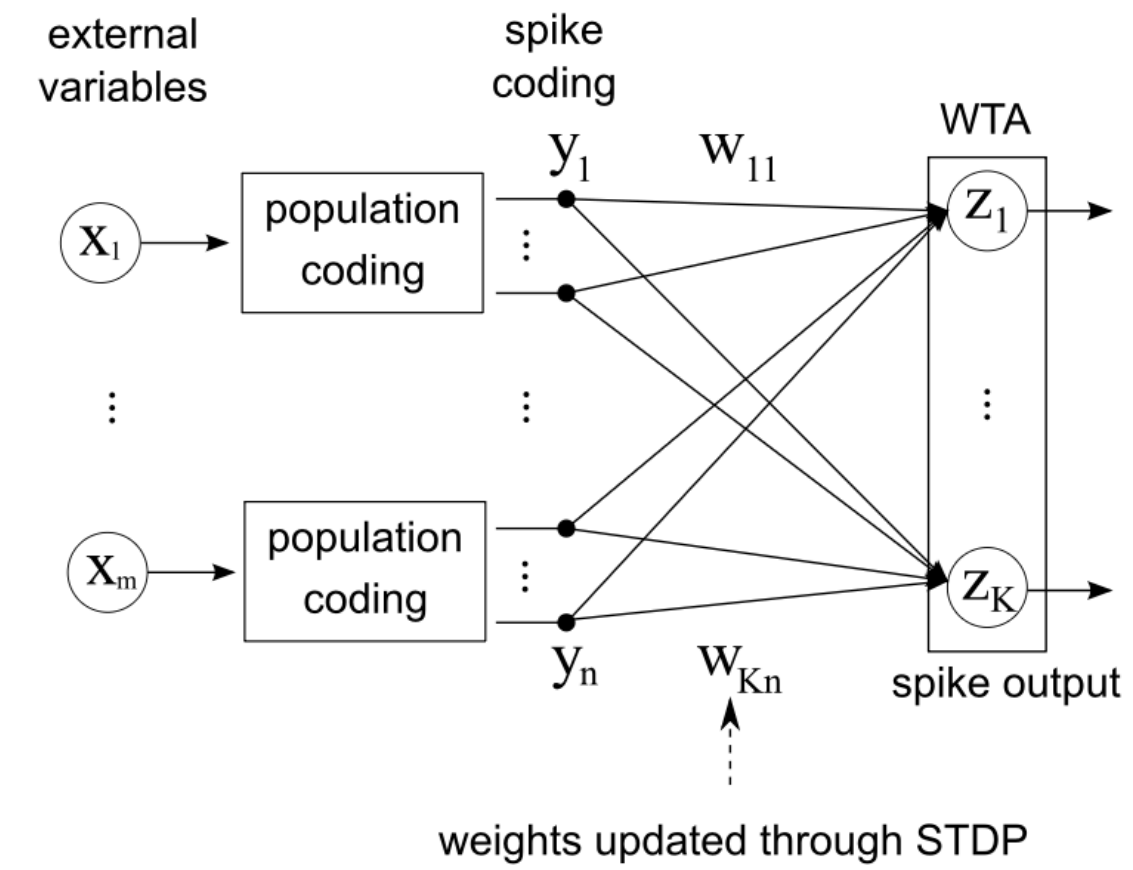
Learning in cells across types

Cell type	Habituation	Sensitisation	Association
Prokaryotic unicells	—	<i>Escherichia coli</i> [Mitosch et al. 2017; Govers et al. 2018]	—
Unicellular eukaryotes	<i>Stentor coeruleus</i> [Rajan et al. 2023] <i>Physarum polycephalum</i> [Boisseau et al. 2016]	<i>Saccharomyces cerevisiae</i> [Guan et al. 2012]	<i>Paramecium caudatum</i> [Hennessey et al. 1979] <i>Stentor coeruleus</i> [Doan et al. 2026]
Metazoa	<i>Rattus norvegicus</i> PC12 cells [McFadden & Koshland 1990; Cheever & Koshland 1992] <i>Aplysia californica</i> [Pinsker et al. 1970]	<i>Aplysia californica</i> [Pinsker et al. 1973] <i>Homo sapiens</i> monocytes [Quintin et al. 2012]	<i>Aplysia californica</i> sensory neurons [Walters & Byrne 1983; Eliot et al. 1994] <i>Mus musculus</i> [Gornov et al. 2026]

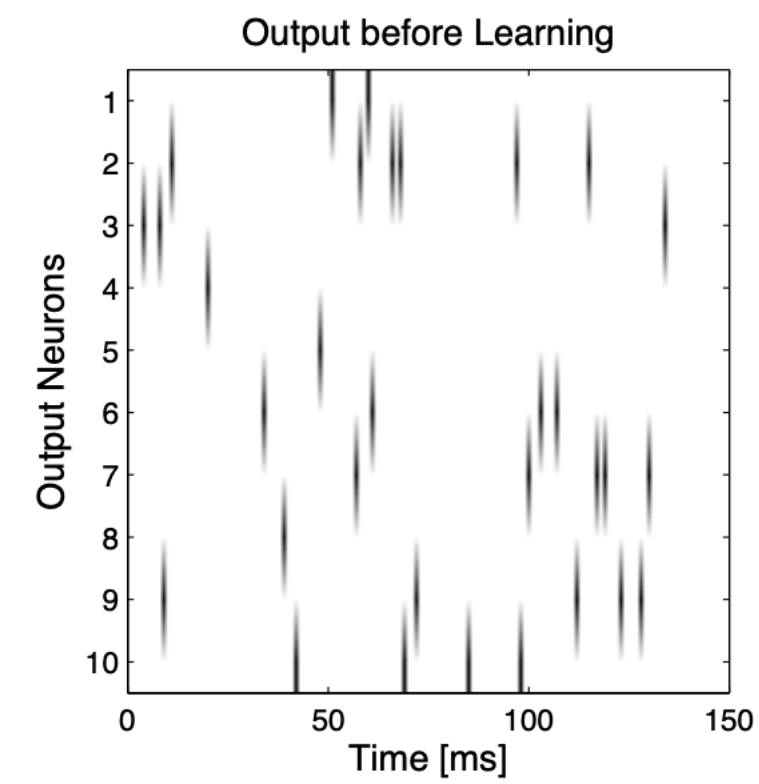
Individual neurons are highly capable cellular learners



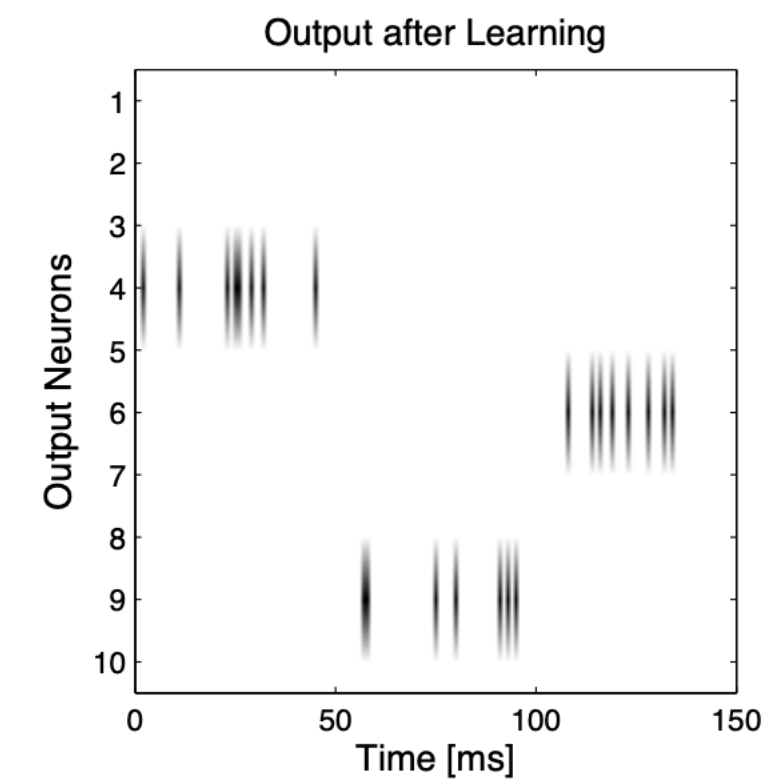
Nervous systems are constituted through local learning rules



A



B



C

What is it like to be a Stentor coeruleus?