Australian Government
Department of Defence
Defence Science and
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What can natural Complex Adaptive Systems teach us about how to create a robustly adaptive force?

Dr Anne-Marie Grisogono
Defence Science and Technology Organisation
Australia

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What makes a system complex?

a great many 'agents' or elements interacting in great many ways

→ near-'infinity' of possible kaleidoscopic 'patterns'

- Might be all one kind or many kinds of elements
- Looks simple(r) at level of pairs
- Interactions may be just pairwise, or there may be correlations
- Pattern = static state/configuration of system, or…
- … more interestingly see dynamic patterns i.e. time evolution of patterns
- hierarchical structure emerges – patterns interact, forming higher order patterns..
- Complex systems exist in & interact with, a context, have porous boundaries

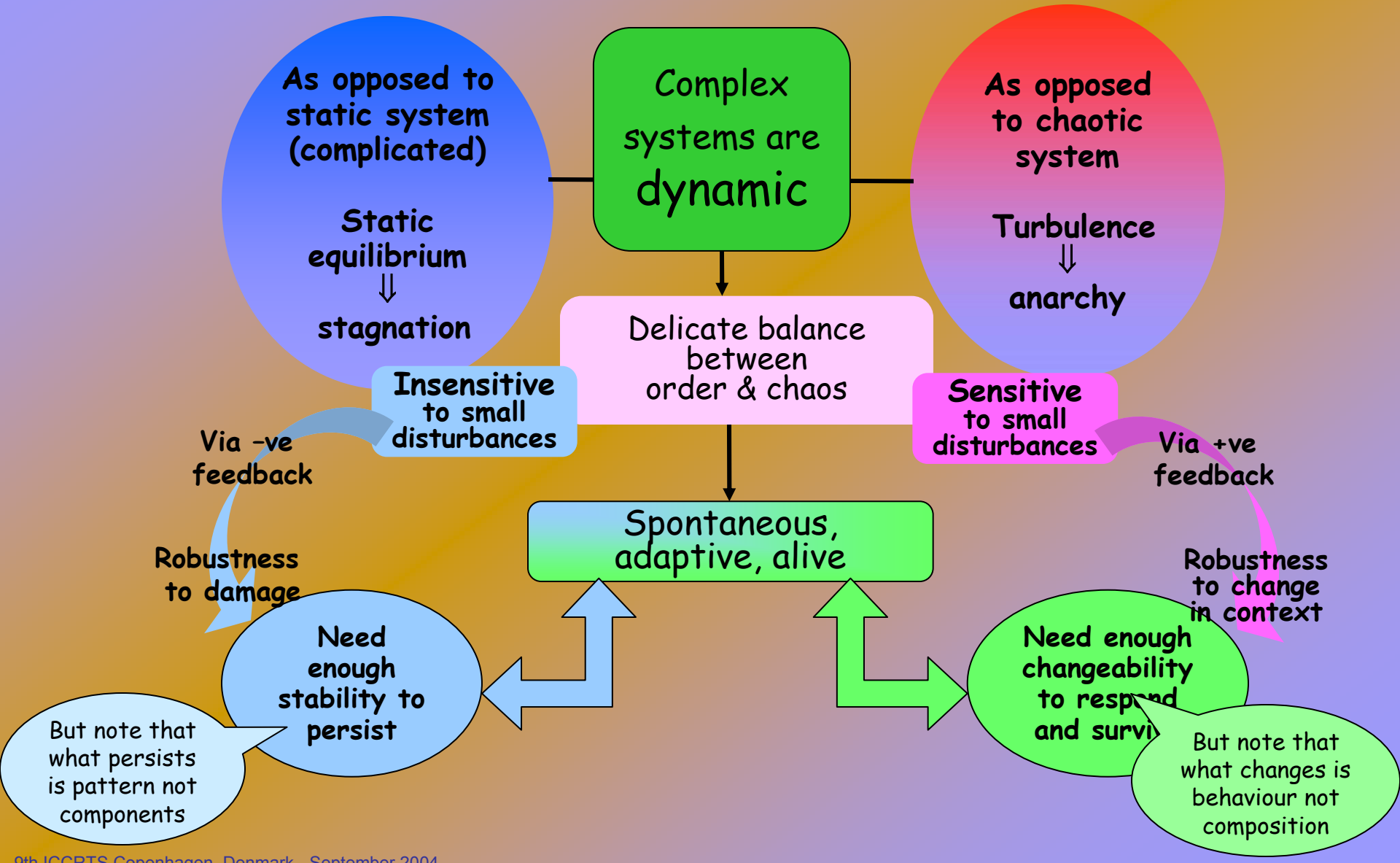
Examples:

SYSTEM	ELEMENT	INTERACTIONS	PATTERN	EMERGENT
molecule	particles	physical forces	orbitals	chemistry
ecosystem	species	consume, compete, cooperate	food chains	species evolution
economy	people, goods	create, demand, consume	markets	inflation, recession…
brain	neurons	fire, stimulate/inhibit	thoughts	memory, reason
flock	birds	see, seek/avoid	flocking	flock migration
genome	genes	switch on/off, express	growth, diff/n	embryo→organism

Common themes

➔ common underlying principles
➔ try to build common theoretical framework

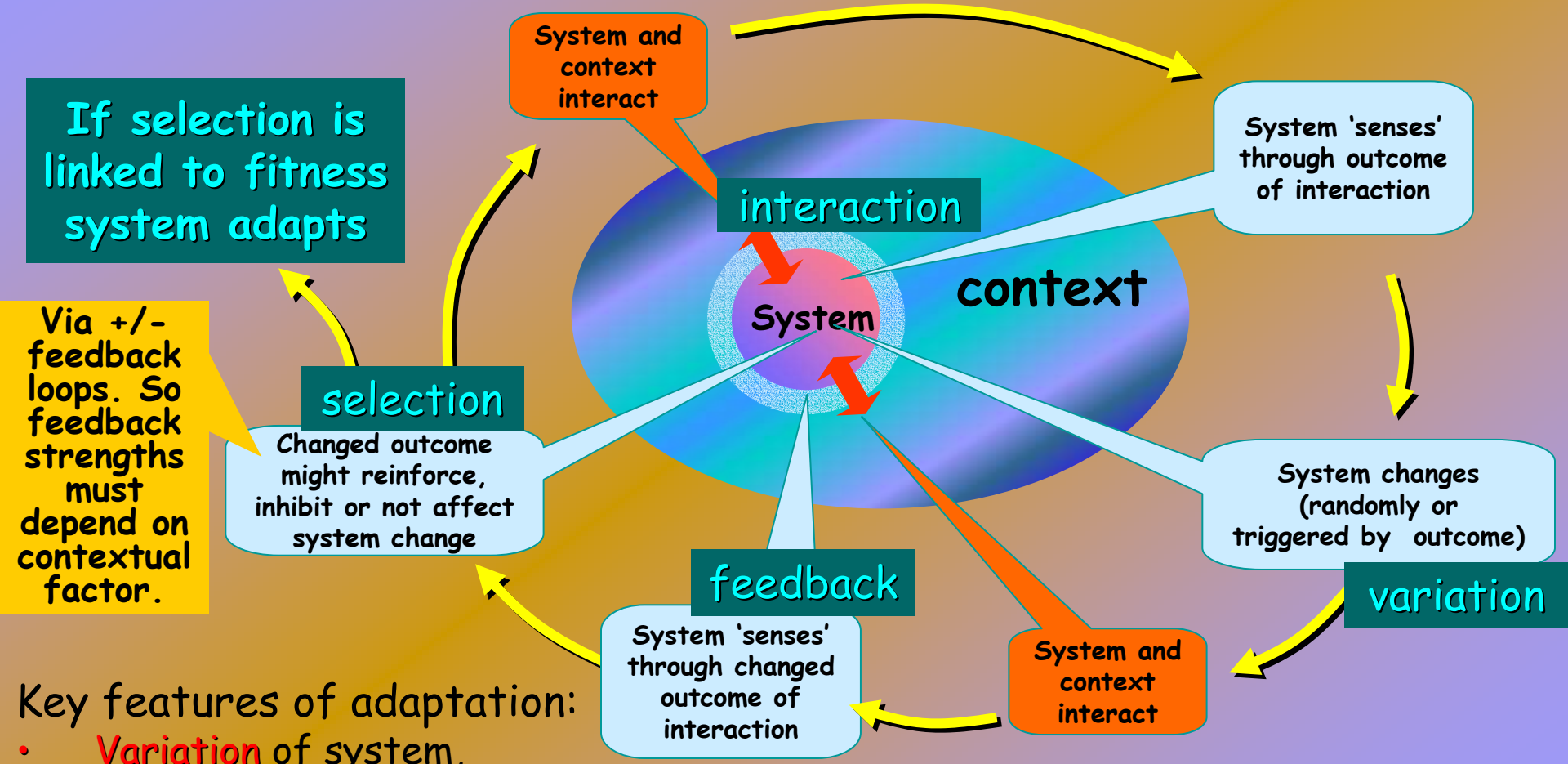
Complex systems are on the "edge of chaos"



Emergence of adaptivity

- **Dynamic patterns emerge…**
  - many simple agents interacting via local simple rules → interesting behaviours and patterns
  - Time evolution of patterns of interaction in complex systems may generate higher order patterns → emergent properties.
- **….but are they adaptive?**
  - System may appear to be changing in ordered way, but changes are not necessarily adaptive – might simply result from fixed rules.
  - 'adaptive' ➔ a concept of 'better' or 'fitness', something to do with context outside of system
  - What is interesting is when changes **are** adaptive, and the system starts to encode information about the context
  - The ability to change is a **precondition** for adaptivity

Adaptation - key feature of complex systems

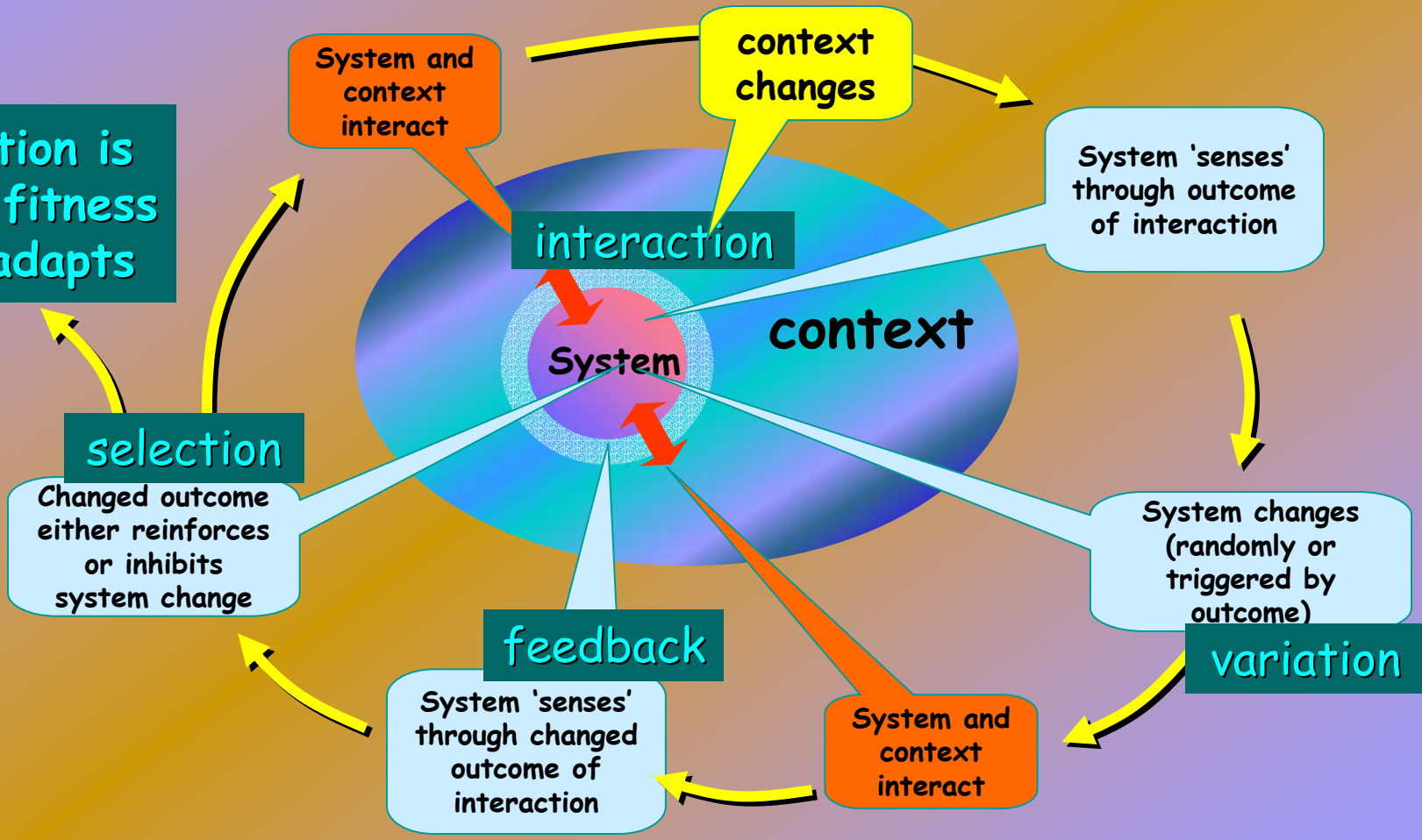


Key features of adaptation:

- Variation of system,
- Feedback through interaction with context, and
- Selection of adaptive change by fitness-linked reinforcement or inhibition

if start with no fitness link, selection may become adaptive through evolution. This is a fixed context, with system fitness improving over time

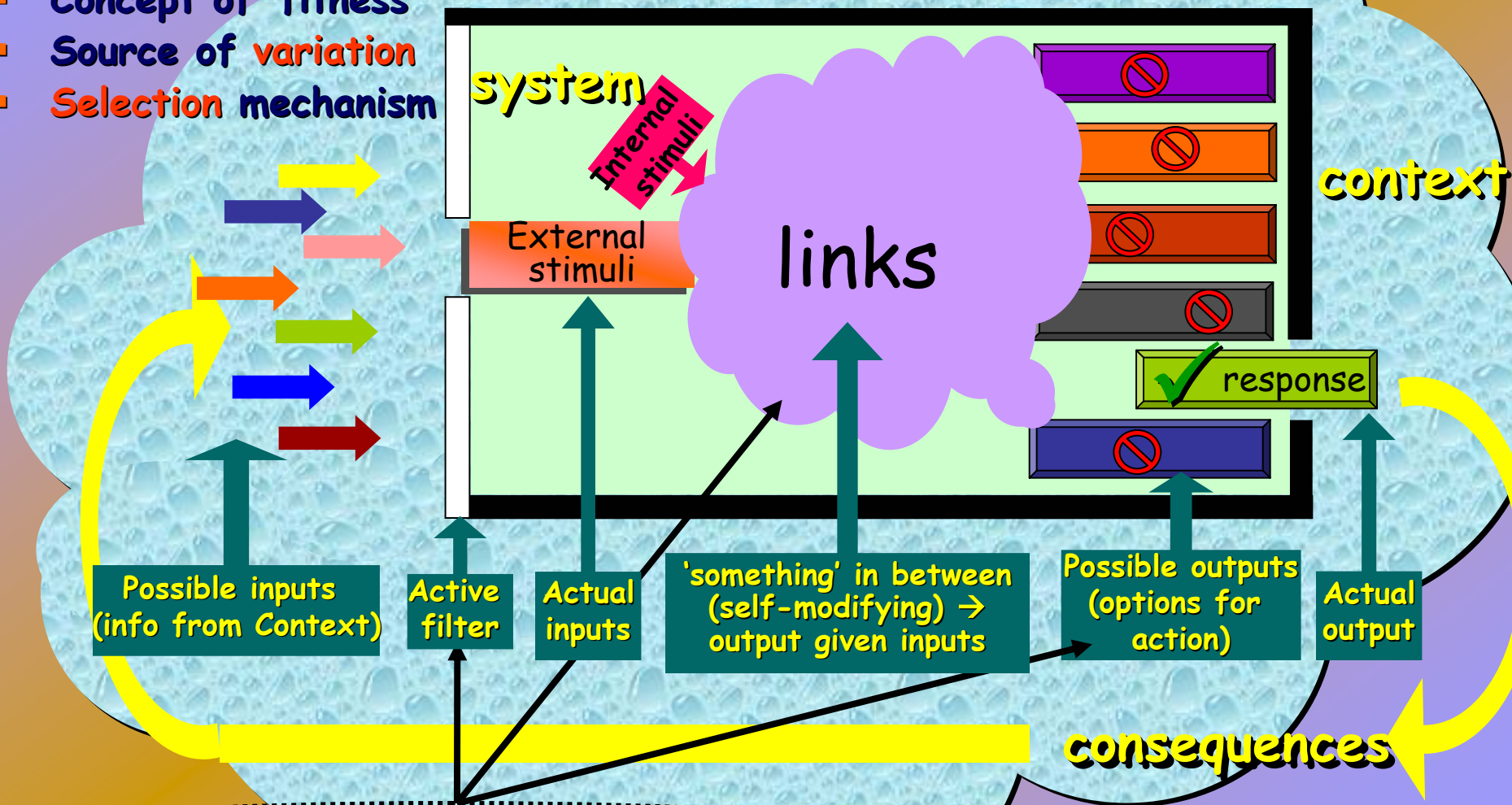
Adaptation enables systems to respond to change



System can track changes in its environment and remain adapted provided $\tau_{context} >> \tau_{adaptation}$

Key features of adaptation

- Concept of 'fitness'
- Source of variation
- Selection mechanism



- interaction properties, feedback strengths encode info about context

ratchet-like mechanism extracts info from context by selective retention of fitness-enhancing variations and discarding of fitness-decreasing ones.

Adaptation in Natural Complex Systems

increases information content of system so as to improve 'fitness'

ADAPTATION	Organism: LEARNING	Species: EVOLUTION	Society: D[illegible] of CULTURE
Where is information	In system [illegible]ween sensing & acting – eg stimulus-response circuits, brain, biochemistry…	In population of genomes (types & frequencies)	Extra-somatic, in media
What is 'fitness'?	Probability that individual thrives	Probability that individuals survive so that their genes are passed on in viable offspring	Prob that culture thrives? (ideal) or that cultural objs proliferate? (tautological)
Interaction mechanism *serial/parallel *what stimuli include *responses available * How linked	Serial interaction process. Links between sensed stimuli and responses produce options **1 direct**: try it in the world: feedback from interaction with context → modify links, attention to inputs, **2 indirect**: try it in your head: preselection of likely 'winners' and avoidance of 'killers' by modelled interaction .	Highly parallel interaction process, not context sensitive. Natural genetic variation in population + sexual selectn determine what gets tried. So 'stimuli' & 'link' are N/A	Highly parallel process. Vast number of ideas, practices, structures are generated in response to vast no of context conditions
Feedback & Selection mechanism *what to keep *what discard ***fitness correlation**	Response → consequences → sticks and carrots → good outcomes reinforce **whole** (stim, link, resp) activation pattern, bad inhibit → prob of future 'good' response↑ thru better context-sensing, better options, better choices. Strength of fitness correln variable…	Differential reproduction as result of interaction with context and within system through competition for limited resources reqd for reproduction. Selection totally correlated with fitness.	→differential proliferation → some 'prevail' / disappear → custodian survival prob ?? Selection processes weakly linked to ideal fitness. .. But varies widely
Variation Source of new info (stim, link, resp)	Random: trial & error Others: imitation + error Creative: recombination From culture: education	Mutation, copying errors, recombination, retroviruses	Scientific research; creativity; analysis of recorded information; random?
OUTCOME	**More responsive to local environment** - improves how fixed design is used; gain is local (time & individual).	**More responsive to large scale changes in environment** Explores design space nbhd → new design features	?? Impacts on learning and evolution – **new adaptation mechanisms may arise**

increases information content of system so as to improve 'fitness'

Adaptation in Designed Complex Systems

ADAPTATION	LEARNING	EVOLUTION	CULTURE
	ADAPTIVE SYSTEMS	**FORCE DEVELOPMENT**	**eg Def role in society?**
Where is information	In system bet. sensing and acting – datastores, system parameters	In SoS architecture, in tech designs, doctrine & process, organisational struct…	Outside of the system, in media
What is 'fitness'?	Ideal: externally defined cost and effectiveness	Ideal: externally defined: force meets strategic reqts.	Prob that concepts about Defence proliferate and adopted by key players?
Interaction mechanism *serial/parallel *what stimuli include *responses available * How linked	Basically serial but can be parallel-ised – in single sys, or in population. Stimuli & response options may be open or fixed i.e. adaptive or not. Links (option selection) may be: **1 direct:** feedback from context **2 indirect:** preselection of likely 'winners' and avoidance of 'killers' by modelling interaction with context, based on sensed info	Parallel only at low end. Multiple complex inputs: serial processes of strategic analysis, force assessment, tech watch, Response options are various cap delivered by sys eng, sys integration, acquisition, doctrine development, linked by complex serial decision processes, supported by modelling and analysis… plus political, sociological and economic factors.	Deliberate shaping of a highly parallel process with many co-existing responses to many aspects of perceived contexts ??
Feedback & Selection mechanism what to keep what discard	Depending on design, how success or failure is measured - data from context can be used to modify variable aspects of inputs, responses and links. Strength of fitness correln is variable	Interaction with context and within system via competition for limited resources reqd for implementation. Active selection based on modelling to preselect likely winners etc Plus other factors…. Selection criteria are Prob that dev is implemented, prob decision-makers think dev will → reqd intent?	?? Have to understand reinforcement and suppression mechanisms
Variation Source of new info (stim, link, resp)	Random: trial and error By design: fixed inputs, menu, and algorithms Creative: recomb/n, neural nets, search algorithms	Scientific research; human creativity; computer-aided design, analysis of recorded information …	?? Analysis, extrapolation, recombination, what ifs…
OUTCOME	**More responsive to local environment** - improves how fixed design is used; gain is local… but shareable.	**More responsive to large scale environment changes** Explores design space nbhd → new design features	Maintain conditions for continued success in capability evolution?

System in the force | the force | the world

So… how **do** we make a force robustly adaptive??

Generalisation of Ashby's law of Requisite Variety

Have to distinguish between learning systems and evolutionary systems – both are adaptive, but have different strengths and issues.

'Learning' type systems

- Usually serial, local,
- tunes use of design
- Action mechanism has three information-containing elements:
  - Inputs = Stimuli
  - "C2" = Processing
  - Outputs = Responses

  ALL THREE can be modified through adaptation, i.e. by
  - variation,
  - interaction providing feedback, and
  - selection.

Create variety

Decide what to keep

- We need to address problems:
  - What is intended "fitness"?
  - Find heuristic measures correlating with intended (longer-term) fitness but providing feedback over faster adaptation timescale
  - accelerate whole adaptive cycle
  - How to simultaneously adapt at multiple levels: "learn to learn"
  - Figure out what/how to disseminate what is learnt

'Evolutionary' type systems

- MUST BE highly parallel, can be distributed,
- produces new designs
- Action mechanism has two information-containing elements:
  - System 'genotypes'
  - Frequency distribution of 'genotypes' in population

  both are modified through adaptation, i.e. by
  - variation,
  - interaction (compete to reproduce), &
  - Selection (what turns up in next generation)
- We need to address problems:
  - If simulating, what is intended "fitness"?
  - Find heuristic measures correlating with intended fitness estimable in simulation environment
  - Simulate and accelerate co-evolution
  - Costly
  - Slow

Summary: Critical Aspects of Designed Adaptation

What is hard – and what is worth paying attention to to increase adaptivity!

1. Lack of clarity about what intended fitness is
2. Measuring fitness/success in real world, estimating it in models
3. Disconnect between fitness and selection mechanisms operating
4. Deciding what to sense in context/ what stimuli to pay attention to (inputs)
5. Generating new more successful responses (outputs)
6. Encoding of information about the world into the system, evaluating candidate responses and understanding under what conditions to pick which response (links)
7. Understanding the reinforcement and suppression mechanisms already operating and being able to modify them to support the intended adaptation
8. Deconflicting self-organised and imposed mechanisms
9. Being able to execute adaptive cycle fast enough to keep pace with changing context
   - How to parallelise the selection process
   - How to forecast rapidly changing context
   - How to quickly implement adpative changes identified
10. Linkages between levels of adaptation – decoupling them for manageability, managing the coupling for creating conditions for success
11. Handling an adaptive context (internal and external to own force) … danger of instabilities … Managing co-evolution.