Adaptive Systems

Lecture 1.2: Introduction to Adaptive Systems

University of Sussex

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Spring 2026

Contacting me

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Canvas discussions

- Everyone can see my answers
- I will normally check these at least twice a week

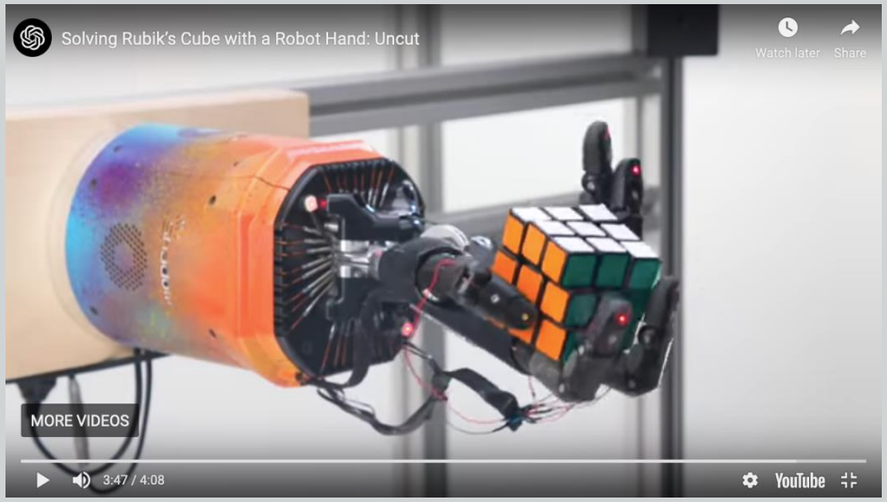
My office hours

- TBD

Lecture learning outcomes

In this lecture, I will introduce some core ideas, and then we will start to look at

1. **Systems and their environments**
2. **Timescales and relative rates of change**
3. **Adaptation can be driven in many ways**
4. **“Adaptation” can mean either a process or a characteristic**
5. **Processes of adaptation take place over various timescales**
6. **All adaptation involves change, but not all change is adaptation**



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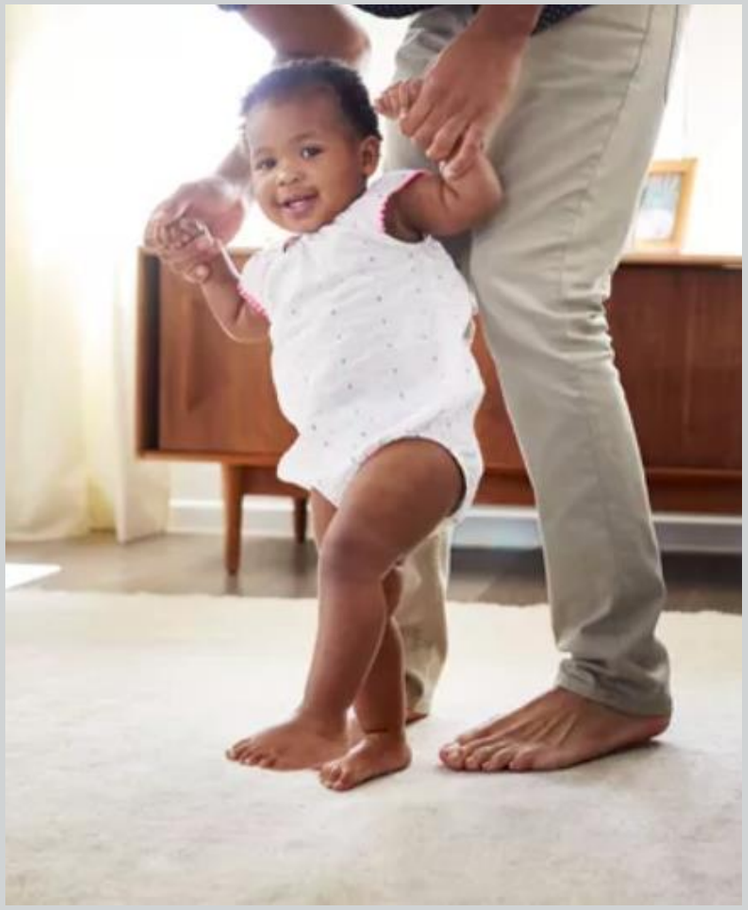

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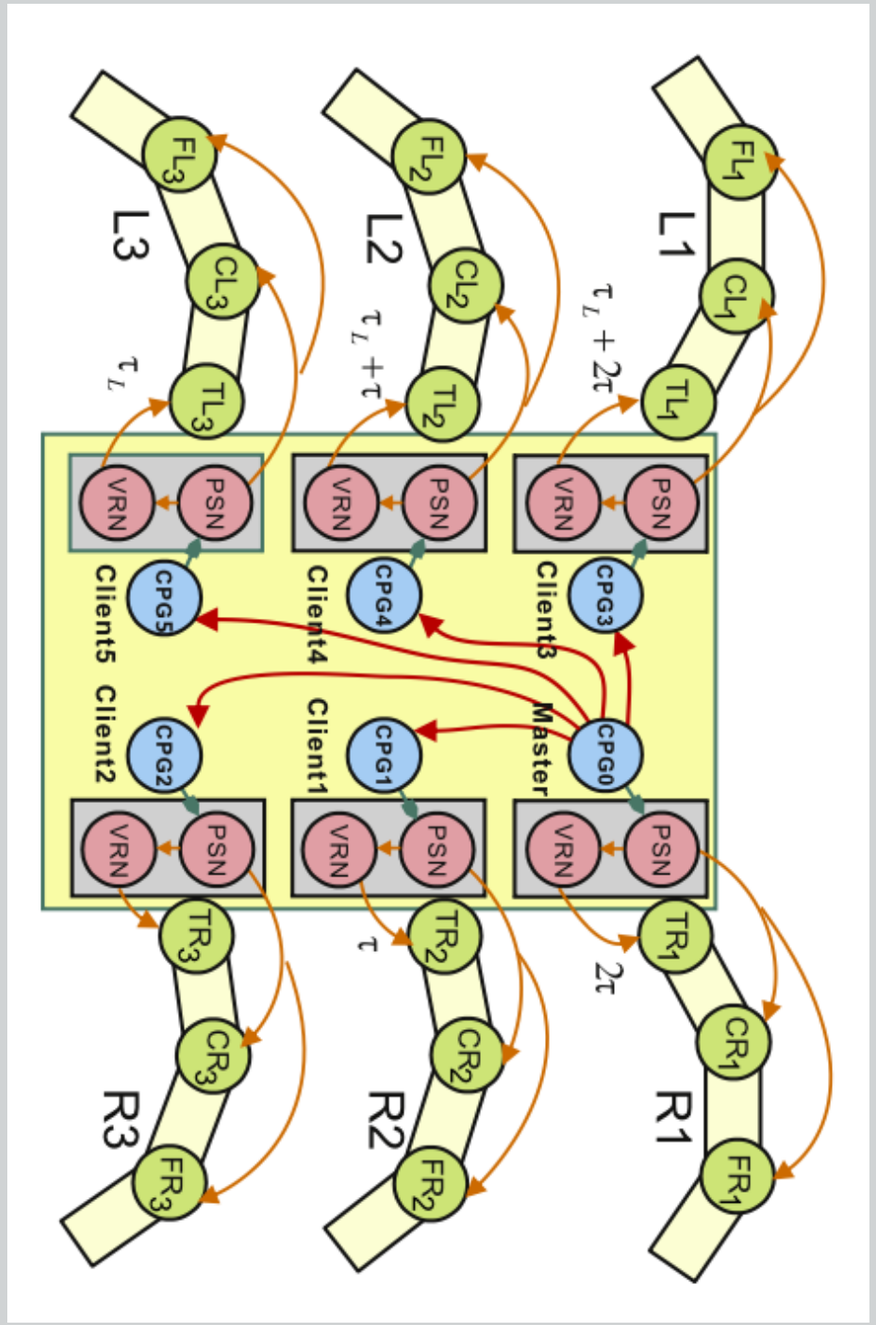
Lecture outline

1. Why study adaptive systems?
2. Module structure
3. Why do systems adapt?
4. Adaptations
    1. Some terminological issues
    2. Not all change is adaptation
5. Adapted vs adaptive - not quite the same thing?



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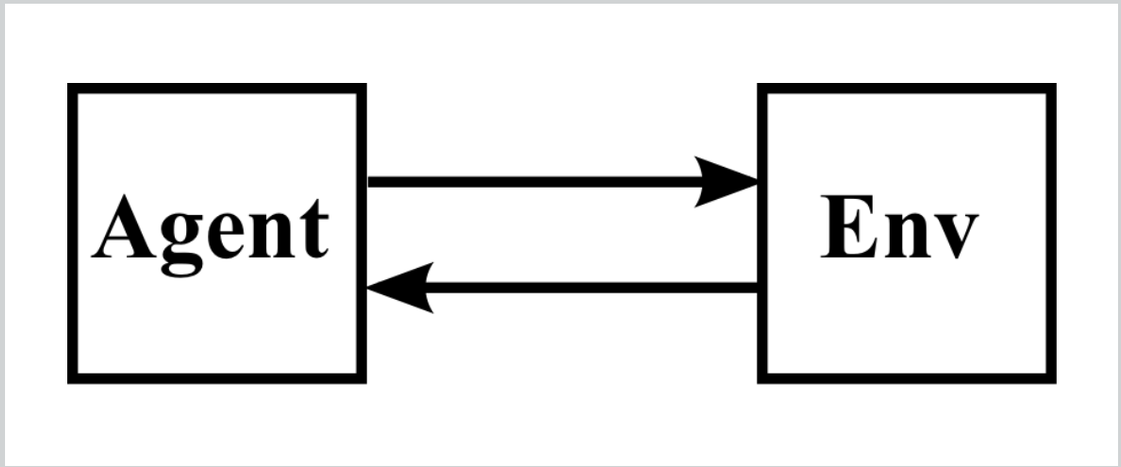
Core idea 1: systems and their environments

Systems and their environments



Coupled systems

- Often, it is convenient to think of a system (or **agent**, in this case) and its environment as being coupled systems
- In this very high-level (i.e. abstract) representation, a single arrow can represent a number of different kinds of interaction
- Because the arrows point in both directions, this is an example of **circular causality**
    - The system influences its environment, which influences the system, and so on…

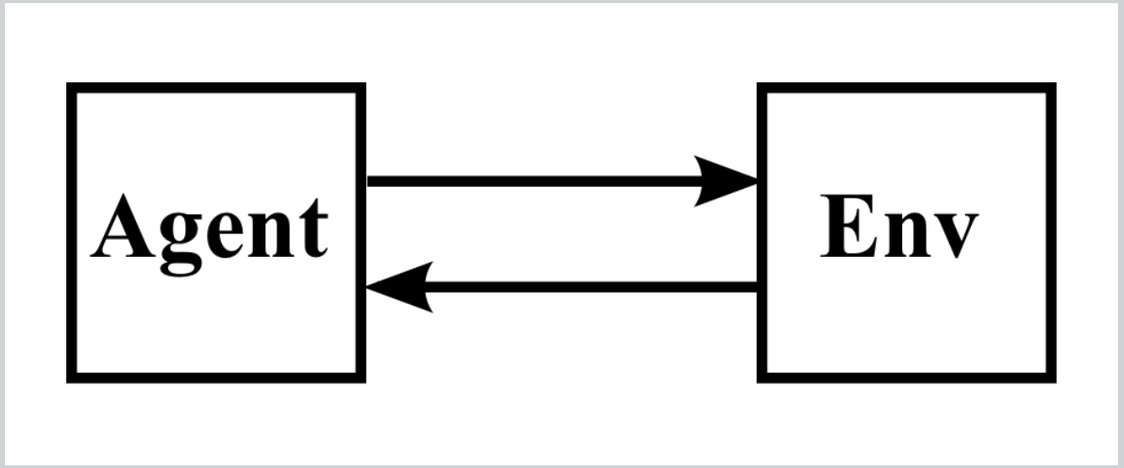
The “fitted-est”

- “Survival of the fittest” - Darwin used these words in later editions of his most famous book, *The Origin of Species By Means of Natural Selection* [30], but they were first written by Spencer [31]

- In his first edition, Darwin wrote about how well species were *fitted* to their environments, and vice versa

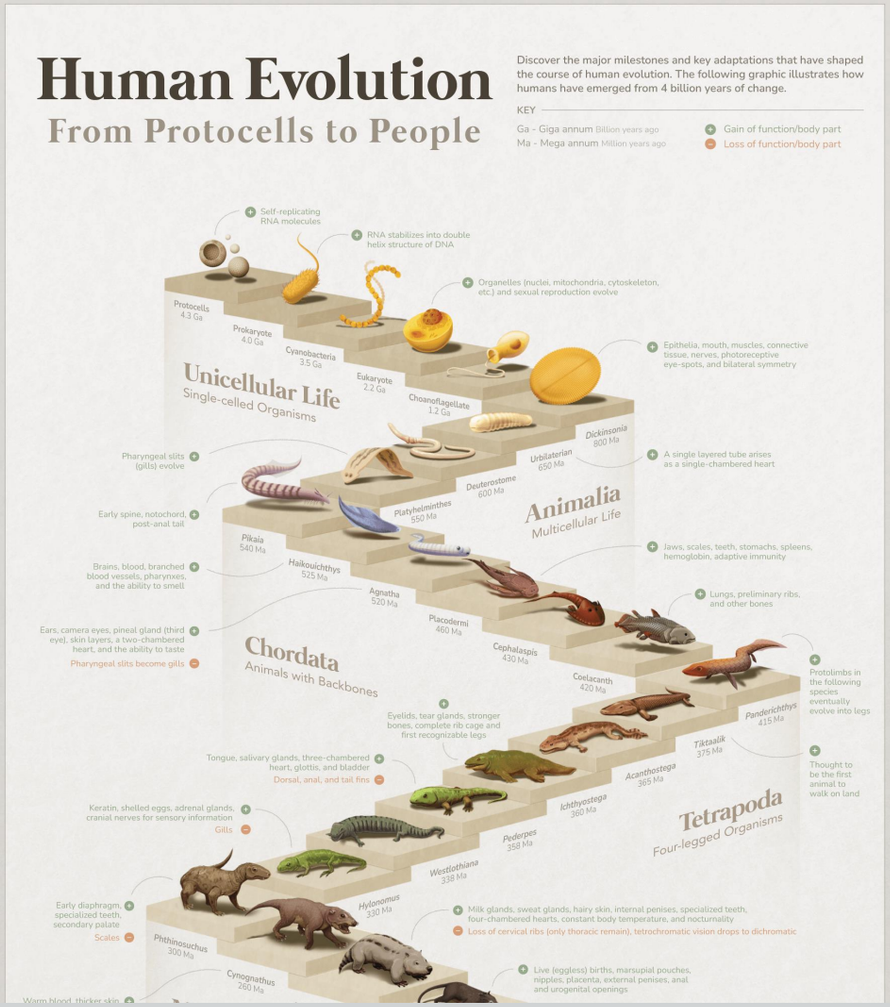
    - i.e. evolutionary **fitness** is a two-way relationship between a population (of a species) and its environment

    - (and *not* fitness as in strength, speed, stamina, or even brain-power)



Coupled systems

The “fitted-est”



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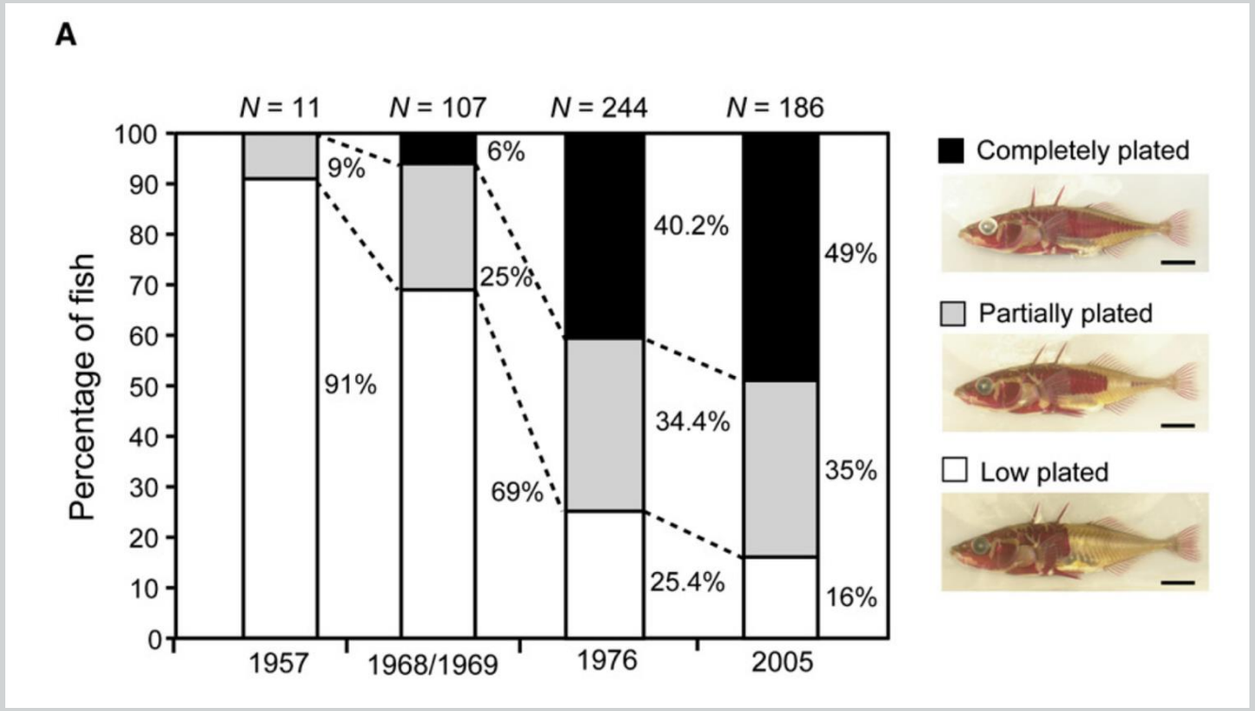
- **Images like this one can give a false impression of evolution through natural selection:**
  - **Firstly, the questionable idea that we are the “best”**
  - **The general trend is *not* towards bigger, better, more complex and more clever**
  - ***Progress* applies more to artificial than to natural evolution**

The “fitted-est”

- **Adaptare: Latin verb “to fit to”**



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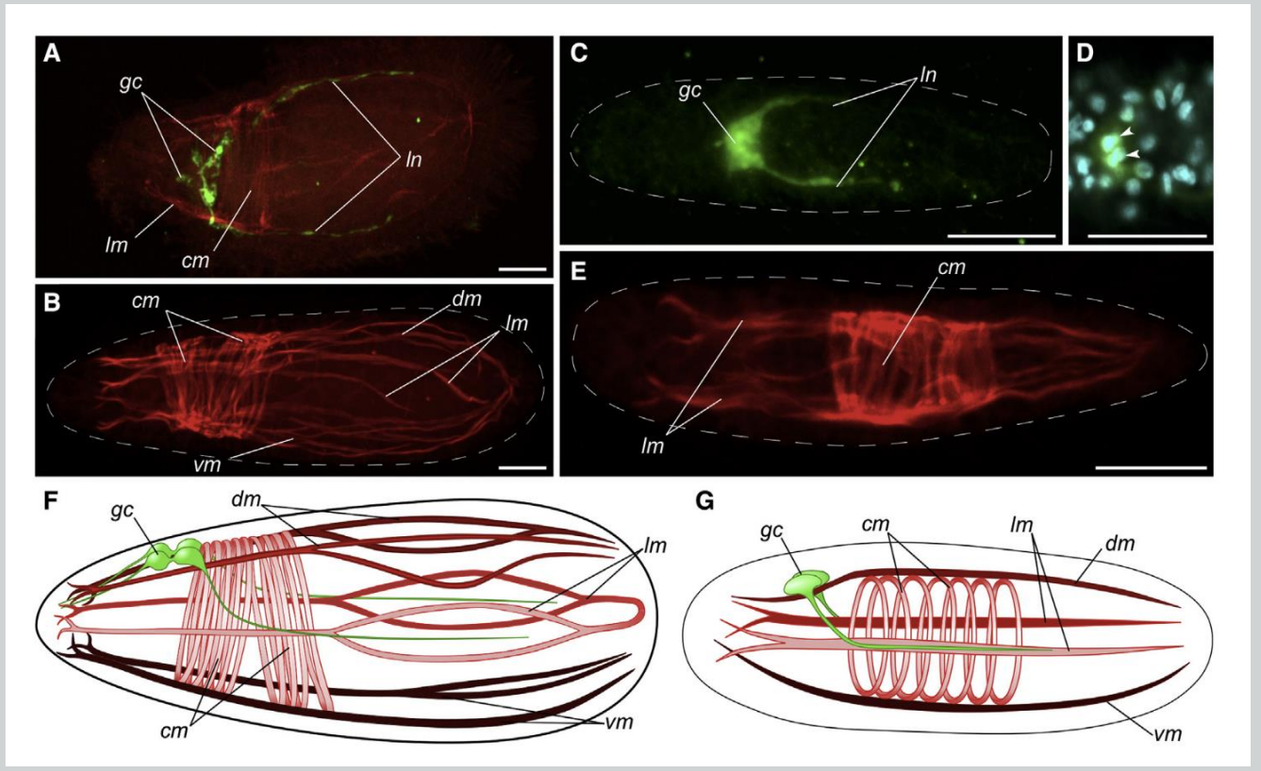

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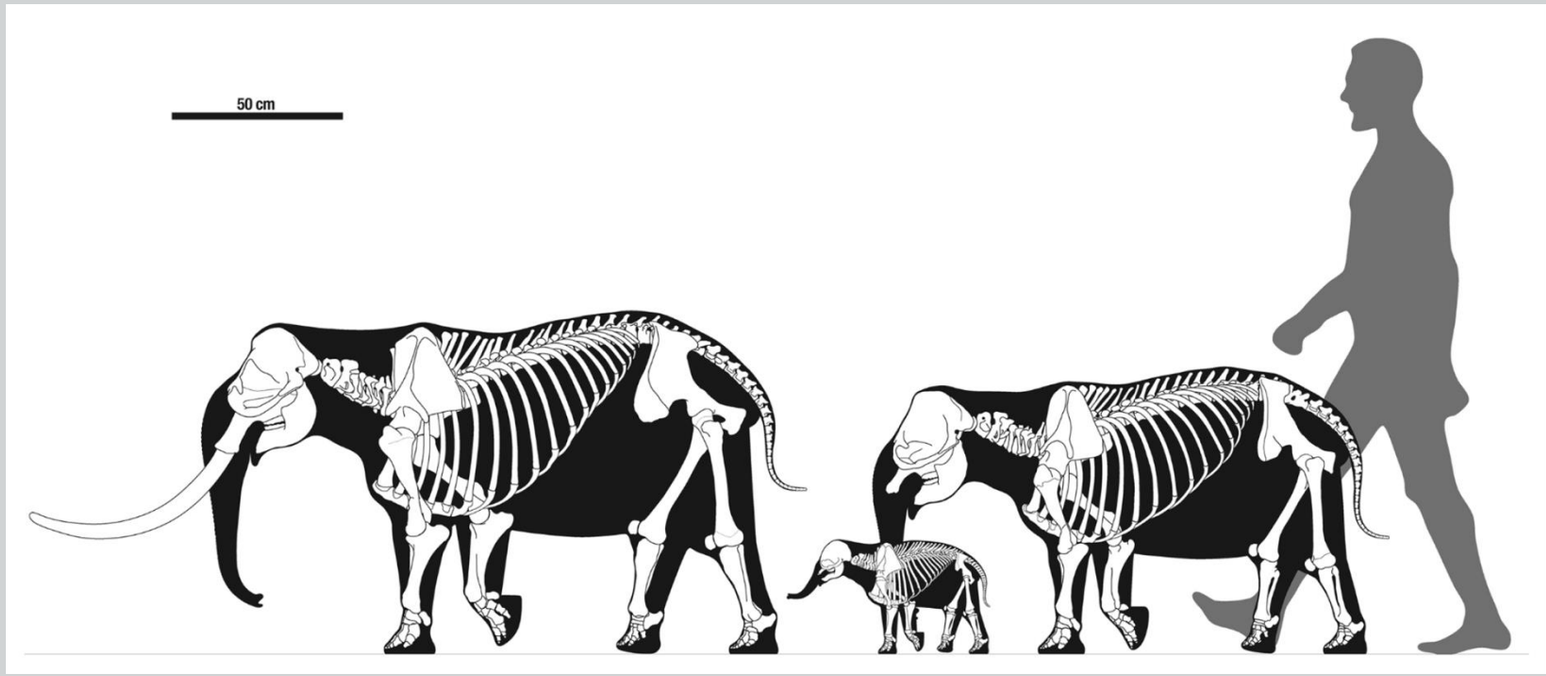

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Maintaining a good fit

- Successful systems fit well in/to their environments
- Often, when systems adapt, they do so in order to maintain a good fit to their environments
  - Of course, what "success" and "fit" mean can vary
    - For living systems, survival (of the individual and the species) takes precedence
    - When we make the systems, we define these terms, or norms
- Highlighting the two-way relationship between a system and its environment, Bateson wrote:
  - "The unit of survival is a flexible organism-in-its-environment." [32]
    - Bateson added that the environment must also be *flexible*
    - And for "flexible", we can substitute "capable of adapting"

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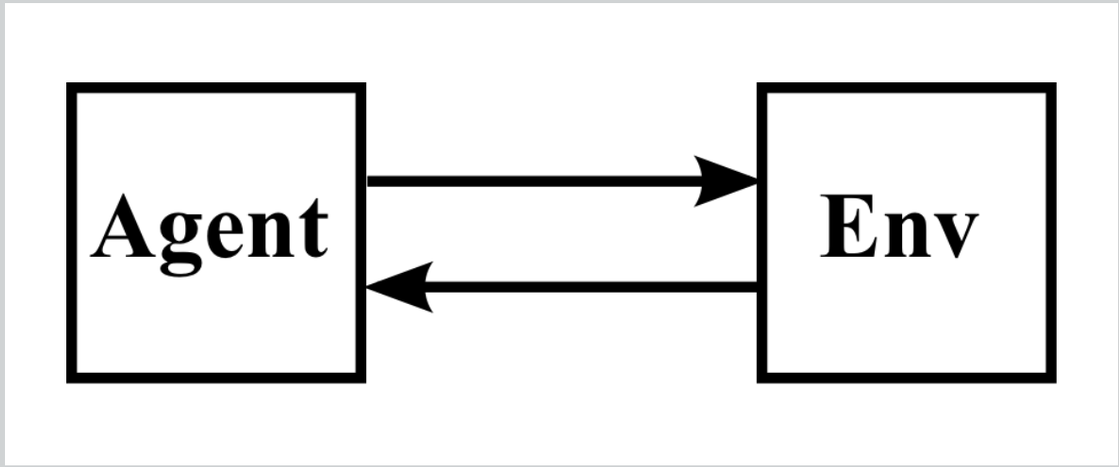
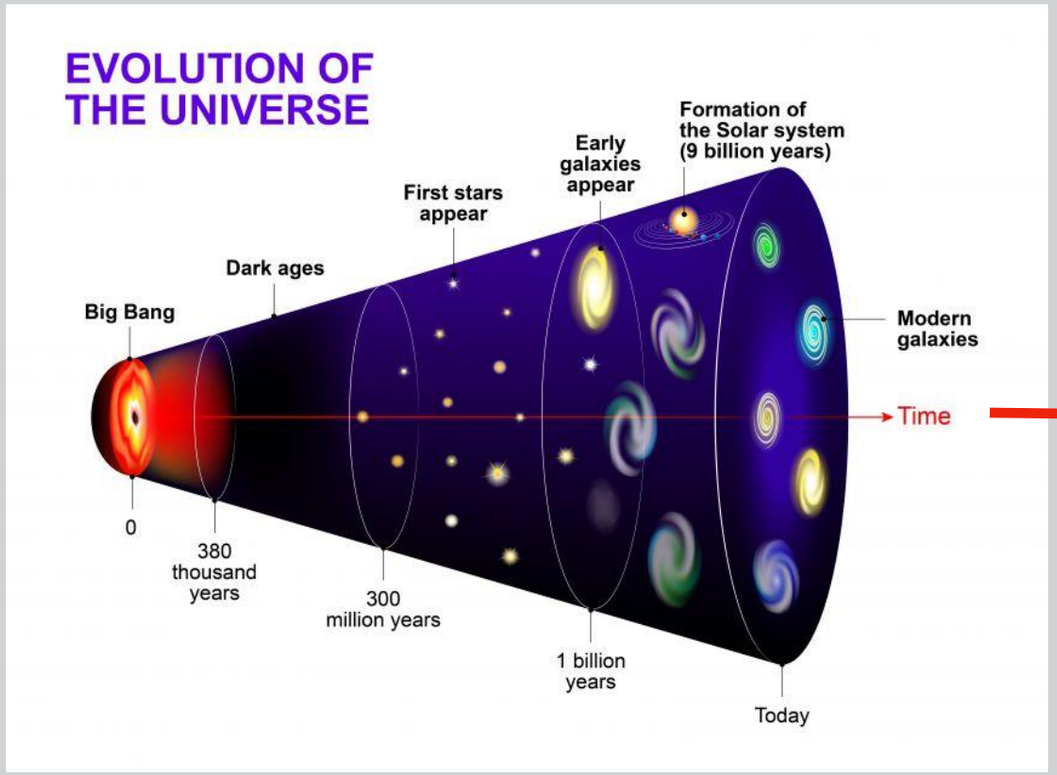


Coupled systems

Core idea 2: timescales

Timescales



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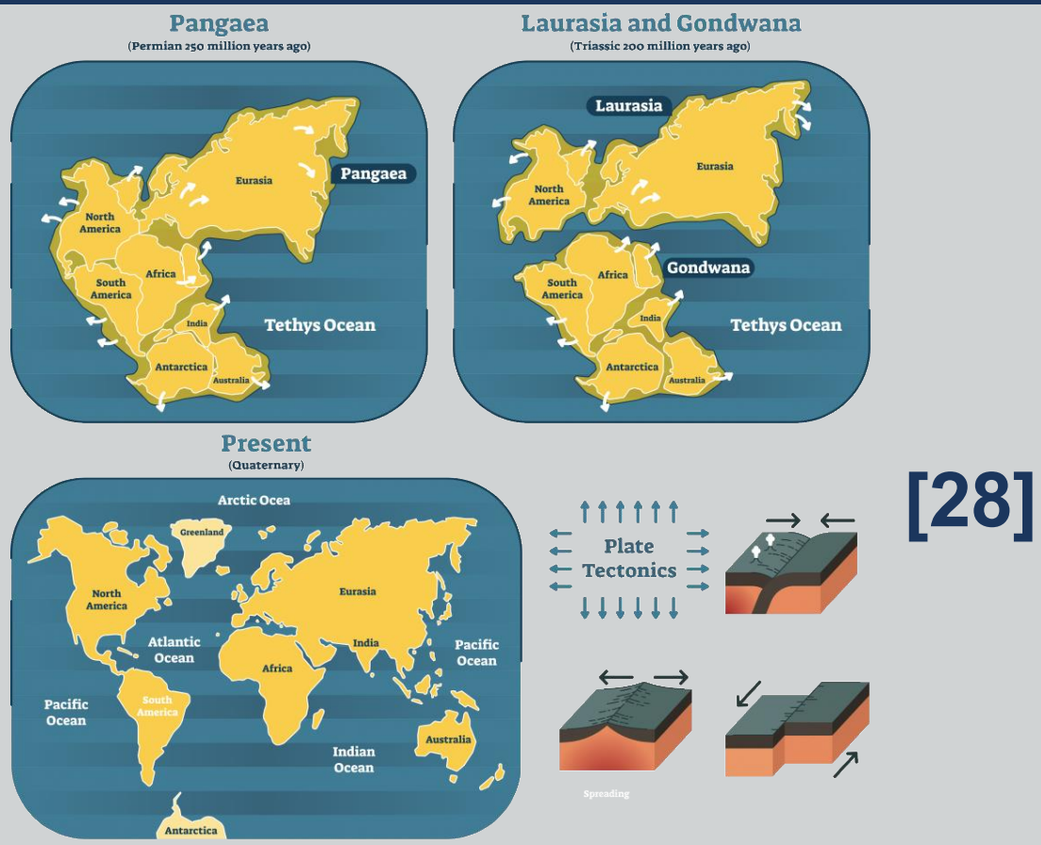

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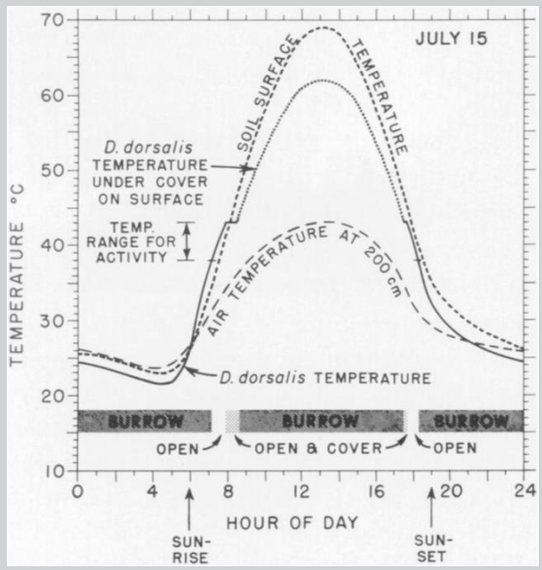

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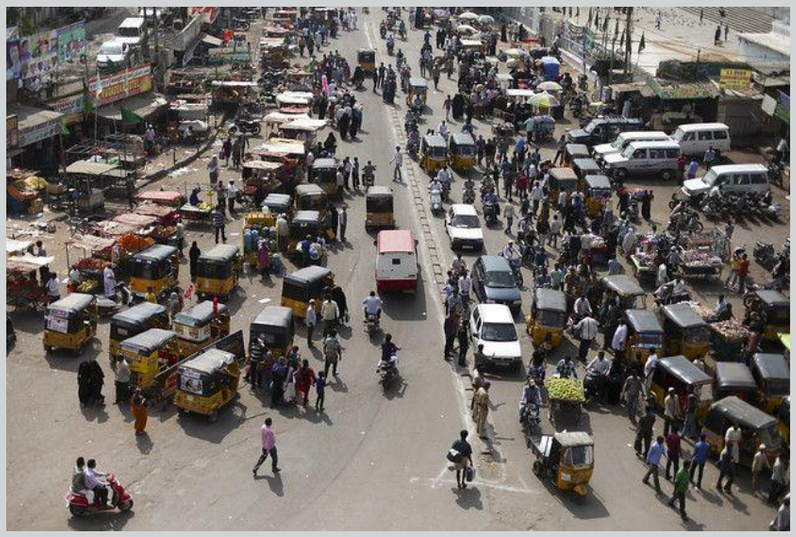

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Timescales

- **Two main timescales apply to adaptation:**
- **Evolutionary – slow adaptation to slow changes**
- **Learning – adaptation to faster changes and unforeseen requirements**

- ***However***
- **The rate of evolution depends on the rate of reproduction**
- **It is much faster for fruit flies than for large mammals**
- **It is even faster for bacteria**

Time

- Time will feature in various ways throughout this module
- Today, our main interest in time is related to **rates of change**, and ***relative* rates of change**, e.g.:
    - The rate of change of ecosystems
        - E.g. global temperatures - today and in the distant past
    - The rate of change of evolution
        - In general, this takes generations, and so can be very slow
        - It may or may not be fast enough to track environmental changes
    - The rate of change of learning
        - Relatively fast, compared to evolution
    - The rate of change of traffic on a busy road
        - Fast, compared to the rate of change of learning

Time

- In the previous example, it is the ***relative*** rates of change that are the issue
  - Fast moving traffic is faster than learning
  - It is also very dangerous – making trial and error learning risky!

How do we learn how to negotiate fast moving and dangerous environments without getting hurt?

Why do systems adapt?

Some examples

Why do systems adapt?

- To learn
  - a behaviour or an action
  - how to solve a problem

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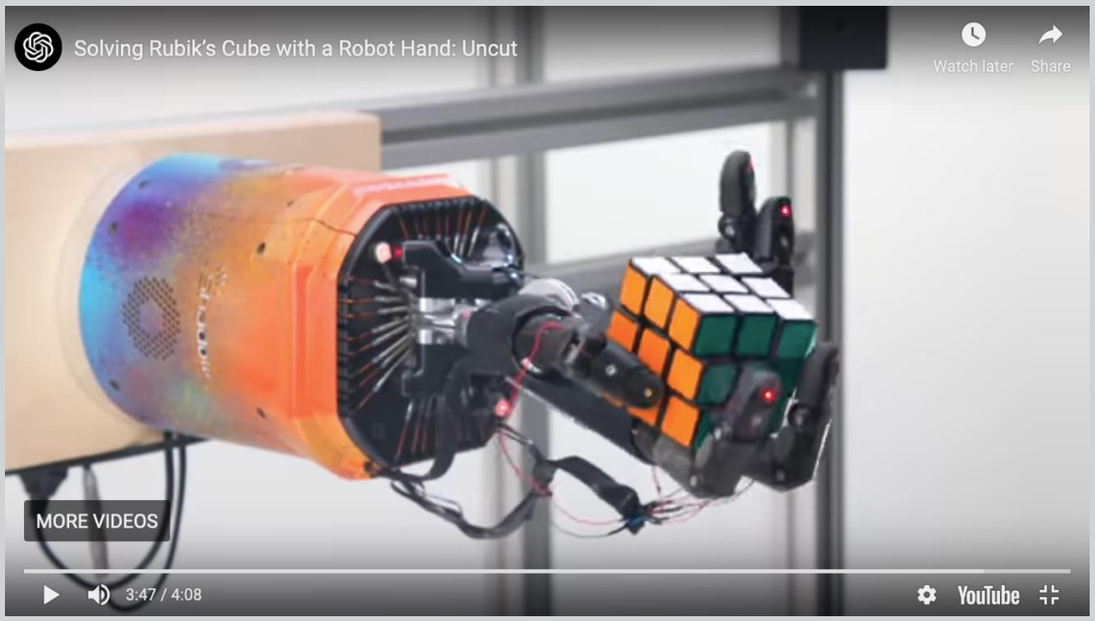

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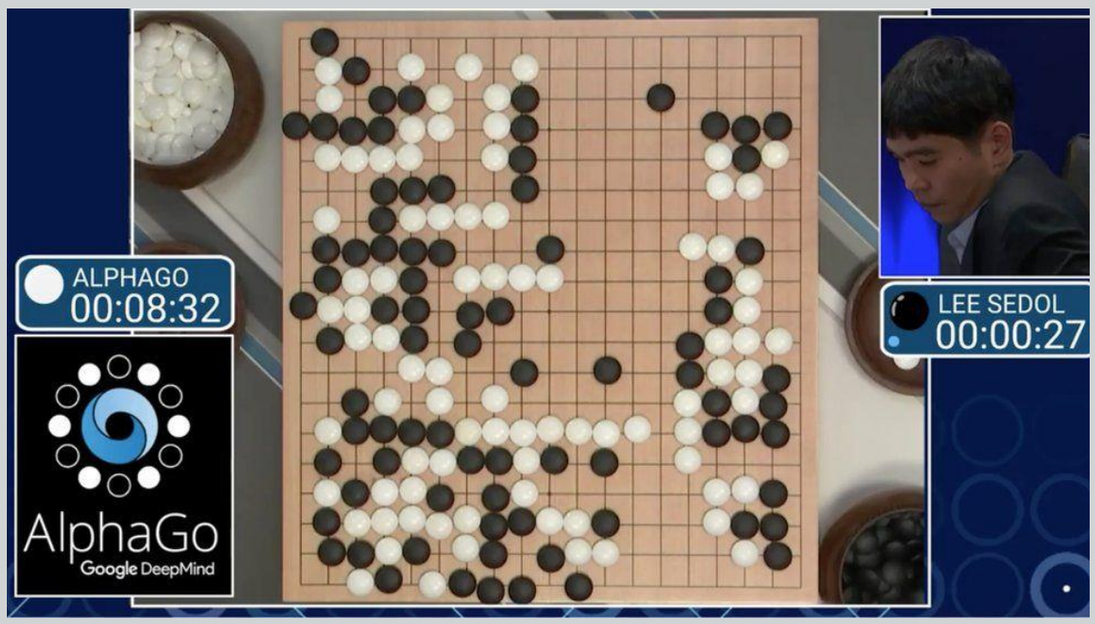

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Why do systems adapt?

Why do we take so long to learn things like how to walk?

Why do systems adapt?

- To compensate for injury or damage

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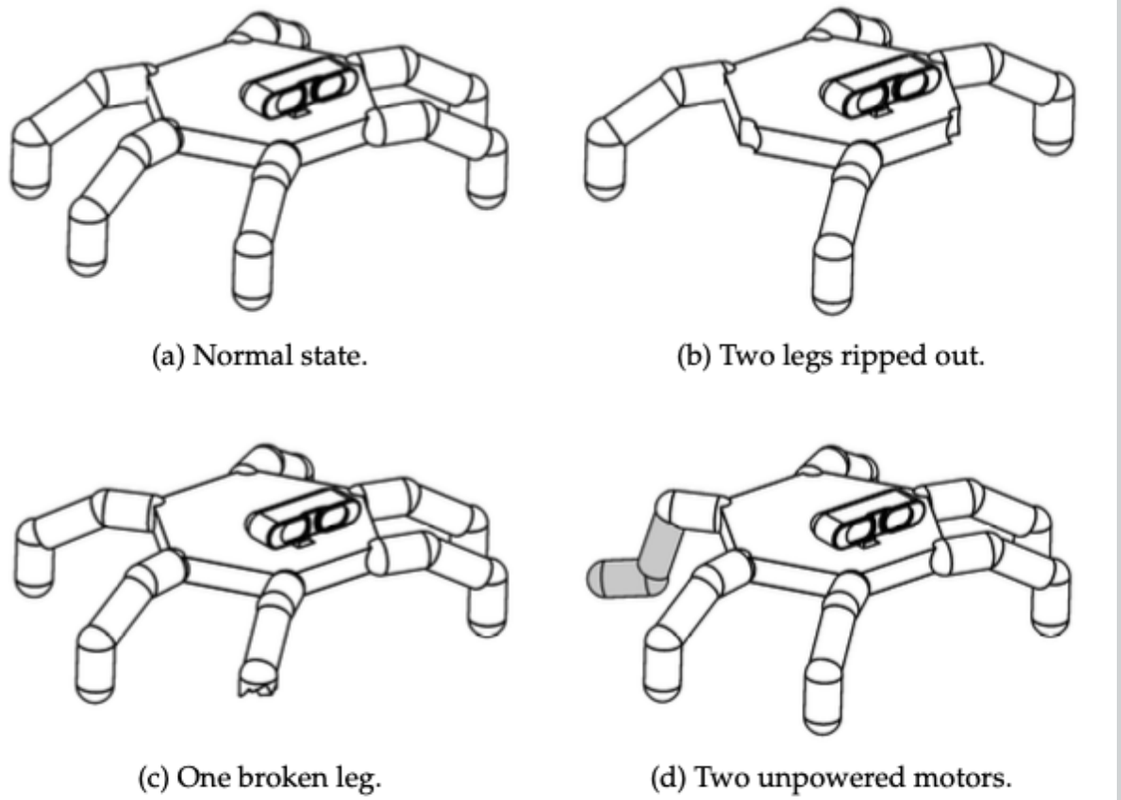

(a) Normal state.

(b) Two legs ripped out.

(c) One broken leg.

(d) Two unpowered motors.

Figure 1: Examples of situations in which an autonomous robot needs to discover a qualitatively new behavior to pursue its mission: in each case, classic hexapod gaits cannot be used. The broken leg example (c) is a typical damage that is hard to diagnose by direct sensing (because no actuator or sensor is damaged).

[3]

Why do systems adapt?

- To adapt *to* changes in the environment
  - Changes to conditions, e.g. dramatic climate change
    - The current global warming is our fault, but dramatic climate change has happened before (e.g. there have been multiple ice ages, and therefore multiple periods of global warming)

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Why do systems adapt?

- To adapt *to* changes in the environment
  - Changes to conditions, e.g. dramatic climate change
  - A failure to adapt can be fatal

[10]

Why do systems adapt?

- To adapt *to* changes in the environment
    - Changes in populations, e.g. the introduction of a new predator or competitor to an ecosystem
        - Failure to adapt may lead to death, of individuals, or even of entire species

[8]

Predator

[6]

Competitors

Why do systems adapt?

- To adapt *to* changes in the environment
  - Your environment can change around you, or you can change it by moving
  - Human adaptations to new environments are largely *cultural*, and are often learned over many generations

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Why do systems adapt?

- To adapt *to* changes in the environment
  - When you move, you change your environment
  - The woolly mammoth was descended from elephants which migrated to the north, and adapted to their new environment

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Why do systems adapt?

- To adapt *to* changes in the environment
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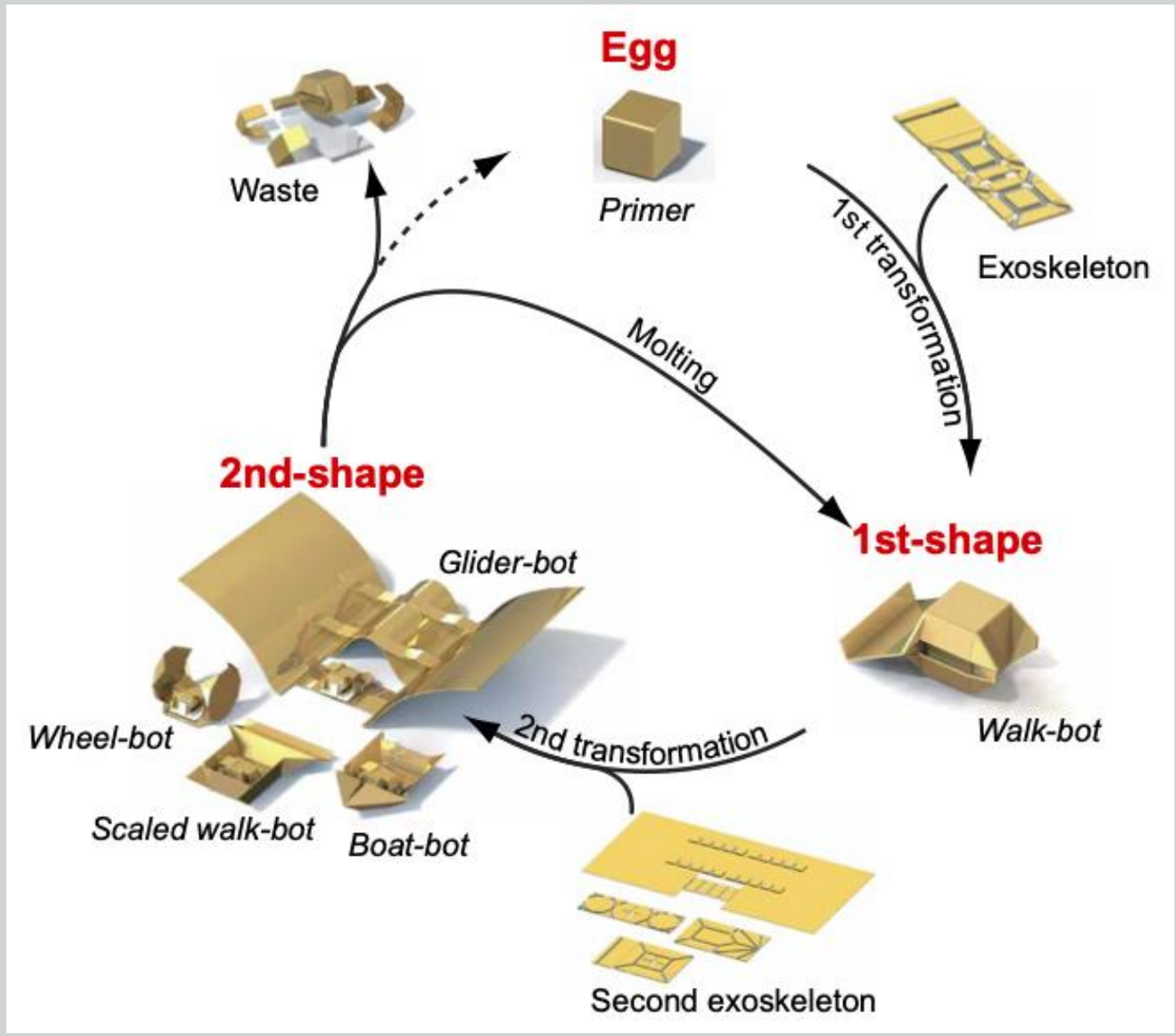

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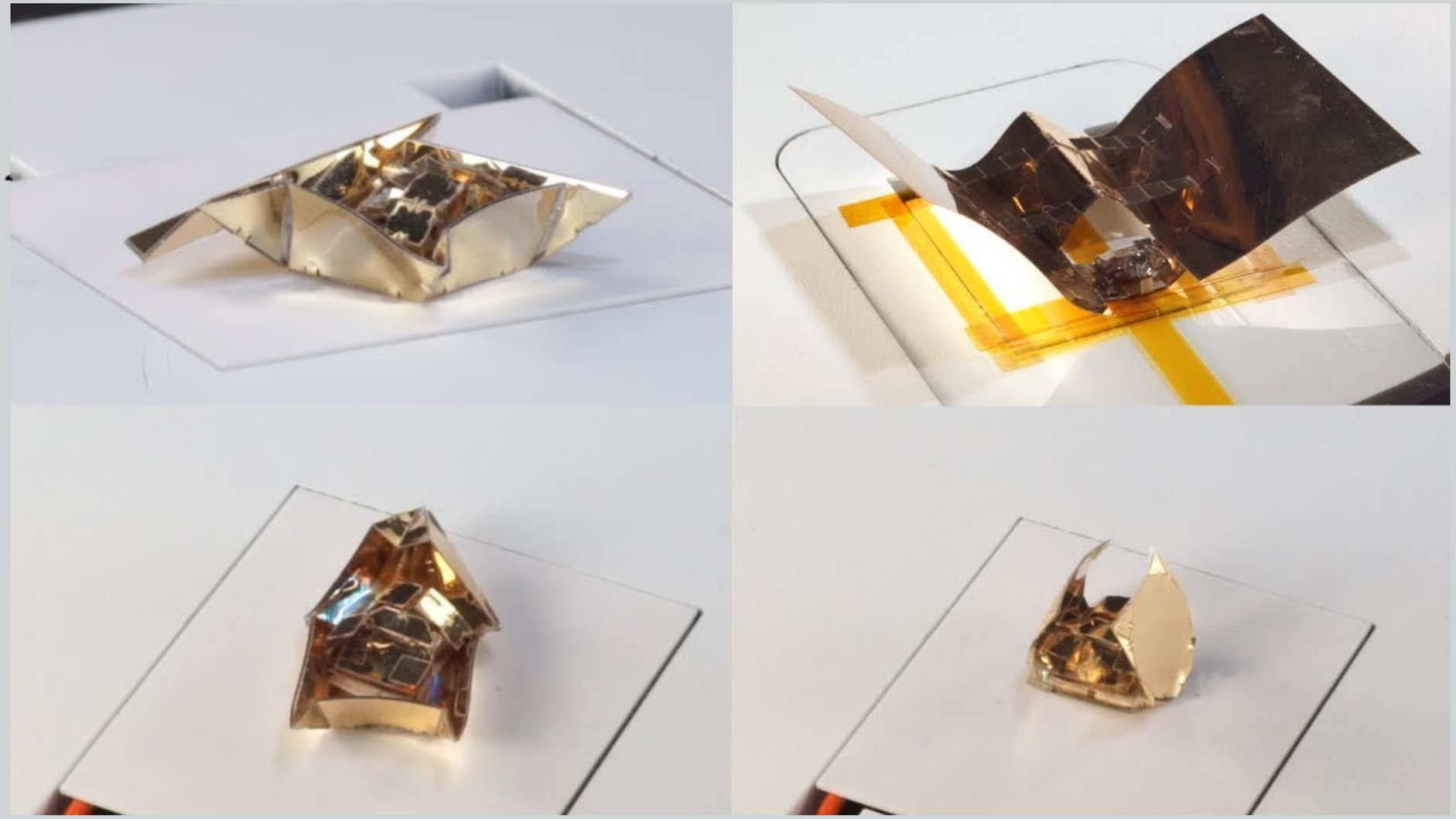
Why do systems adapt?



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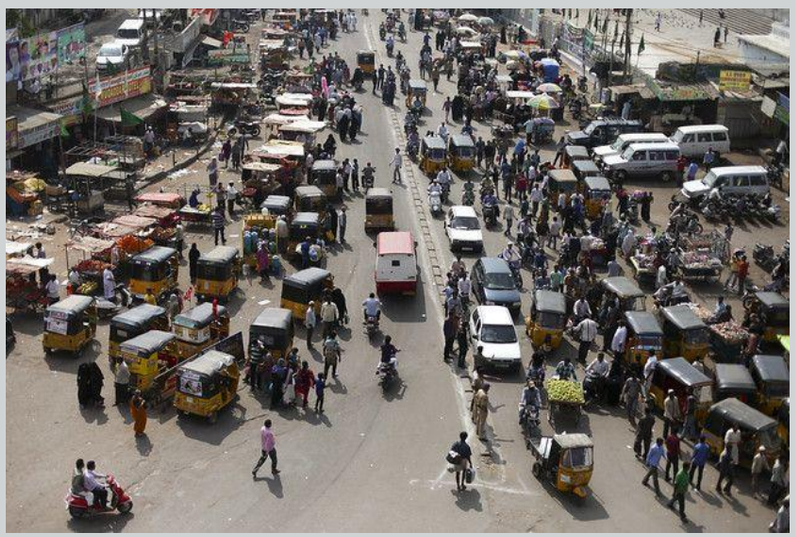
- Adaptive systems can be *shape-shifters*
- This robotic **metamorphosis** is an example of **morphological** adaptation
  - But I would call this a **borderline** or ***trivial*** case, as the robot really just *switches* between different *modes*

Why do systems adapt?

- In general, environments are dynamic, i.e. constantly *changing,* and therefore they are unpredictable
  - Slow changes in the environment *may* be adapted to by a process of evolution
  - Faster changes, and other **surprises** may be adapted to by learning
- Very fast changes may be *adjusted to* by processes of regulation and control (which are not necessarily processes of *adaptation*)



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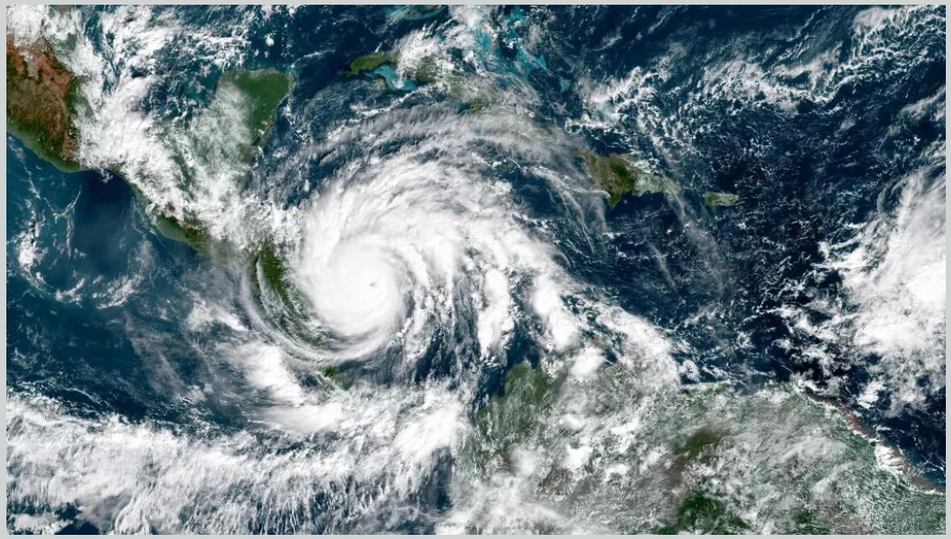

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Adapting and being adaptive: processes and characteristics

Some problematic terminology

- Often, key concepts and words in adaptive systems have multiple definitions

- Even within a single discipline, like biology

- An example from the study of evolution through natural *selection*:

  - **Adaptation** is a central concept in biology. The word has two related meanings.

    1. "Adaptation" means the evolutionary *process* by which, over the course of generations, organisms are altered to become **improved** with respect to features that affect survival or reproduction.

    2. "An adaptation" is a *characteristic* of an organism that evolved by natural selection.

       [Futuyma and Kirkpatrick, "Evolution" (P66)]

Some problematic terminology

- Also in the study of evolution through natural selection, sometimes "*an* adaptation" is referred to as an "*adaptive* trait"
- This causes a similar problem for us to the one with the word adaptation, because:
  - An adaptive trait is a characteristic
  - However, when we refer to an adaptive system, we often mean a system which can adapt itself (through some adaptive process)
    - We can call this a *self-adaptive* system

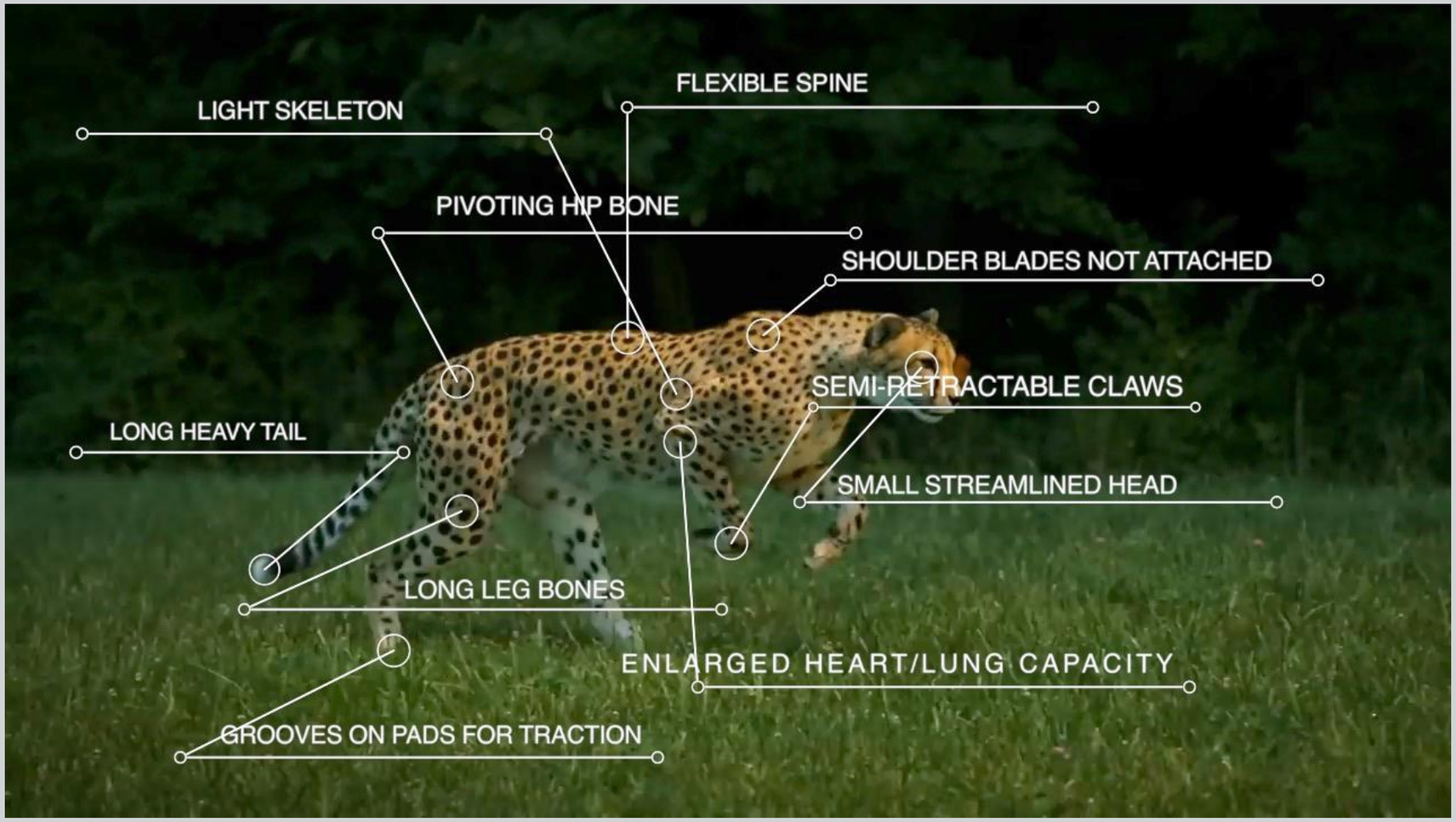
- When I use these words, I will always try to be clear about whether I am describing processes or characteristics
  - I would like you to be clear about this too, in seminars and on Canvas discussions, *and* in your reports
  - If I am ever unclear about this, please let me know!
    - Because we will certainly point out if you are unclear, when we mark your reports!

Adaptation (as a process)

- A few examples of adaptive processes:
  - Learning, in humans
  - Learning, in artificial neural networks
  - Evolution through natural selection
    - Searching for “good”, or sometimes *optimal*, solutions with genetic algorithms
- Adaptive processes must be *directed* somehow (not all change is adaptation)

Adaptive trait (an adaptation)

- An example:
  - Speed is an advantage, for predators and prey



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- The cheetah is the fastest animal on land, and has *multiple* adaptive traits which **synergistically** contribute to its speed

Adapted vs self-adaptive

- I will talk more about this later in the module, but will give you a preview now:
  - When I talk about an adapted system, I mean a system which has been adapted by another system or process(es) to have desirable or beneficial characteristics
    - e.g. by an ecosystem and natural selection
    - e.g. by a simulated environment and a genetic algorithm
- When I talk about a self-adaptive system, I mean a system which has the ability to adapt itself
  - e.g. by learning
  - e.g. by changing its body – through reconfiguration (as in the earlier robot) or by exercise

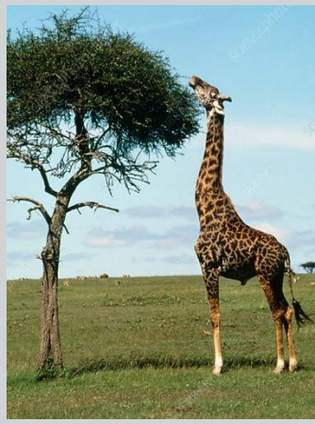
Adapted vs self-adaptive

- On this module, we are principally interested in:
  - The self-adaptive systems, which adapt themselves (e.g. living organisms and robots or software systems which can learn)
  - *As well as* the systems and processes which can adapt *other* systems
- Often, the systems that we will study will be both adapted and self-adaptive
  - E.g. we are *evolved* (adapted) to be systems which *learn* (i.e. self-adaptive systems)

Not all change is adaptation

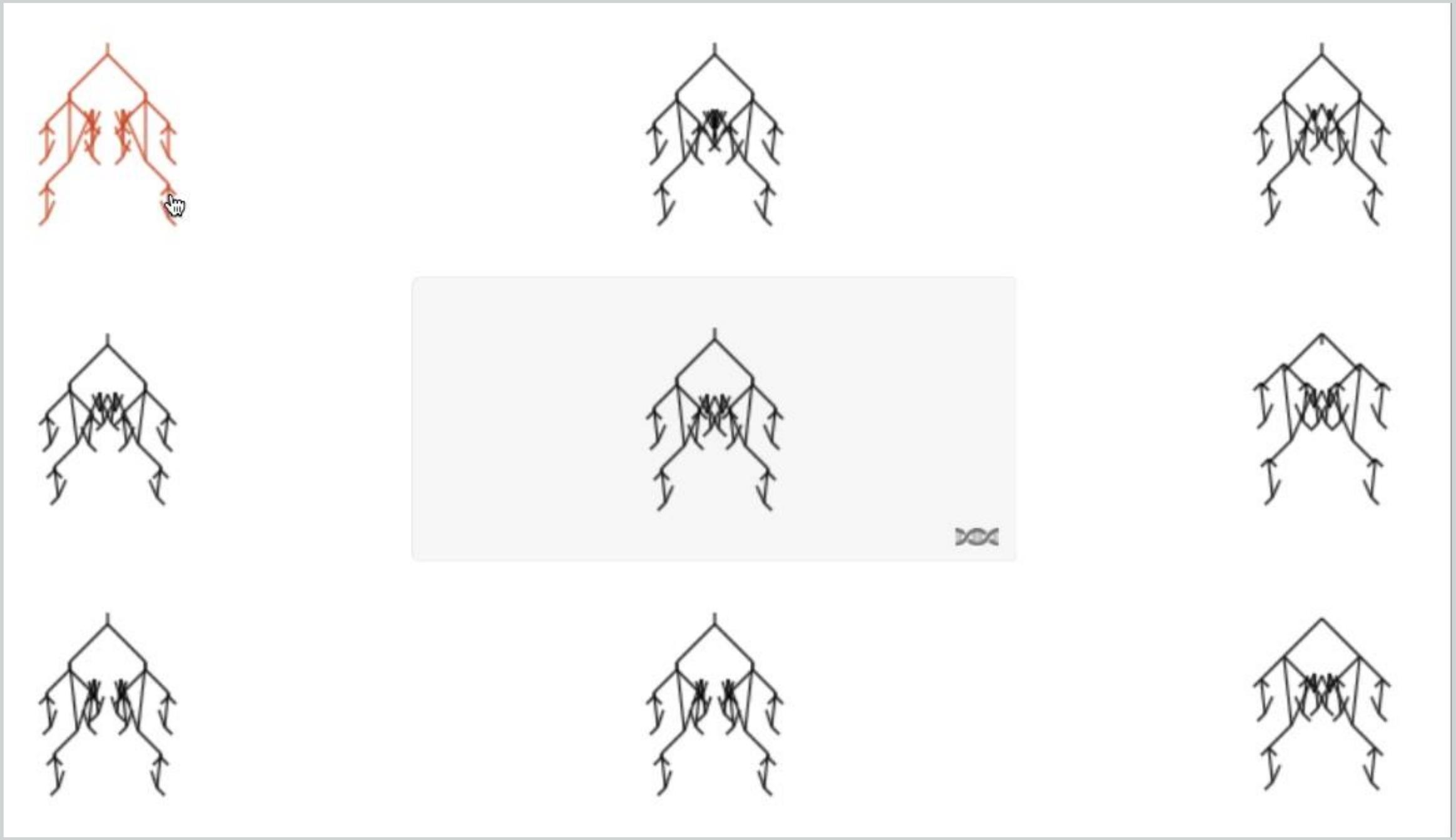
Not all change is adaptation - evolution

- A process of adaptation always involves change, but not all changes are adaptations
- Successful organisms are *adapted to* their environments, for example:
    - By evolution (over multiple generations)
    - By learning (during their lifetimes)
- Genetic mutations are random, but, over many generations, mutations which make organisms less likely to survive and reproduce are selected *against*
    - By this *process of elimination*, beneficial genes *tend to* survive and multiply
- Alternatively, you will often read of beneficial mutations or traits being selected *for*
    - E.g. giraffes born with short necks might be selected *against*, as it is difficult for them to reach high branches of trees
        - But we could equally say that giraffes with long necks are being selected *for*, as they reach those branches more easily
- In other words, natural selection can both drive and direct evolution



Not all change is adaptation

- ***Randomly*** **selected**



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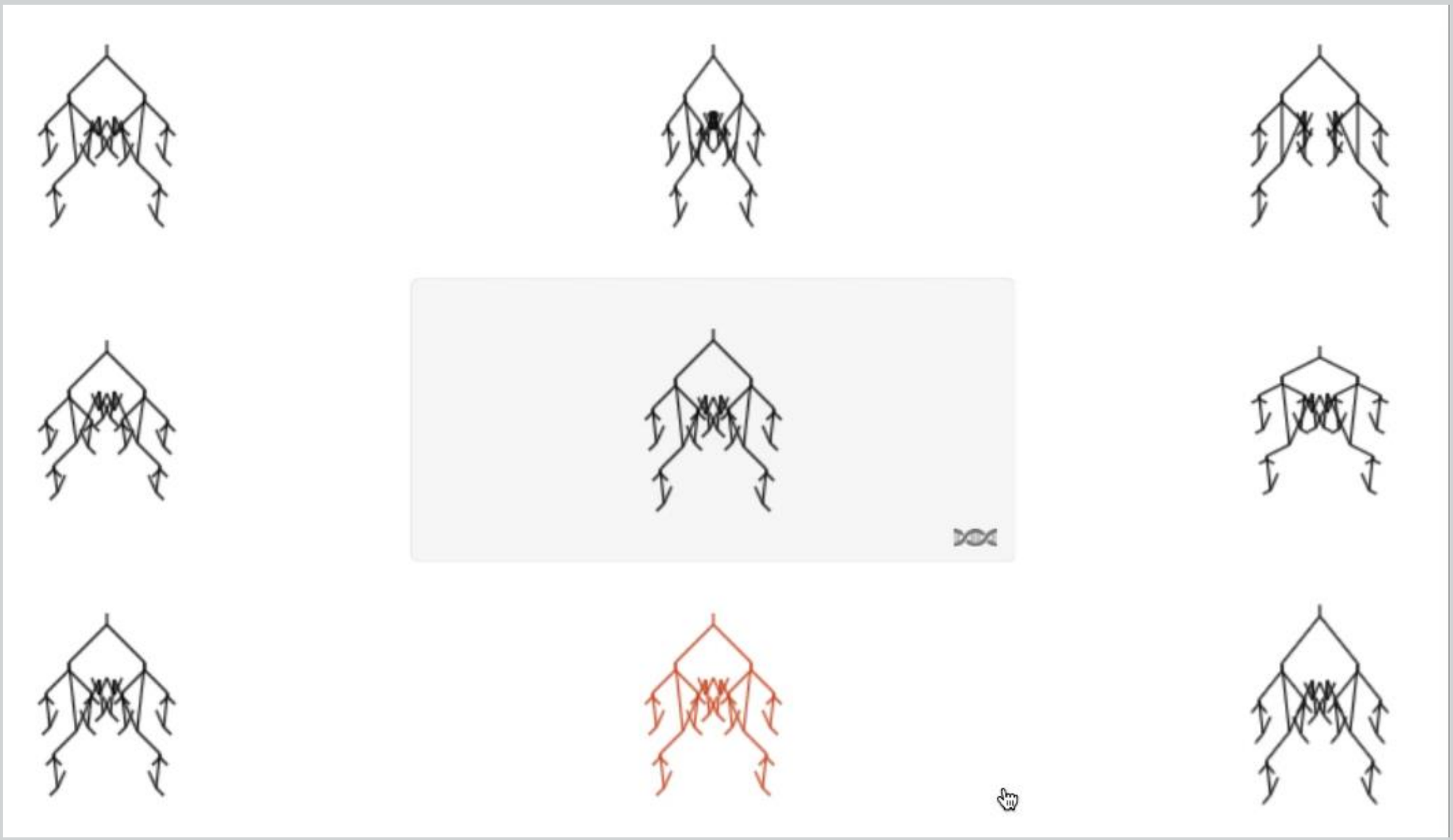
- **Not a*dapted*** **(no rule of selection)**

Adaptation based on selection

- ***Selected for* wideness:**



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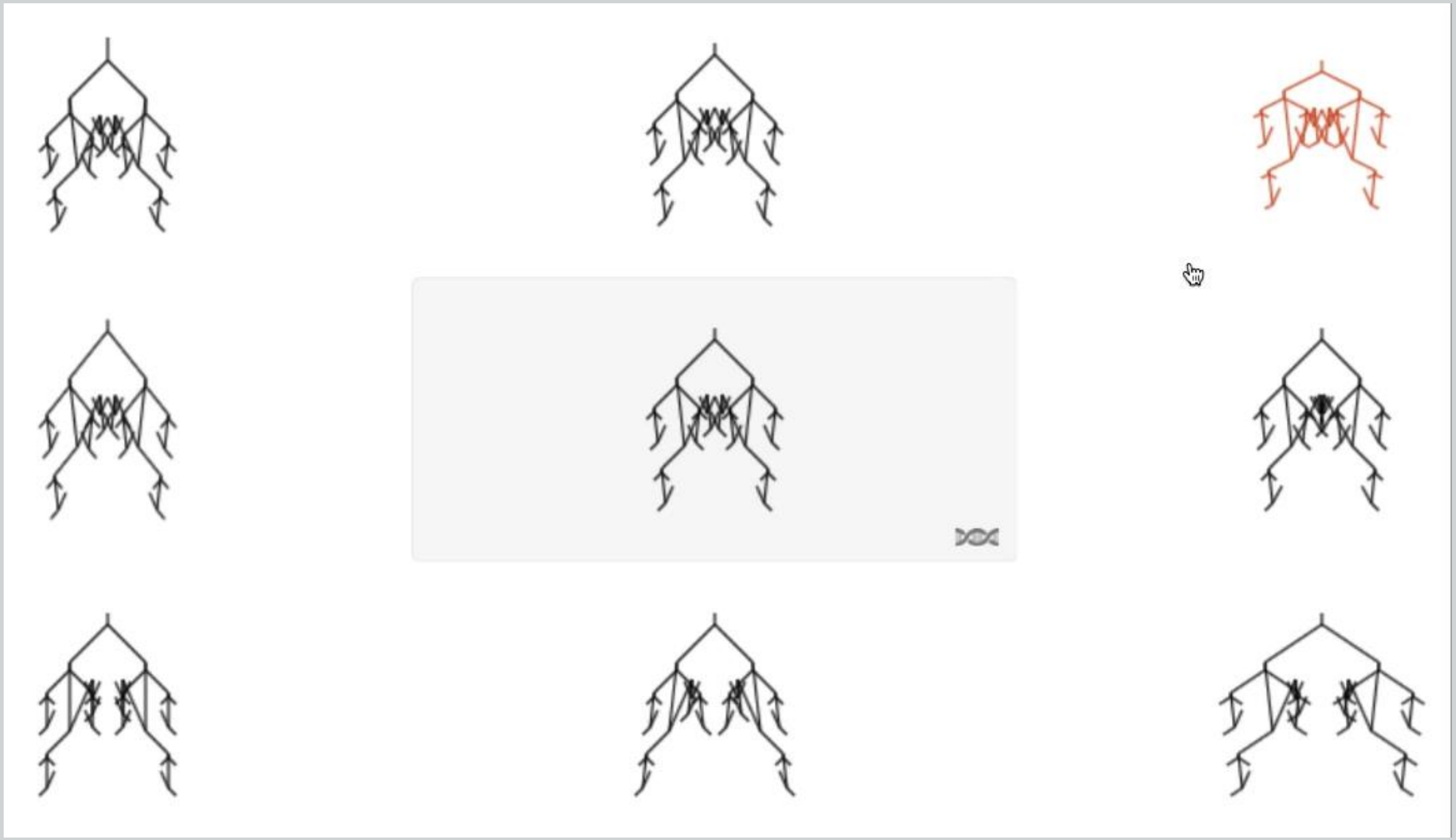
- ***Adapted to* the criterion (or rule) which *I* set**

Adaptation based on selection

- ***Selected for*** **thinness (or *against* wideness):**



[5]

- ***Adapted to*** **the criterion (or rule) which *I* set**

Not all change is adaptation - learning

- A process of adaptation always involves change, but not all changes are adaptations
- Like evolution, learning also must be *directed*, by rules or algorithms which tend to lead to desirable or effective results
- Some examples:
  - Hebb's rule
  - Spike-timing-dependant plasticity (STDP)
  - Back-propagation
  - Reinforcement learning
- Every one of these mechanisms, if used correctly, can lead to improvement of the system they are applied to

Summary

- *An adaptation* is a characteristic of a system, which is the *result* of a process
- But *adaptation* can also mean the process by which a system is adapted
- We can distinguish between systems which are **self-adaptive**, which means that they can adapt *themselves* (a process), and systems which are adapted *by* other systems or external processes
  - I use *self-adaptive* here to distinguish from *adaptive,* which is often used otherwise, e.g. in “adaptive traits” or “adaptive behaviour”
- While all *processes* of adaptation involve change, not all change is adaptation - only changes which are *selected* or *directed* according to some set of *rules* or *laws* can lead to adaptation
- Adaptive processes can be driven in many ways, but often the change involved in a system’s adaptation is prompted by changes in its environment
- Which kinds of adaptive processes (if any) are effective in a given situation or environment is determined by relative rates of change

Bibliography

Recommended articles and books

[1] Ren, G., Chen, W., Dasgupta, S., Kolodziejski, C., Wörgötter, F., & Manoonpong, P. (2015). Multiple chaotic central pattern generators with learning for legged locomotion and malfunction compensation. Information Sciences, 294, 666–682. https://doi.org/10.1016/j.ins.2014.05.001

[2] D. J. Futuyma and M. Kirkpatrick, *Evolution*, 4th ed., Sinauer Associates, 2017

[3] Koos, S., Cully, A., & Mouret, J. B. (2013). Fast damage recovery in robotics with the t-resilience algorithm. The International Journal of Robotics Research, 32(14), 1700-1723.

[24] Miyashita, S., Guitron, S., Li, S., & Rus, D. (2017). Robotic metamorphosis by origami exoskeletons. Science Robotics, 2(10).

Bibliography

Recommended articles and books

[33] Slyusarev, G. S., Starunov, V. V., Bondarenko, A. S., Zorina, N. A., & Bondarenko, N. I. (2020). Extreme genome and nervous system streamlining in the invertebrate parasite Intoshia variabili. *Current Biology*, *30*(7), 1292-1298.

[34] Kitano, J., Bolnick, D. I., Beauchamp, D. A., Mazur, M. M., Mori, S., Nakano, T., & Peichel, C. L. (2008). Reverse evolution of armor plates in the threespine stickleback. *Current Biology*, *18*(10), 769-774.

[35] Larramendi, A., & Palombo, M. R. (2015). Body Size, Biology and Encephalization Quotient of Palaeoloxodon ex gr. P. falconeri from Spinagallo Cave (Hyblean plateau, Sicily). *Hystrix*, *26*(2).

Bibliography

Relevant websites

[4] https://openai.com/blog/solving-rubiks-cube/

[5] http://www.emergentmind.com/biomorphs

[6] https://news.sky.com/story/red-and-grey-squirrels-go-head-to-head-in-nut-iq-test-11258591

[7] https://www.wildlifetrusts.org/saving-species/red-squirrels

[8] https://theconversation.com/is-it-too-late-to-bring-the-red-fox-under-control-11299

[9] https://cheetah.org/canada/2020/08/09/how-is-the-cheetah-skeleton-different-from-other-cats/

Bibliography

Relevant websites

[10] https://www.nhm.ac.uk/our-science/our-work/origins-evolution-and-futures/mammoth-evolution-model-for-species-origins.html

[21] https://www.quantamagazine.org/new-brain-maps-can-predict-behaviors-20211206/

[22] https://www.bbc.co.uk/news/technology-35785875

Bibliography

Other cited articles and books

[30] Darwin, C. (1873). The Origin of Species By Means of Natural Selection, Sixth Edition

[31] Spencer, H. (1866). The Principles of Biology

[32] Bateson, G. (2000). Steps to an ecology of mind: Collected essays in anthropology, psychiatry, evolution, and epistemology. University of Chicago Press.

Bibliography

Other websites (sources of pictures)

[11] https://www.verywellfamily.com/when-should-a-baby-stand-2634693

[12] https://www.wowamazing.com/trending/new-tech/funny-video-of-robots-falling-down/

[13] https://www.wallpaperflare.com/cats-acrobatics-indoors-one-animal-mammal-focus-on-foreground-wallpaper-sduey

[14] https://esgclarity.com/global-warming-set-to-wipe-at-least-10-from-gdp/

[15] https://www.nationalgeographic.com/travel/article/photography-jordan-desert

Bibliography

Other websites (sources of pictures)

[16] https://www.ibm.com/cloud/learn/neural-networks

[17] https://www.reference.com/world-view/eskimos-live-modern-times-77d6f505385f0846

[18] https://thecityfix.com/blog/india-worst-road-safety-record-world-new-law-aims-change-amit-bhatt/

[19] https://commons.wikimedia.org/wiki/File:Fossa_River_and_Waterfall_2.jpg

[20] https://static01.nyt.com/images/2016/07/29/sports/30CRUTCHES/30CRUTCHES-jumbo-v2.jpg?quality=75&auto=webp

[23] https://www.nationalgeographic.com/science/article/131222-amazon-kayapo-indigenous-tribes-deforestation-environment-climate-rain-forest

[25] https://www.nasa.gov/feature/goddard/2021/nasa-and-hurricanes-five-fast-facts

Bibliography

Other websites (sources of pictures)

[26] https://www.ox.ac.uk/news/science-blog/other-side-big-bang

[27] https://www.psychhelp.com.au/your-life-stage-can-impact-your-mental-health/

[28] https://www.internetgeography.net/topics/what-is-continental-drift/

[29] https://www.researchgate.net/figure/shows-the-predicted-environmental-temperatures-and-core-temperature-for-the-desert-iguana_fig11_225258595

[36] https://www.visualcapitalist.com/path-of-human-evolution/