Lecture

Organic Computing II

Summer term 2020

Chapter 3: Quantitative Organic Computing

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Motivation

ORGANIC COMPUTING

Organic Computing means:

- Using concepts such as self-organisation in technical systems.
- As a result:
  - Traditional design-time decisions are moved to runtime.
  - From the engineer to the systems themselves.
  - Goal: Higher robustness, reduced complexity.

Engineering means:

- Quantification of system properties
- “Prove” that an organic system is better that any other.

→ We have to define the basic “ingredients” of OC systems.
→ We have to quantify the required aspects.

ORGANIC COMPUTING

What makes an OC system special?

- Emergence may occur.
- The system is self-managing.
- This self-managing process requires objectives or a utility.
- Systems come with a control mechanism that acts autonomously.
- This control mechanism can be distributed in various ways.
- It recovers the system after disturbances occurred.
- Self-organisation takes place to change the system's structure.
- Self-adaptation takes place to change the system's configuration.

Agenda

ORGANIC COMPUTING

Content

- Motivation
- Autonomy and self-organisation
- Quantification of self-organisation
- The survival cycle of an organic system
- Robustness
- Autonomy
- Conclusion and further readings

Goals

Students should be able to:

- Define what the terms self-organisation, autonomy, adaptability, utility, robustness, disturbance, and variability mean.
- Explain the behaviour of an organic system according to a state space model.
- Describe the OC survival cycle.
- Quantify robustness, self-organisation, and autonomy.

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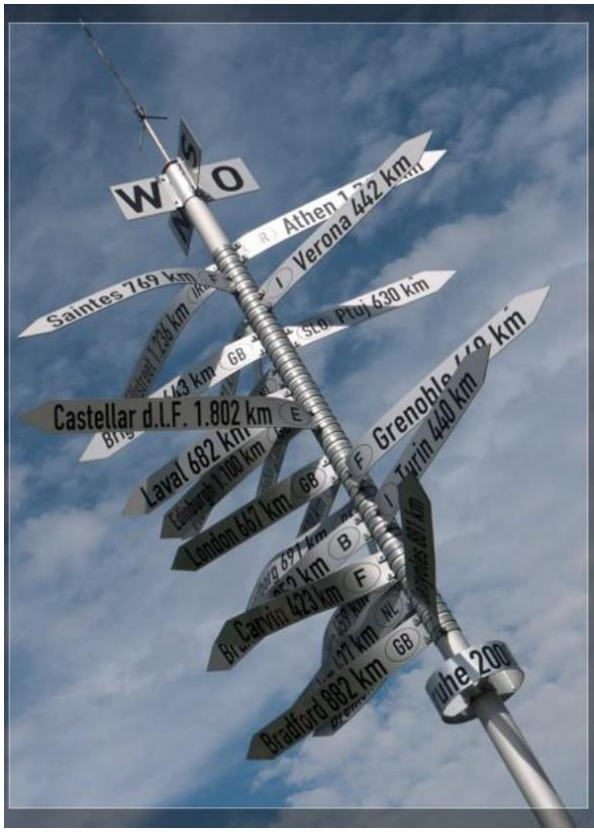

Example: An ordering game

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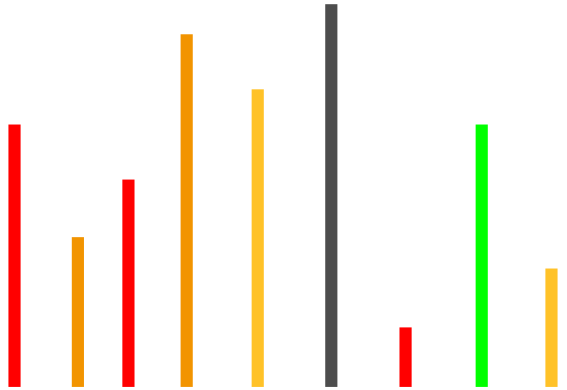
- Properties of each stick
  - Length
  - Colour
- Ordering objectives
  - increasing length
  - decreasing length
  - colour clusters

Ordering activity?



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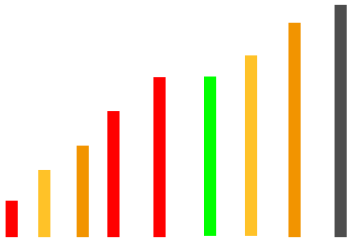

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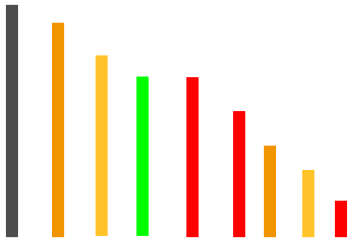

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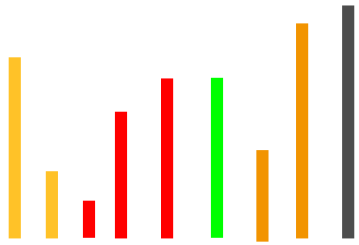
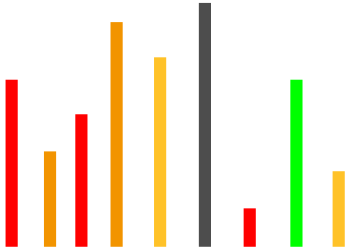
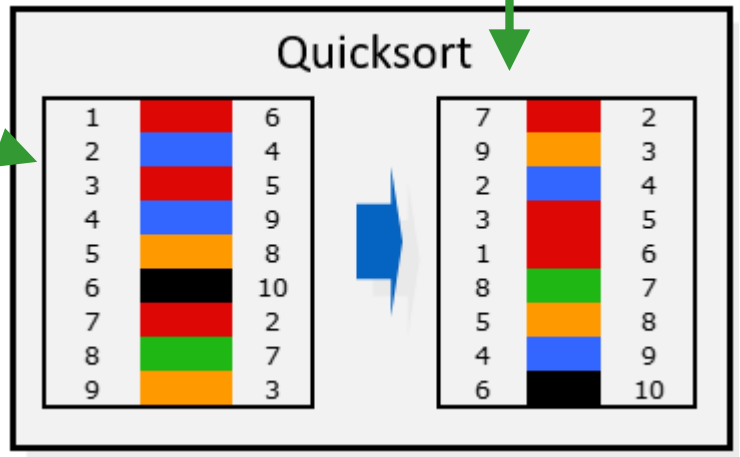


Example: An ordering game (2)

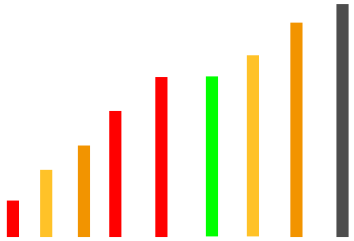


Global objective a := increasing length

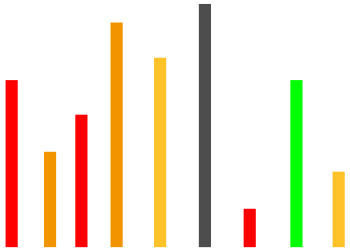


1 Observation
2 Model building
3 Simulation

4 Enactment



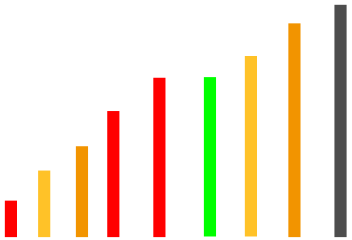
Example: An ordering game (3)



Global objective a := increasing length

1. Local objective: right > myself
2. Local observation: right < myself
3. Local decision:
   if right < myself then Switch places;
   else: nil
4. Local enactment
5. Go to 2

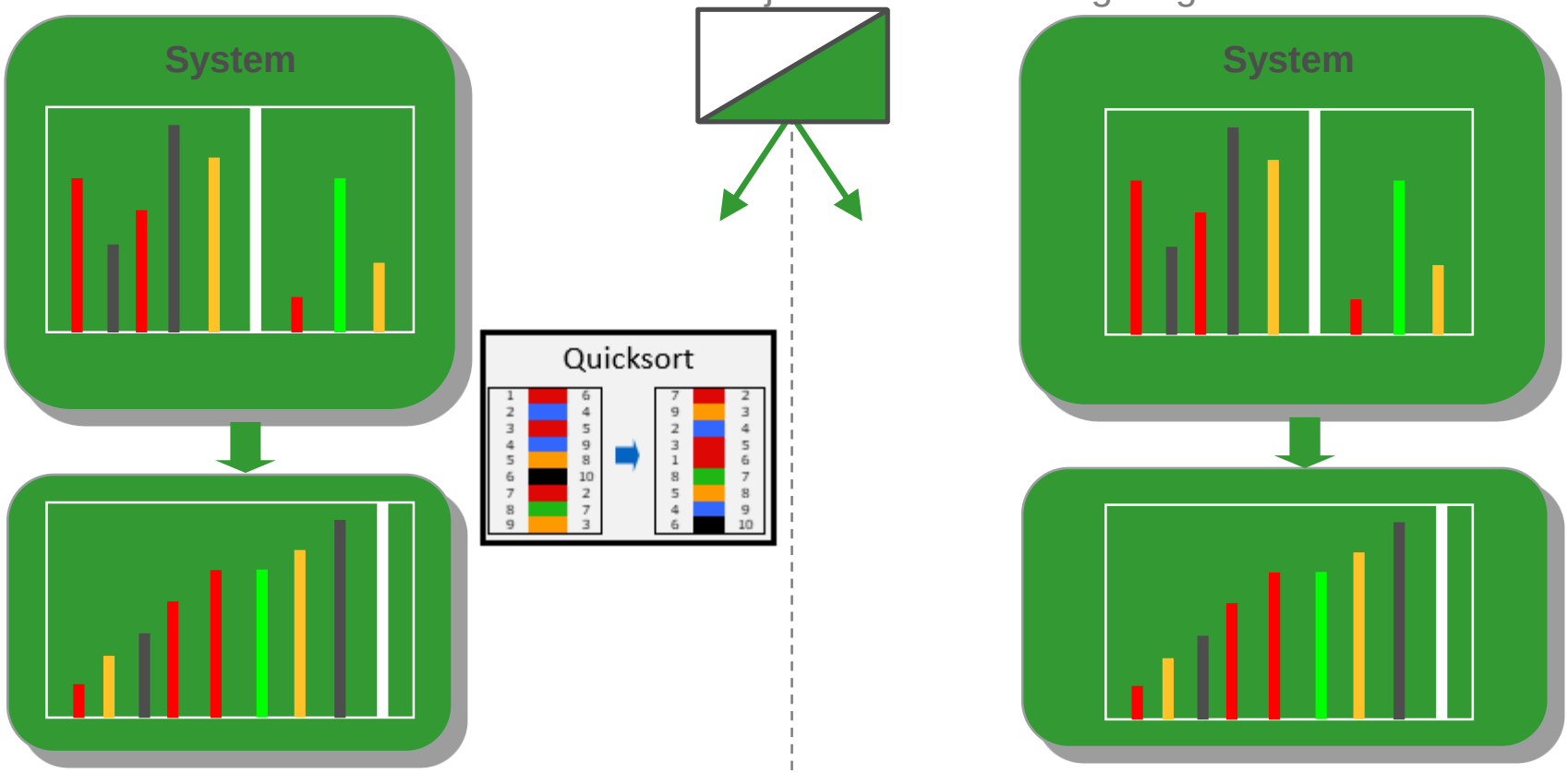
An “intelligent system“ that autonomously acts in the “game“.



Example: An ordering game (4)

Question: Is this self-organisation or autonomy?

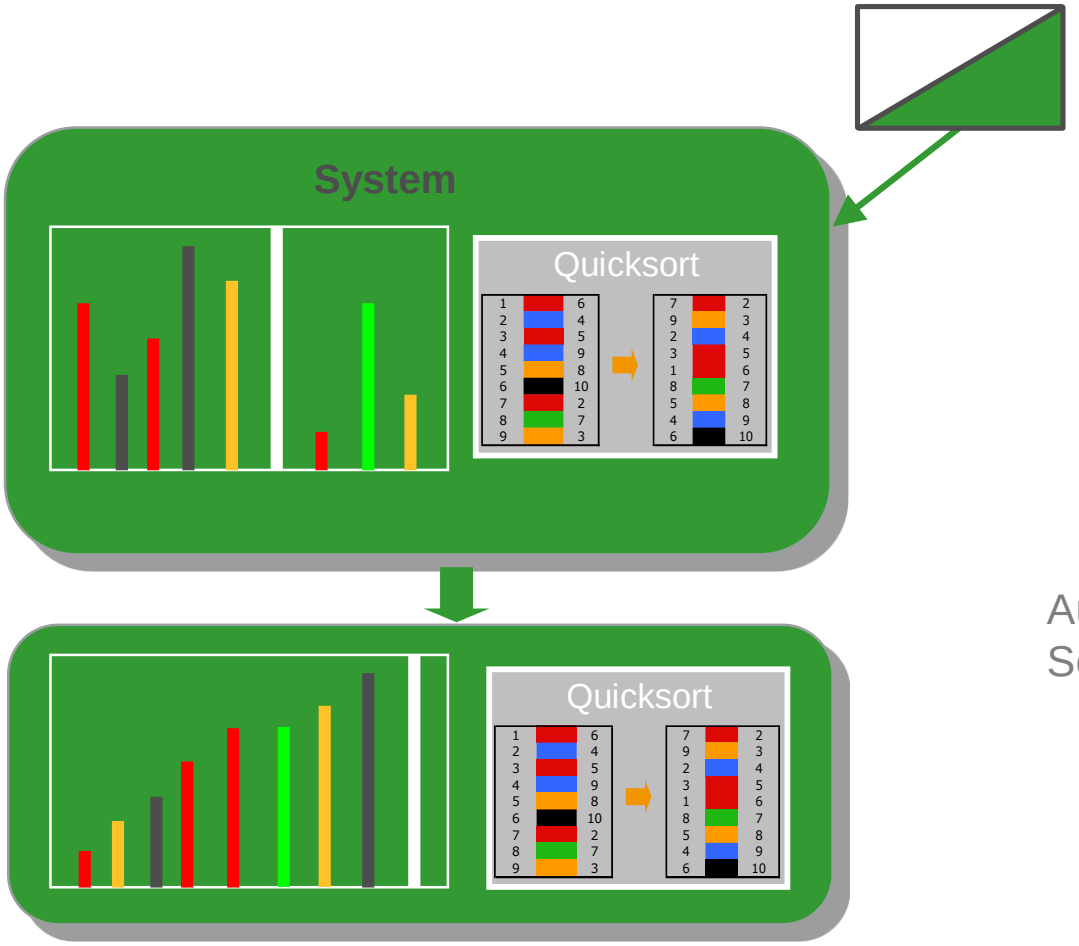
Global objective := increasing length



Autonomy No
SO? No

Autonomy? Yes
SO? Yes

Example: An ordering game (5)



Global objective
:= increasing length

Autonomy? yes
Self-organisation? maybe

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What can we learn from these examples?

- Preliminary definitions
  - Autonomy:
    - A System changes its structure without explicit external control.
    - There must be some kind of internal control mechanism!
  - Self-organisation:
    - The internal control mechanism is distributed (to a certain degree).

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What is self-organisation?

- Intuition suggests that a self-organising system is
  - a multi-element system (consisting of m elements, m > 1)
  - which needs no (little) external control to restructure itself (i.e., it has a high degree of autonomy).
- Common assumption:
  - System consists of one or more productive parts (i.e., the m elements) and an internal control mechanism (CM).
  - CM of a self-organising system is (to a certain degree) distributed over the *m* elements.
- The control mechanism (CM) can be:
  - centralised (one CM)
  - distributed over the m elements (m CMs)
  - distributed over a hierarchy of CMs.

Distribution of the control mechanism

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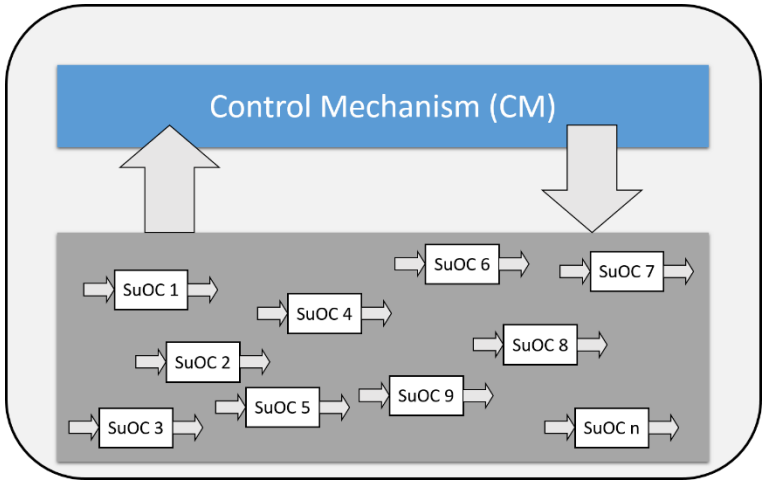

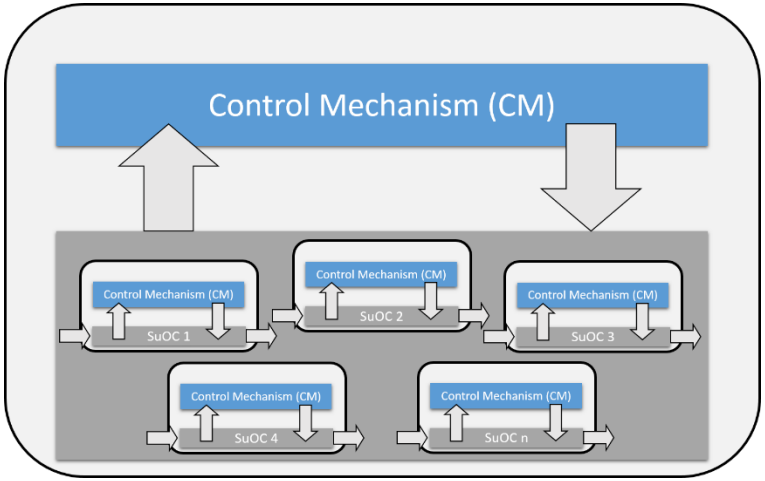

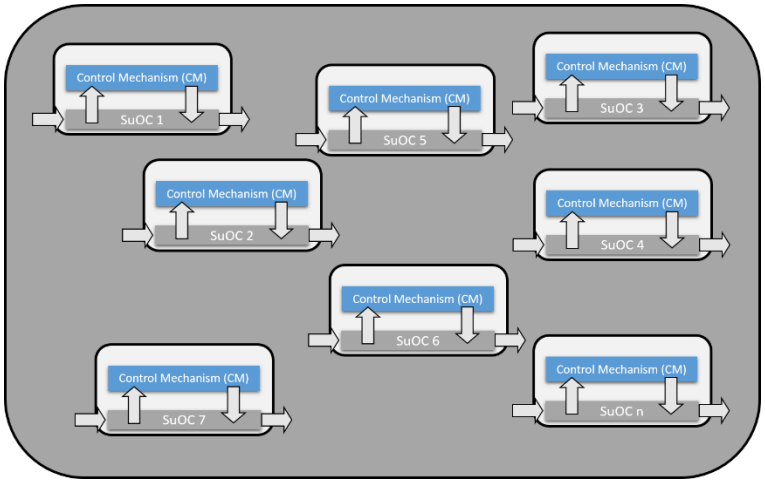

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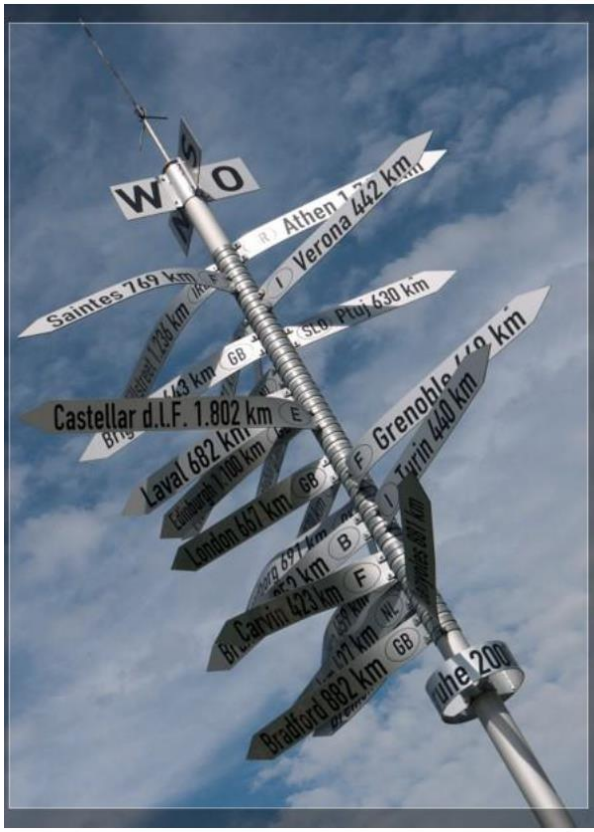

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Quantification: static degree of self-organisation

- Let S be an adaptive system consisting of m elements (m > 1) with large degrees of autonomy (α and β) and fully or partially distributed k control mechanisms CM (k ≥ 1) leading to a degree of self-organisation of (k : m).
- S is called strongly self-organised, if k = m, i.e. the degree of self-organisation is (m : m).
- S is called self-organised, if k > 1, i.e. it has a medium degree of self-organisation (k : m).
- S is called weakly self-organised, if k = 1, i.e. there is a central control mechanism and the degree of self-organisation is (1 : m).
  → Assumption: all CM are internal!

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Assumption:

- Exclude pathological organisational forms, e.g. the concentration of all CMs on a single controller, hidden CMs, etc.

Distinguish between following terms:

- Systems can be modified at runtime in terms of (i) structure and/or (ii) parameter values.
- Self-configuration relates to a (re-) parameterisation of a system.
- Self-organisation relates to change of the structure of a system (i.e. of components and their links).
- Self-management comprises self-configuration, self-organisation, and possibly further self-* mechanisms.

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Static degree of self-organisation

- Assumes full access to the design concept.
- Needed to identify and count the CM structures.
- A quantification of self-organisation from an external point-of-view, i.e. without interfering with the system's logic and design, needs a different approach.
- In the following, self-organisation is considered as a process at runtime instead of as a static value.

Self-organisation as a process

- Self-organisation: system's ability to modify its structure autonomously and in order to optimise a certain utility function.
- System is expected to make use of its self-organisation capability in response to certain events rather than as a permanent change.

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When is self-organisation observed at runtime?

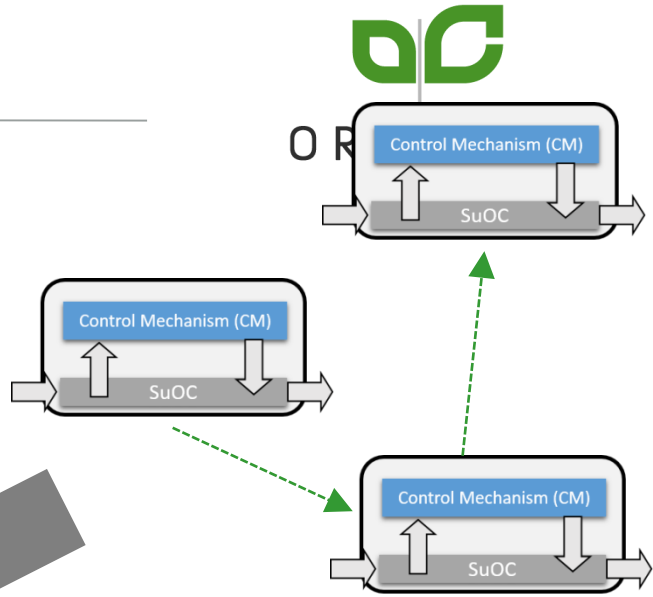
- When the system increases its degree of organisation and builds up a structure (i.e. at system start),
- When a disturbance happens and the system recovers to its previous degree of organisation.

Approach

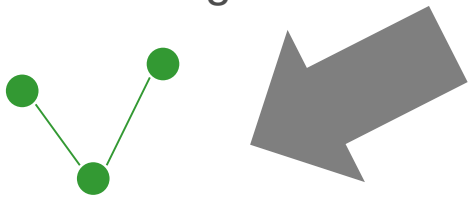
- Internal values are not accessible.
- Observe each (distributed) component of the entire system.
- Relationships between distributed components of the entire system define the structure of the system.
- Relationships are established and altered using communication.

→ Observe the communication and estimate relationships out of this behaviour.

Self-organisation as a process (2)



- Build a graph G = (V, E)
  - Each component/entity is modelled as a node.
  - Each relationship is modelled as an edge.



- From this graph, we can derive two aspects of self-organisation:
  1. The changes between two consecutive points in time that signalise that the structure in the system has been altered. This information is used to quantify to which degree self-organisation processes occurred in the system.
  2. The difference between the possible relationships and the actually utilised relationships over time. This information signalises to which degree the system makes use of its organisation potential.

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Approach: build a graph at both time steps (i.e. t_0 and t_1)

- Assumption: all communication is observable from the external and this communication is purpose-oriented.
- Communication is encoded with origin and destination.
- Messages are distinguishable at a semantic level: Those related to structure information are turned into an edge of the graph.
- Message model: unicast (or multicast) messages.
  → Broadcasts for bootstrapping reasons only (neglected here).

$$\Delta(G_1, G_2) = \frac{|\{e_{ij} : e_{ij} \in E_1 \oplus e_{ij} \in E_2\}|}{0.5 * (|V_1| + |V_2|)}$$

- Value of Δ : quantifies self-organisation that occurred in the system in the considered time frame.

E_k : set of edges of the k-th graph (i.e. G_k)
V_k : set of nodes of the k-th graph (i.e. G_k)
Each edge e_{ij} : directed connection from node i to j

Quantifying the potential for self-organisation

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- Isolated information of Δ just highlights that something happened.
- Good indicator when observing just one system to decide whether self-organisation appears or not.
- Goal: compare different systems
  - Put information of how much self-organisation has been observed into relation to the possible decision potential.
  - Quantify to which degree the system made use of its ability to self-organise.
- Required: estimate the decision potential (corresponds to the possible communication partners). Two approaches are possible:
  1. information is available by design or
     → designer specifies possible communication partners for each node.
  2. it has to be approximated at runtime.
     → method needed.

Approximation of self-organisation potential

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Approach:

- Continuously observe all structure-related communication of the node under consideration and analyse each message.
- Maintain a list of interaction partners I_j (either as origin or as destination of the observed messages) for each node j.
- Every time, a new interaction partner is observed, add it to the list.
- Pessimistic alternative, a worst case estimation is possible by assuming that each node is able to interact with each other node, resulting in a fully connected graph.

Please note: approach only results in meaningful information after observing the system for a certain period of time. Comparing the actual relationships to those ever observed in the system has only impact after a certain amount of change has occurred.

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Approach (ctd.):

- At a certain point t_{quant} consider set of interaction partners I_j.
- Build directed graph: edges connecting node j and its partners.
- Result of this process is reference graph G_r.
- Instead of the previous approach, where two distinct points in time are represented as graphs in terms of snapshots of conditions, we now consider the entire process.
- Compare all observed changes over time (i.e. the number of modified edges) to the reference graph to come up with a (dynamic) degree of self-organisation until a certain time t_{quant}.

$$SO(t) = \frac{|E_t|}{|E_r|}$$

Set E_t contains all edges that have been changed from system start to time t, and E_r contains all edges of the reference graph. Please note that by definition $|E_r| > |E_t|$.

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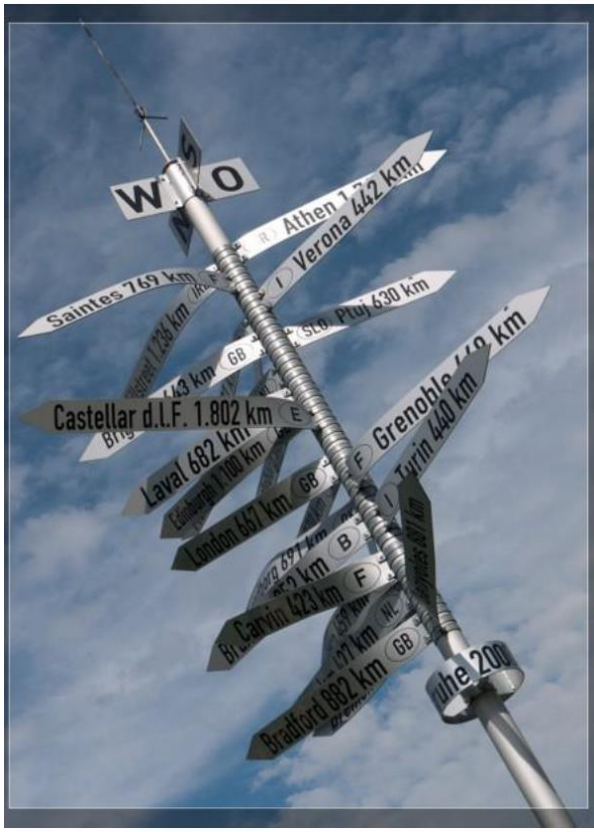

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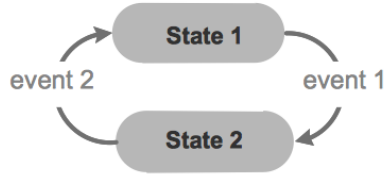
Motivation

- Systems face the challenge to survive in an ever-changing world.
- Behaviour can be modelled as survival cycle.
- Model is used for formalisations and metrics afterwards.

An initial model

- State machine
- External events change the state of the system in a pre-programmed way.



Example: state machine with 2 states.

- Automaton encodes a predefined sequence of steps to be executed depending on the received input information (the events).
- There is no way to express preferences or ambiguities, though, since all transitions are deterministic and all states are equivalent.

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An OC approach

- Adopt the method of a state description, add preferences!
- Perspective of an agent:
  - has the goal to survive.
  - there are certain system states more desirable than others.
- Agent is at any given time in a state **z**.
- Moved to a different state by an event. Origin can be:
  - internal (e.g. a malfunction of the agent itself) or
  - external, i.e. a change in the environment.
- A state so far is neutral and does not indicate a value (i.e. good or bad).
- Needed: a state's utility in relation to a given goal.

Survival cycle (3)

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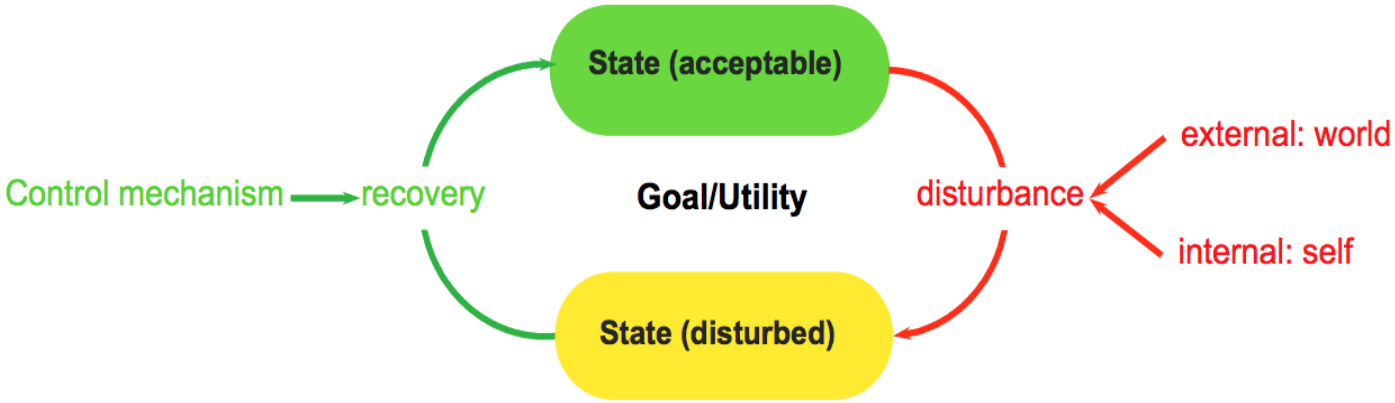
- Goals distinguish good states from bad ones (same holds for influences):
  - In relation to a given goal, a state is acceptable or disturbed (i.e. not acceptable).
  - An OC system always tries to stay in an acceptable state.
  - A disturbance causes a deviation from the acceptable state, the control mechanism will initiate recovery actions to guide the system back into an acceptable state.



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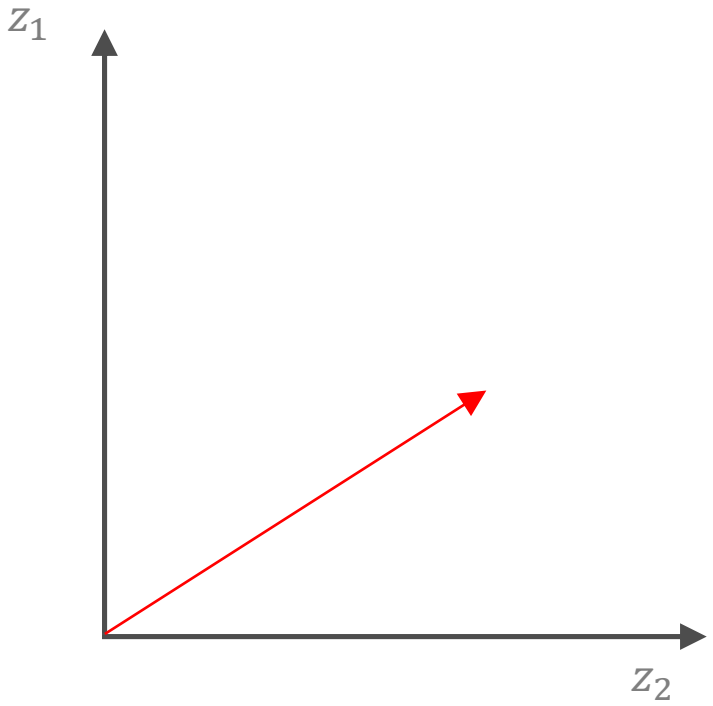
The system state

- Given by a vector **z**.
- With single attributes as components.
- Any useful metric to characterise the system state possible.
- But:
  We are interested only in observable metrics (by system itself).



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- Example:
  - State of a robot with a GPS localisation system might be defined as its x and y coordinates.
  - Robot is able to determine these coordinates itself: x and y are self-observables and part of the state vector.
  - Without a GPS: coordinates are known only from the point of view of an external observer.
    → Not part of the state vector.
- Further examples of state vectors are:
  - Ordering game: z = (length of stick 1, colour of stick 1, length of stick 2, colour of stick 2, …)
  - Traffic controller: z = (traffic flow in cars/hour for all turnings of the intersection)
  - Router: z = (length of message queues, link status)

State (3)

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- Observables might originate from the “world”.
  - I.e. perceived via the external sensory equipment of the agent.
  - Or from its internal sensors (indicating e.g. the battery level, the functional status of a motor, or the length of a task queue).
- In a stricter sense, all observables are internal since even perceptions stemming from the external world are first transferred (possibly under some distortions) into the agent’s internal world model before they can be used for control purposes.
- This is equivalent to the “beliefs” in the BDI agent model.
- At any given time t, the system S is in a state **z**(t).
- If there are n observable attributes used to describe the state of S, **z**(t) is a vector in an n-dimensional state space Z^n.

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- State vector of a system S is a neutral and (as far as possible) objective statement about the knowledge (or beliefs) of S.
- It becomes a statement about values (good or bad or something in between) by assigning values to the state.
- Assignment is achieved by a utility function η.
- The function η maps the system state into a set of real numbers **u**:

$$\mathbf{u} = \eta(\mathbf{z});\ u_i \in R$$

- **u** is used to represent the objectives to be achieved by the control mechanism of S.
- Objectives can be a maximisation or a minimisation.
- **u** can consist of different utilities u1, u2 … resulting from different state attributes and their combinations.
- Utilities can even contradict each other (multi-criterial optimisation).

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Examples for utility assignments:

- Ordering game (with increasing order): Let **u** denote the number of local mis-orderings (i.e. the number of locations i where the height of stick i + 1 is lower than the height of stick i); then reduce **u** to zero!
- Distributed workers having to work on a number of tasks: Let **u** be the aggregated differences in the number of tasks per worker; make **u** as small as possible.
- Vehicle passing a network (from A to B): Let t_{travel} be the travel time from A to B and t_{opt} the optimal realistic travel time, then define the utility as **u** = $t_{travel} - t_{opt}$ and minimise **u**.

→ An additional conflicting objective could be to minimise the fuel consumption of the vehicle.

Utility (3)

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- Utilities can be used to visualise the problem faced by the agents.
- If each state is mapped onto a utility value, we obtain for an n-dimensional state space an n+1-dimensional fitness landscape.
- The agents navigate in this landscape and try to assume a state with a high utility (corresponding to a high fitness).
- In case of a 2-dimensional state space, the utility or fitness landscape is a 3-dimensional surface (utility = fitness).

Utility (4)

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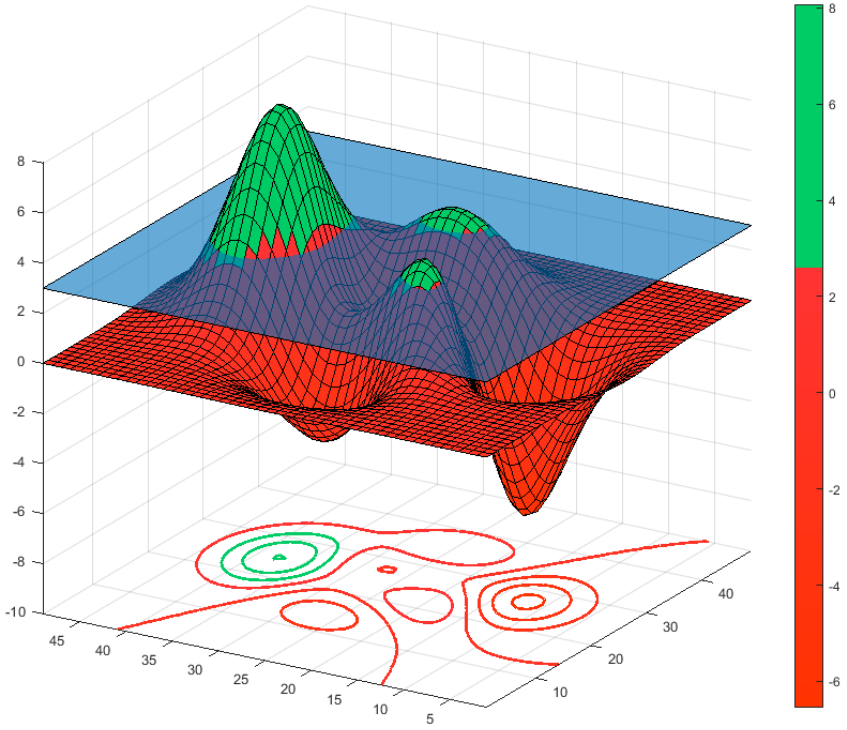
Example:

- 3-dimensional fitness landscape for a 2-dimensional state space.
- Fitness threshold (e.g. an acceptance threshold) is a plane (blue) cutting the fitness “mountains” horizontally.
- All states with a utility higher than the threshold are acceptable (green).

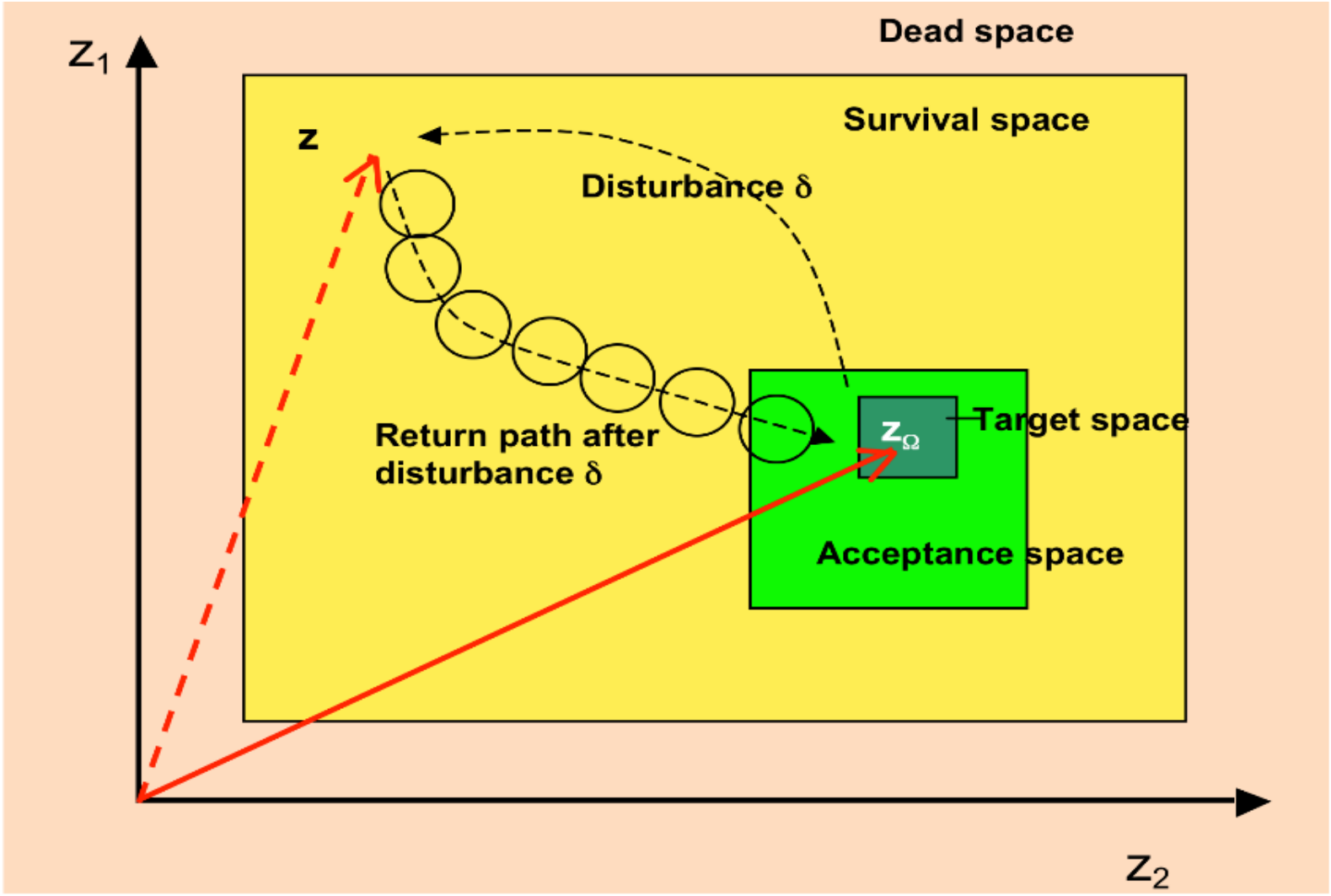


ORGANIC COMPUTING

From state and utility to state spaces

- State vector of a system S is a neutral and (as far as possible) objective statement about the knowledge (or beliefs) of S.
- Utilities are used by control mechanism to compare the current state with an ideal system state.
- If the actual utility is lower than the desired one, the control mechanism has to trigger actions to reduce the difference, i.e. to optimise the system.
- Needed: Thresholds categorising behaviour.
- Goal:
  - Classify states according to utility!
  - Provide different state spaces that require different actions from the control mechanism.

State spaces (2)



State spaces (3)

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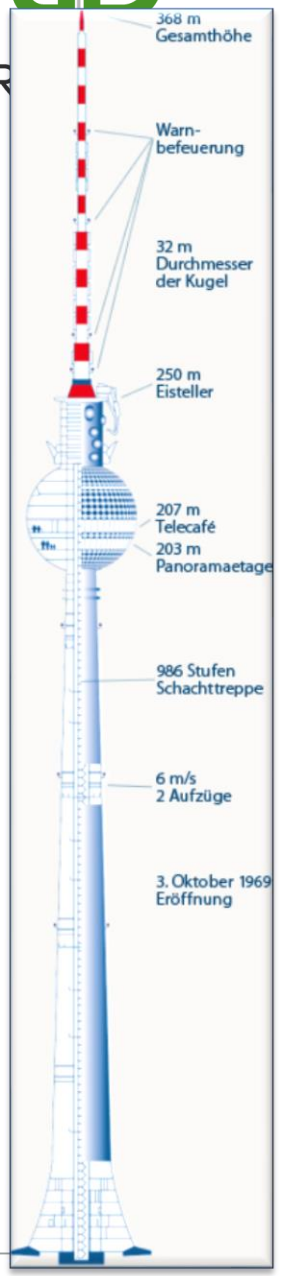
Distinguish state spaces:

- Target Space: All states with a utility u ≥ u_{target} belong to the target space Z_{Ω} (might also be just *one* globally optimal state).
- Acceptance Space: We denote those system states as acceptable whose utility is greater than or equal to u_{acc}. The set of all acceptable system states is called acceptance space $Z_{acceptable}$.
- Survival Space: An OC system will always try to return to an acceptable state. Such a recovery is possible only from a certain subset of states, the Survival space.
- Dead Space: Any disturbance δ moving **z** outside the survival space will be lethal for S: Such states belong to the Dead space.

Example: Broadcast Tower

- Tower moves continuously (deflection)
  - Without human perception
  - On top with a radius of about 60cm
  - At the tower cafe with $r = 15cm$
  - The frequency of changing the deflection is about 7 to 10 seconds
- Goal (target): deflection = 0!
- Acceptance: deflection= ±60 cm (still open to the public)
- Survival: deflection >60cm and <120cm (closed to the public)
- Damage*: deflection> ±120 cm



Example: Broadcast Tower (2)

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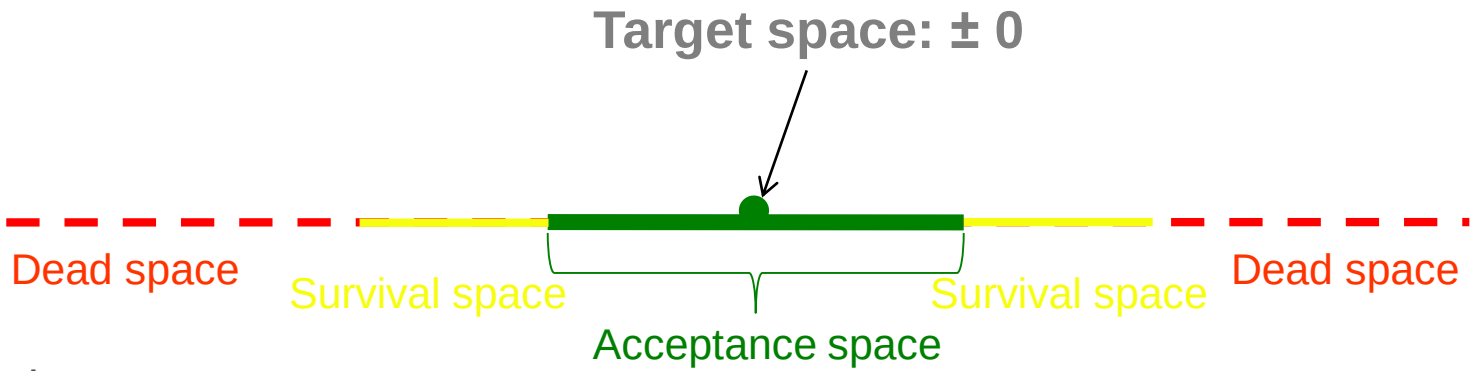
- Formalisation:



- Dead space:

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Disturbances

- The system might be disturbed by environmental influences or disturbances δ.
- A disturbance δ changes the state z(t) into the disturbed state $z_\delta(t) = \delta(z(t))$.
- As a result: utility changes to $u_\delta = \eta(z_\delta(t))$.
- If $u_\delta < u_{acc}$: the system is outside the acceptance space.
- Examples for such a disturbance:
  - Sudden relocation of a stick (in the ordering game).
  - Failure of some component (e.g., in the travel scenario, a vehicle could get a flat tire or a road might be blocked by an accident).

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Notion of disturbance

- Also includes changes in the evaluation criteria.
- Example: a change from an ascending to a descending ordering objective or from sorting with respect to height to grouping with respect to colour.
- Corresponds to a relocation of target and acceptance space and not a state change of the system!
- For control mechanism: Same concept.
  → It must become active until **z** is again within $Z_{\text{acceptable}}$.
- We refer to a shift in the utility (i.e. a change of the goals given by the user) as **flexibility**.

An OC system is *flexible* if its control mechanism guides the system back to (at least) an acceptable state after a change of the utility occurred (i.e. the state-utility mapping results in modified values); within a predefined time period.

Recovery

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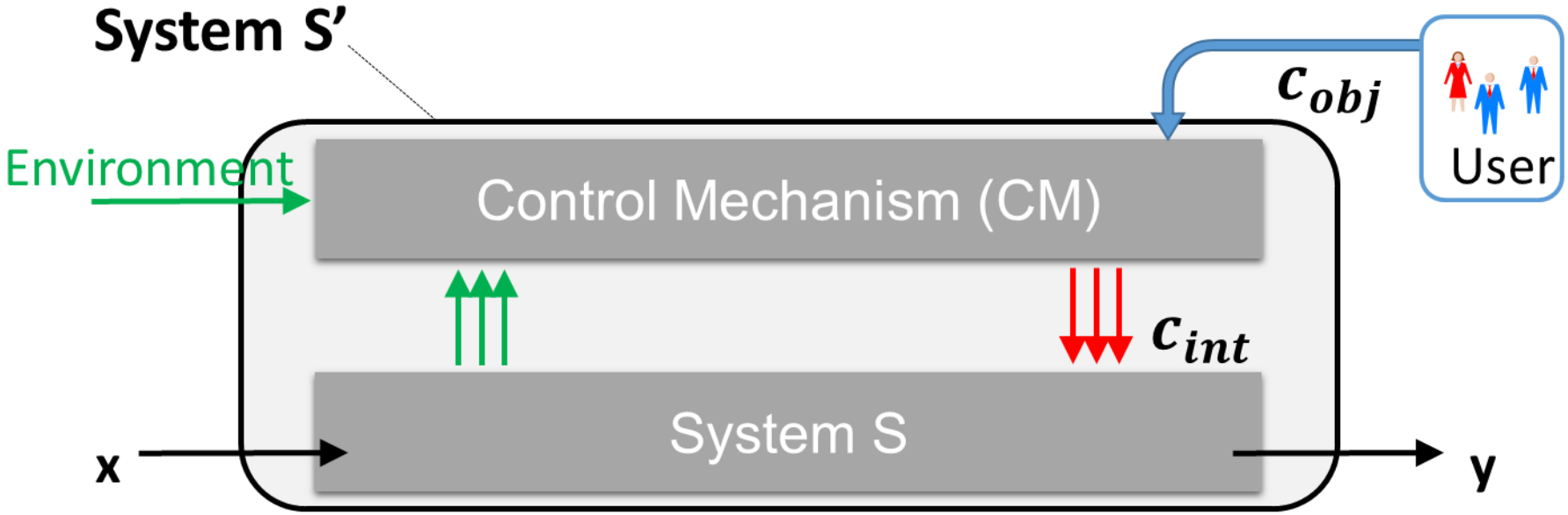
- System state varies over time.
- Consequently: utility differs as well.
- Control mechanism is responsible to guide the system back to the acceptance space after a drop in utility (i.e. from survival space).
- Usually the utility drop occurs very fast after the disturbance while the recovery takes much more time.
- Reasons:
  - Recovery process being typically very noisy and interrupted by setbacks.
  - If the disturbance is still in force while the CM works against it.
- In state space:
  - Recovery of a system is observed as movement of the state vector back into acceptance/target space.
  - Symbolised by the circles.

ORGANIC COMPUTING

Control Mechanism (CM)

- Recovery is not magic and comes for free.
- Recovery is done by built-in CM in organic systems.
- CM influences behaviour of system S by changing some of its attributes.
- System S is called “System under Observation and Control” (SuOC).
- $\mathbf{CS_{int}}$ constitutes the *configuration space* of the SuOC.
- SuOC is the productive system, which does the “actual” work.
- It receives input signals **x** and transforms them into output signals **y**.
- CM initiates control actions (i.e. it issues control signals $\mathbf{c_{int}}$ to S).
- S together with the CM constitute a system S’, which again could be controlled by a higher-level CM via the control signals $\mathbf{c_{obj}}$.

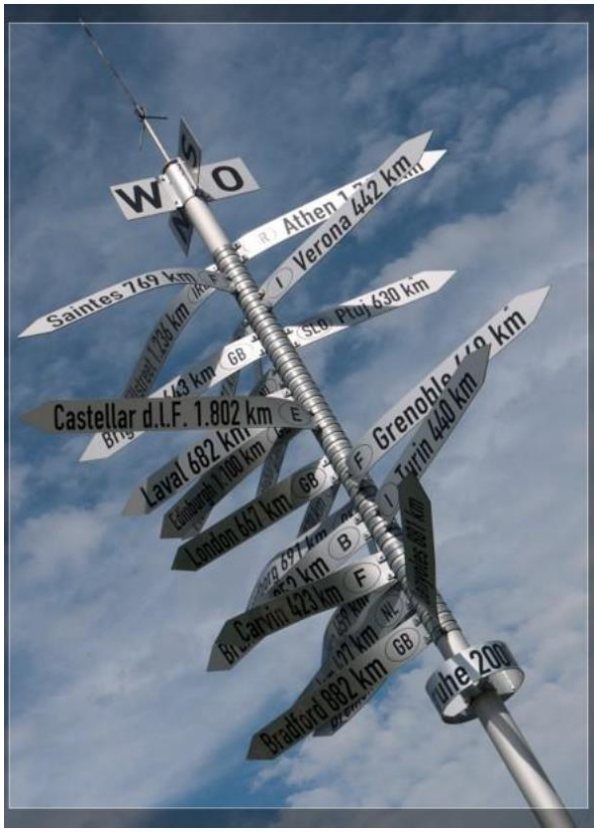


- Important: CM does not change any environmental parameter directly. Even the system state can be influenced only indirectly by setting c_{int}.

Agenda

ORGANIC COMPUTING

- Motivation
- Autonomy and self-organisation
- Quantification of self-organisation
- The survival cycle of an organic system
- Robustness
- Autonomy
- Conclusion and further readings



ORGANIC COMPUTING

Organic Computing systems…

- … are inspired by nature.
- … mimic architectural and behavioural characteristics, such as self-organisation, self-adaptation or decentralised control.
- … avoid a single-point-of-failure to achieve desirable properties, such as self-healing, self-protection, and self-optimisation.

Goal:

- The ultimate goal is to use these concepts to make systems resistant against external or internal disturbances.
- OC systems do not per se achieve a higher performance than conventional systems but they return faster to a certain corridor of acceptable performance in the presence of disturbances.

We call this property: robustness!

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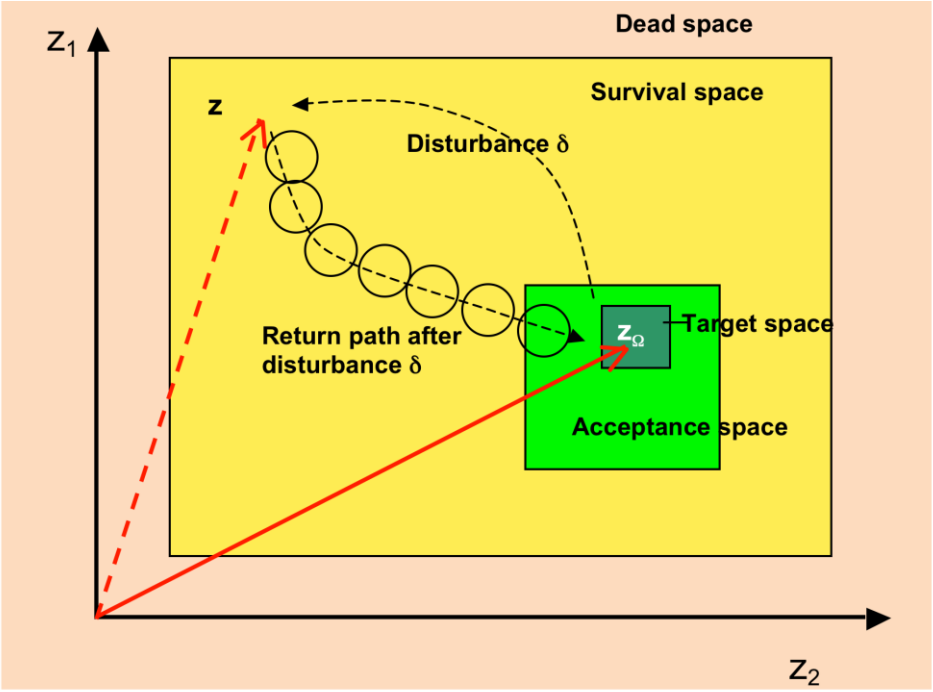
We distinguish two possible reasons for state changes of *S*:

1. The system state $\vec{z}(t)$ changes due to an internal change of the system (e.g. broken component) or a change of the environment (disturbance δ). If the system remains to be acceptable, this corresponds to the common understanding of a **robust** system.



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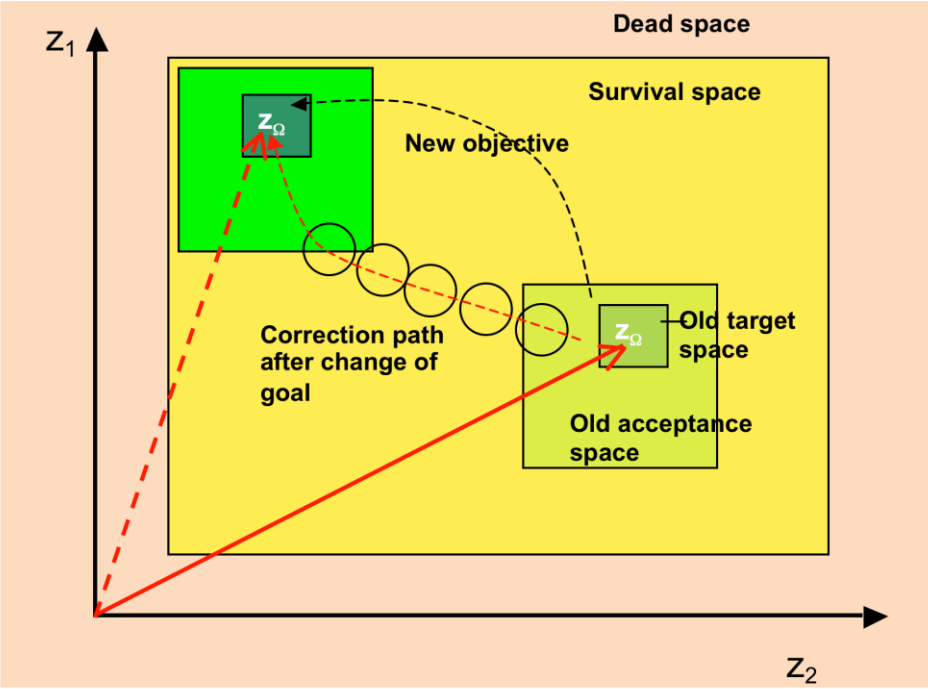
2. The state $\vec{z}(t)$ stays where it is but the evaluation and acceptance criteria change. This moves target and acceptance space – they have a new position within the *n*-dimensional state space. We call a system, which is able to cope with such changes in its behavioural specification, a **flexible** system.



ORGANIC COMPUTING

- We call a system more robust if it has a large number of states that do not lead to a reduced performance or to undesired behaviour.
- Definition: Let D be a non-empty set of disturbances δ:

1. A system *S* is called **strongly robust** with respect to D, iff all the disturbances in $\delta \in D$ map the target space into itself.

2. A system *S* is called **robust** with respect to D, iff all the disturbances in $\delta \in D$ map the target space into the acceptance space.

3. A system *S* is called **weakly robust** with respect to D, iff all the disturbances in $\delta \in D$ map the target space into the survival space and the internal control mechanism CM is able to lead S back to at least an acceptable state.

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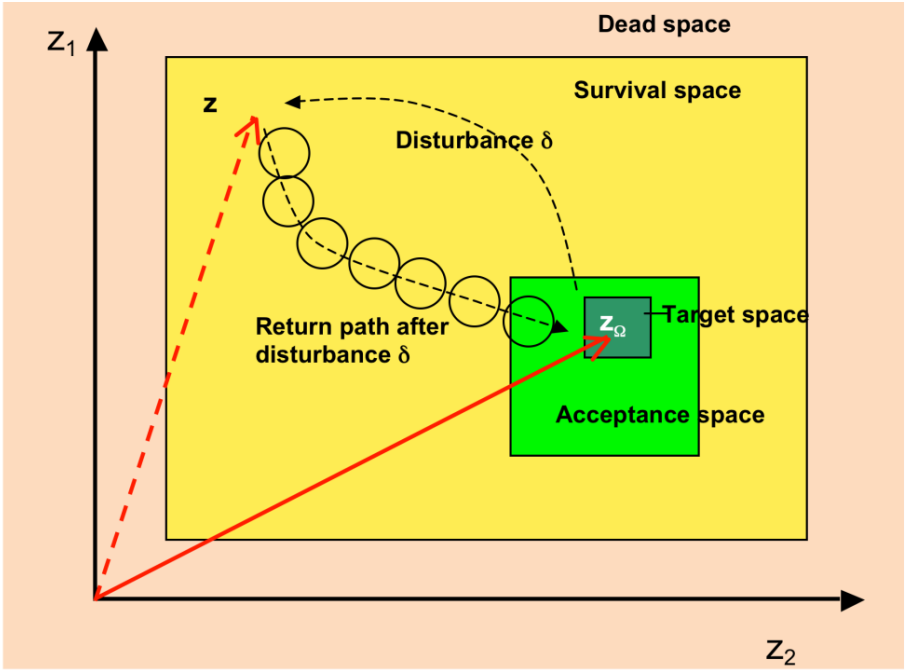
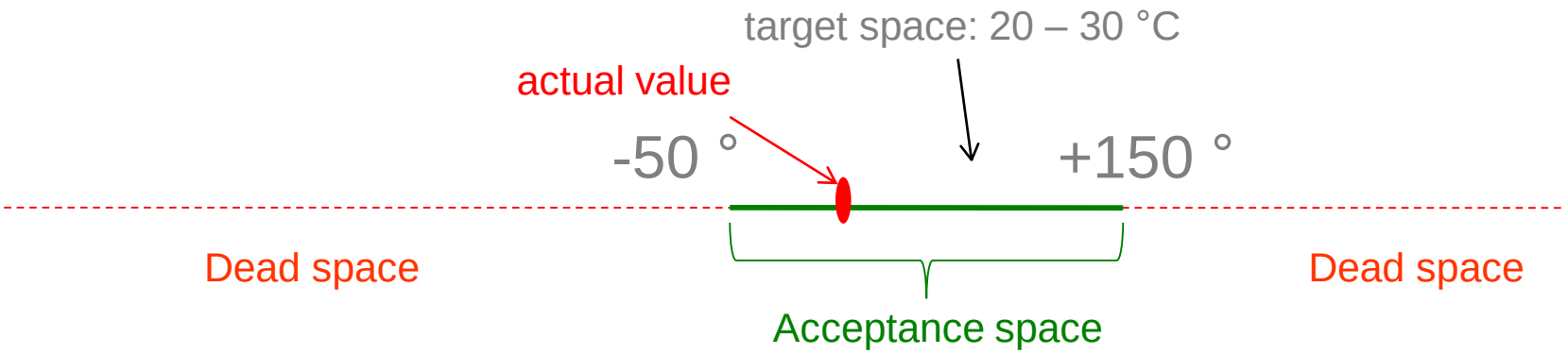
- The (degree of) robustness of a system increases with the size of the set of disturbances *D* the system can handle.
- I.e. the system fulfils the requirements named by the three different robustness classes named before.



ORGANIC COMPUTING

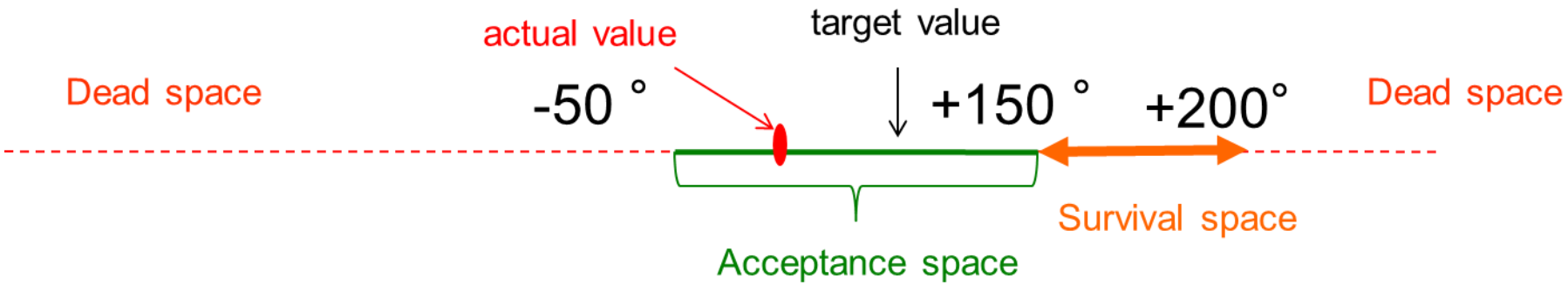
- An integrated circuit IC_1 with automotive specification functions correctly in an environment with temperatures from -50°C to +150°C. It works best in the temperature range from 20 to 30 °C.
  - Within -50°C to +150 °C (acceptance space), there is no control action necessary.
  - It is strongly robust with respect to a change of environment conditions if it stays within 20 – 30 °C.
  - It is robust with respect to a change of environment conditions if it stays within -50 – +150 °C.



Example (2)

ORGANIC COMPUTING

- An integrated circuit IC_2 functions correctly in an environment with temperatures from -50 °C to +150 °C.
  - Within this temperature range, there is no control action necessary (acceptance space).
- Now we add a cooling fan to IC_2 and a temperature sensor. The fan is able to cool the IC_2 if the temperature goes beyond +150 °C (but does not exceed 200 °C).



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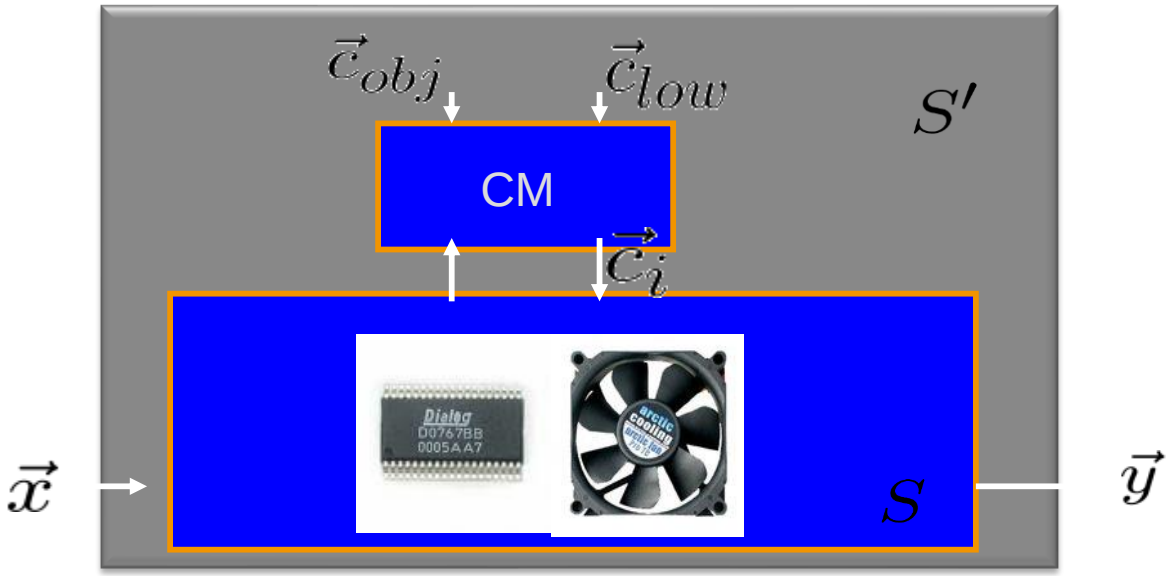
- The fan and the CM (which controls it) turn IC_2 into a weakly robust system with respect to a temperature range of -50 °C to + 200 °C.
  - S = (IC2 + sensor + fan) is an **adaptable** system.
  - S‘ = (IC2 + sensor + fan + CM) is an **adaptive** system.



ORGANIC COMPUTING

Observation

- OC systems “under attack” show a characteristic behaviour (*attack* is a certain instance of the broader class of disturbances).
- I.e. a fast drop in utility after a disturbance (or an intentional attack).
- Followed by a somewhat slower recovery to the original performance (provided that there are suitable OC mechanisms).

Quantification of robustness

- Goal: Estimate the benefit of OC control.
- Approach: compare different CM designs in terms of their ability to provide resilience to external disturbances.
- Focus: use the area of the characteristic utility degradation over time.
  → Area captures (i) depth of the utility drop, (ii) duration of the recovery.
- Note: degradation of zero corresponds to an ideally robust system.

ORGANIC COMPUTING

Generalised approach to quantify robustness:

a) works on externally measurable values,

b) does not need additional information sources (e.g. transactional data-bases),

c) distinguishes between system-inherent (or passive) and system-added (or active) robustness (to allow for an estimation of the effectiveness of the particular mechanism) and

d) provides a measure that allows for a comparison of different systems for the same problem instance.

We derive such a measure step-wise in the following…

ORGANIC COMPUTING

Passive and active robustness

- System in undisturbed state shows a certain target performance.
- Rate a system by a utility measure **u**.
- System reacts to disturbance by deviating from its acceptable utility u_{acc} by Δu.
- Passively robust systems react to the disturbance by a deflection $\Delta u = \Delta x$.
  → Tower example: wind pressure -> Δx in horizontal distance.
- Active robustness mechanisms (e.g. an organic control mechanism) counteract the deviation and guide the system back to the undisturbed state with $\Delta u = 0$.
- OC systems typically have both!
  → We'll refer to passive/active as phase 1 and 2.

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Quantification of robustness

- Phases I and II together constitute the deviation phase.
- Might be difficult to discriminate and may overlap.
  → Active recovery mechanism starts working already at t_δ.
- For quantification, take into account:
  - the strength of the disturbance δ
  - the drop of the system utility from the acceptable utility u (i.e. Δu)
  - the duration of the deviation (the recovery time t_{rec}).

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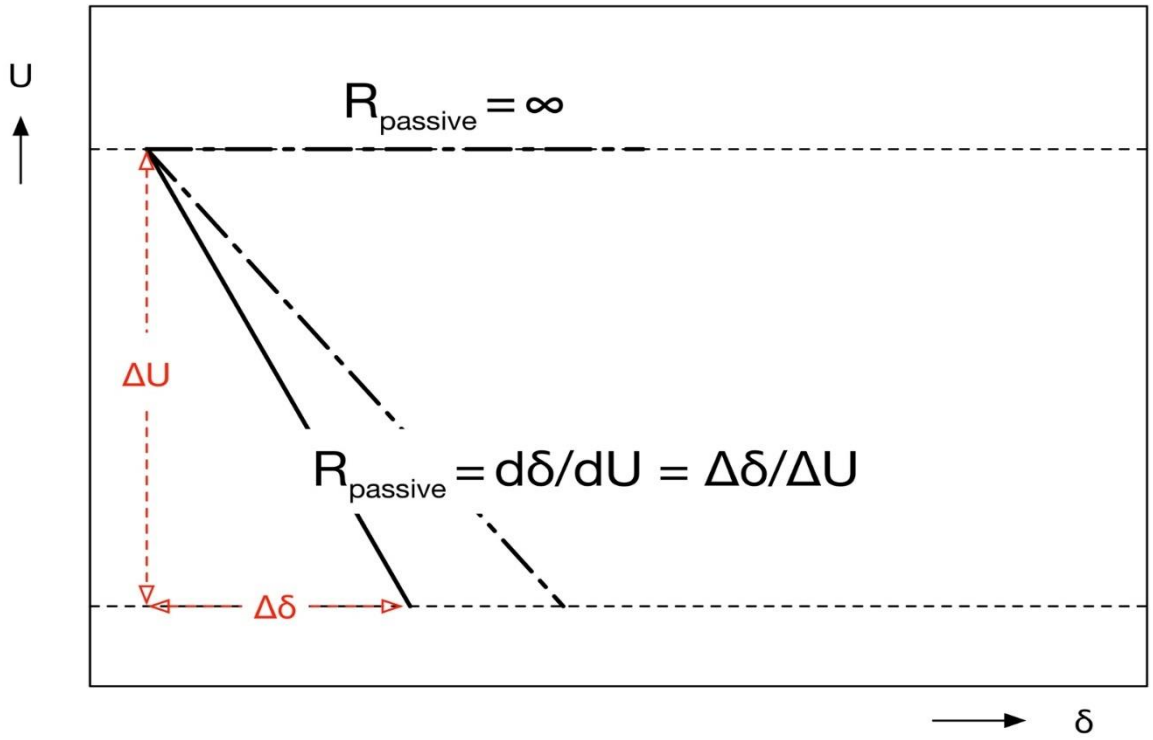
Passive Robustness

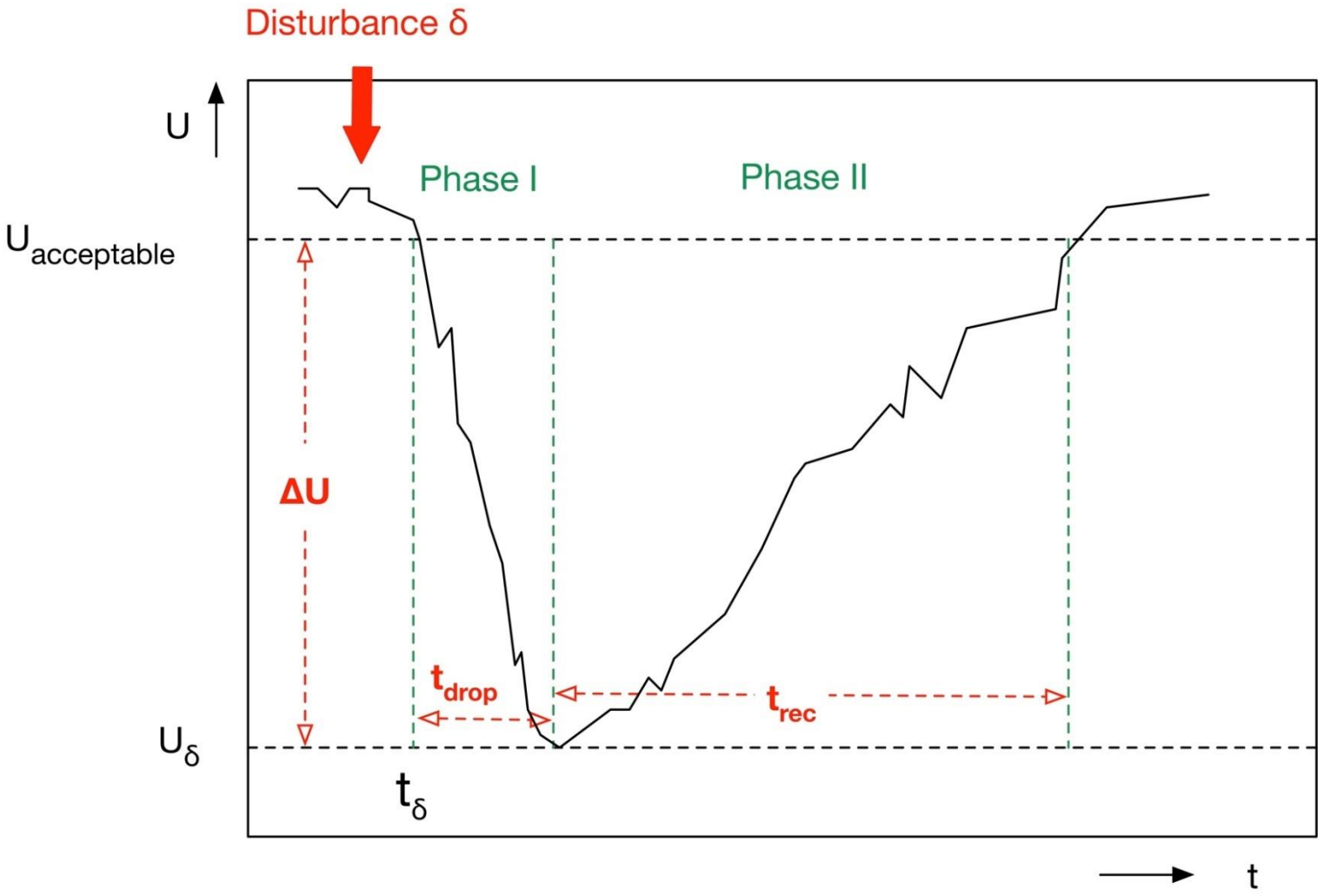
- Determined by the sensitivity of u against δ.
- Measure of the built-in stability of the system without an active CM.
- *Structural sensitivity* σ defined as the utility change caused by a disturbance δ (or the gradient of u(δ)): $\sigma = du(\delta)/d\delta$
- If δ has no effect on a system ($\Delta u = 0$) its sensitivity is $\sigma = 0$.
  - Example 1: A very stable concrete tower, which does not move ($\Delta u = 0$) under a storm of strength δ, is structurally infinitely stable, its sensitivity is $\sigma = 0$.
  - Example 2: A communication link with an error correcting code, which corrects errors up to 3 bits, is structurally insensitive to a disturbance of strength δ = 1 bit.

Passive robustness (2)



- The sensitivity σ determines the utility drop ΔU caused by a disturbance δ.

Robustness process



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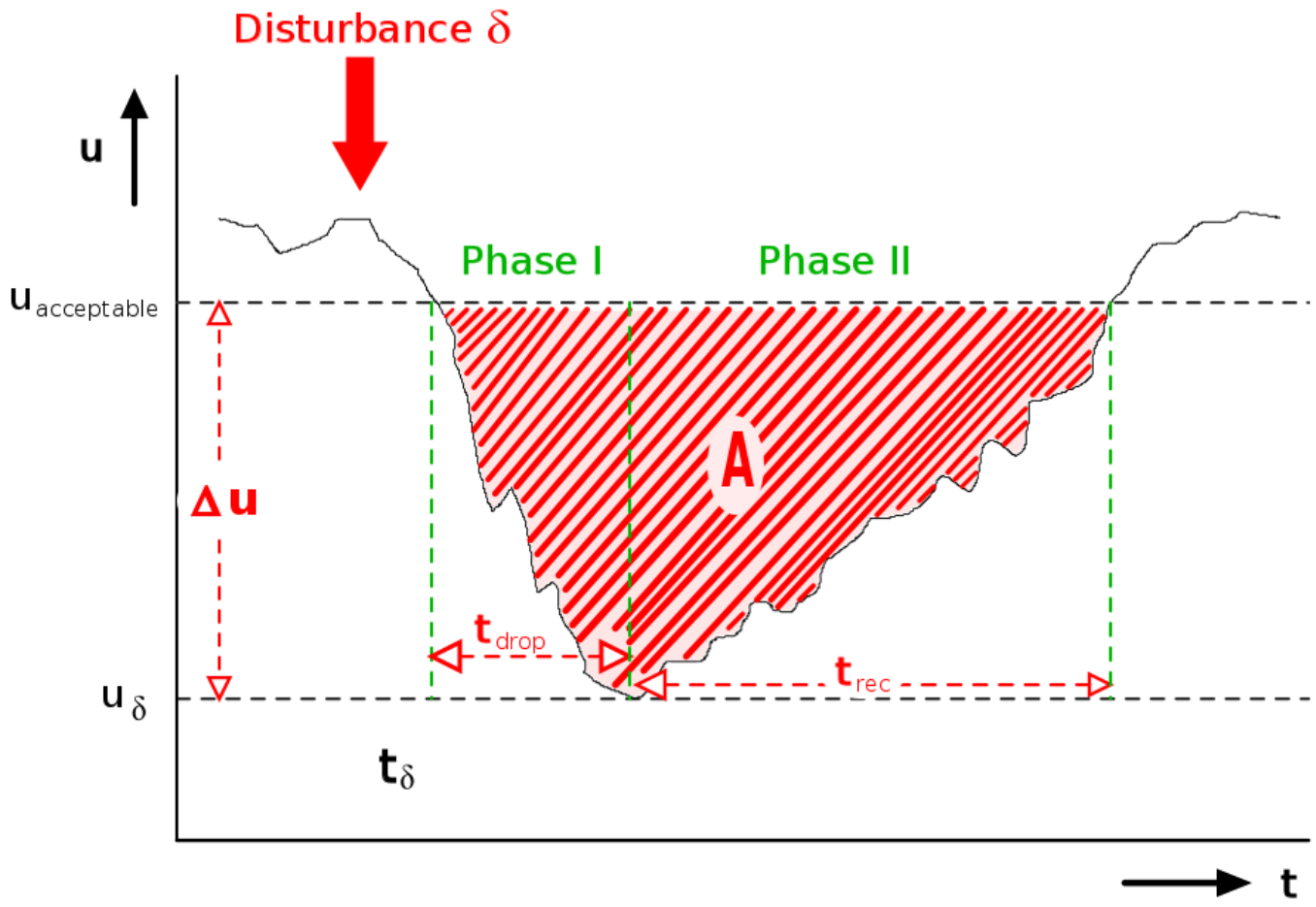
Active robustness

- Determined through the (averaged) recovery speed of the system.
- $s_{active} = du/dt$ or
- $s_{active} = \Delta u / t_{rec}$ (in case of a full recovery).
- With $t_{rec} = \Delta u / s_{active}$ and $\Delta u = \delta \cdot \sigma$ we get
- $t_{rec} = \delta \cdot \sigma / s_{active}$
- s_{active} is a property of the control mechanism (CM).
- Without a CM, the system stays at $u_{disturbed}$ at least as long as the disturbance remains.
- The recovery time t_{rec} depends on the initial utility drop Δu determined by the system's sensitivity against the disturbance as well as the active recovery speed.

Quantification of robustness (2)



ORGANIC COMPUTING

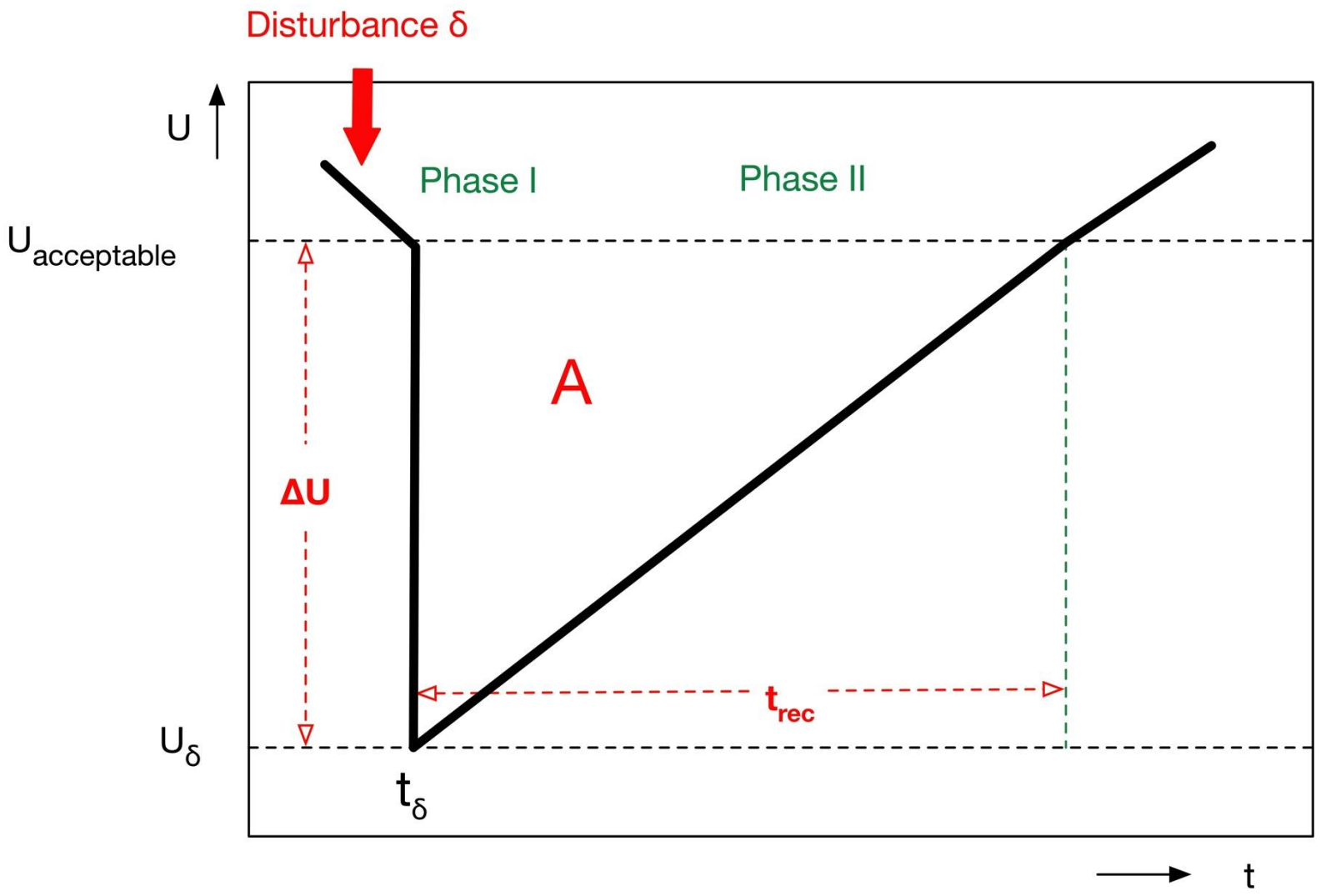
Effective utility degradation

- Robustness of a system under a given disturbance of strength δ is characterised by the triple (δ, Δu, t_{rec}) or (δ, σ, s_{active}).
- To gauge the total effect of the disturbance on the system: use the area A of the utility deviation from u_{acc} until full recovery to u_{acc} is reached.
- The area A between the accepted utility u_{acc} and the actual utility curve is defined as the utility degradation D_U
  (holds exactly only if $u_\delta = 0$, otherwise a correction is necessary).

$$D_u = \Delta u \cdot (t_{drop} + t_{rec}) - \int_{t_\delta}^{t_\delta + t_{drop} + t_{rec}} u(t)\, dt$$

- To achieve a minimal degradation, we have to minimise t_{rec} and Δu.

Approximation of utility degradation



ORGANIC COMPUTING

- Goal: Simplification and better estimation
- Assume that the drop occurs very fast, hence we can set $t_{drop} = 0$.
- Assume for simplification a linear utility increase, which renders the utility degradation triangular.
- Then: $D_u \approx \Delta u \cdot t_{rec} / 2 = ½ \, \delta \sigma \cdot \delta \sigma / s_{active}$
- Effective utility degradation is $D_u = ½ \, \delta^2 \cdot \sigma^2 / s_{active}$
- Observation: Decrease of the sensitivity σ decreases D_u more effectively than an increase of the recovery speed s_{active}.
- Reason: σ influences Δu as well as t_{rec}.
- Formula also shows trade-off is possible between σ and s_{active} depending on the cost incurred for passive (σ) and active (s_{active}) robustness measures.

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ORGANIC COMPUTING

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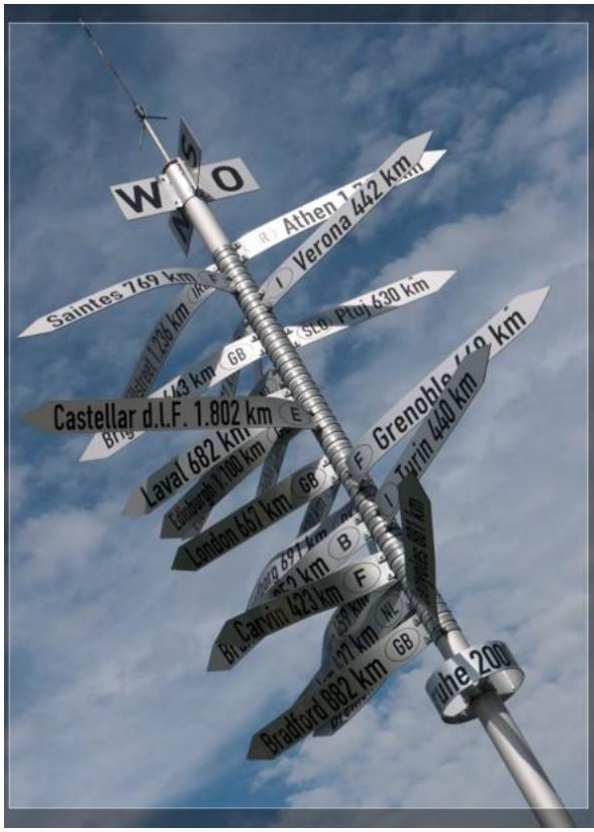
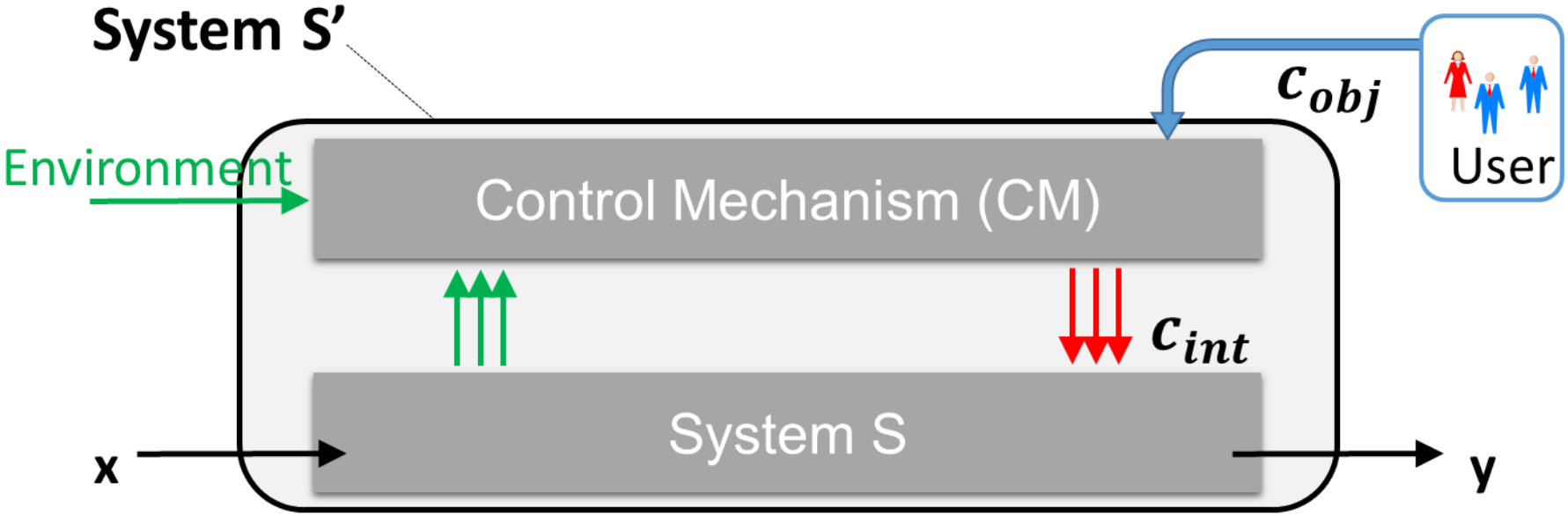


ORGANIC COMPUTING

OC systems

- Primary goal is the survival in a changing world.
- They must be robust and flexible.
  → stay in or to return to the acceptance space.
- Achieved by:
  - Adding control mechanism CM to the productive system S.
  - CM observes the state of S and that of the environment.
  - CM determines deviations of the state **z** of S from the acceptance space.
  - CM takes appropriate action to lead S back into the acceptance space.
  - Acceptance space is defined by the objective $\mathbf{c}_{obj}$ (or goal) as provided by some external authority.

ORGANIC COMPUTING



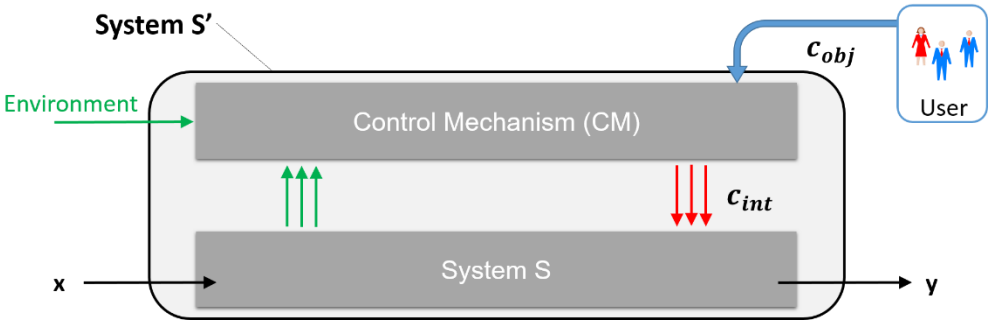
ORGANIC COMPUTING

- Systems that survive in this sense are called *autonomous*.
- Term: “auto-nomy” (auto = self, nomos = law) is interpreted as obeying only some internal objectives of the system itself.
  → This is not what we want!
- System has to fulfil a certain purpose:
  - We want always to be able to control the system from the outside.
  - By prescribing goals and/or constraints the system must follow.
- But: system should act with as little external interference as possible.
- Goal: systems that keep the balance between
  - too much autonomy (makes them uncontrollable) and
  - too little autonomy (requires permanent corrective action from outside).
- Such systems are *semi-autonomous*.

In the following, we will develop a quantitative notion of the “degree of autonomy”, which will allow us to capture the *semi*-autonomy more precisely.

ORGANIC COMPUTING

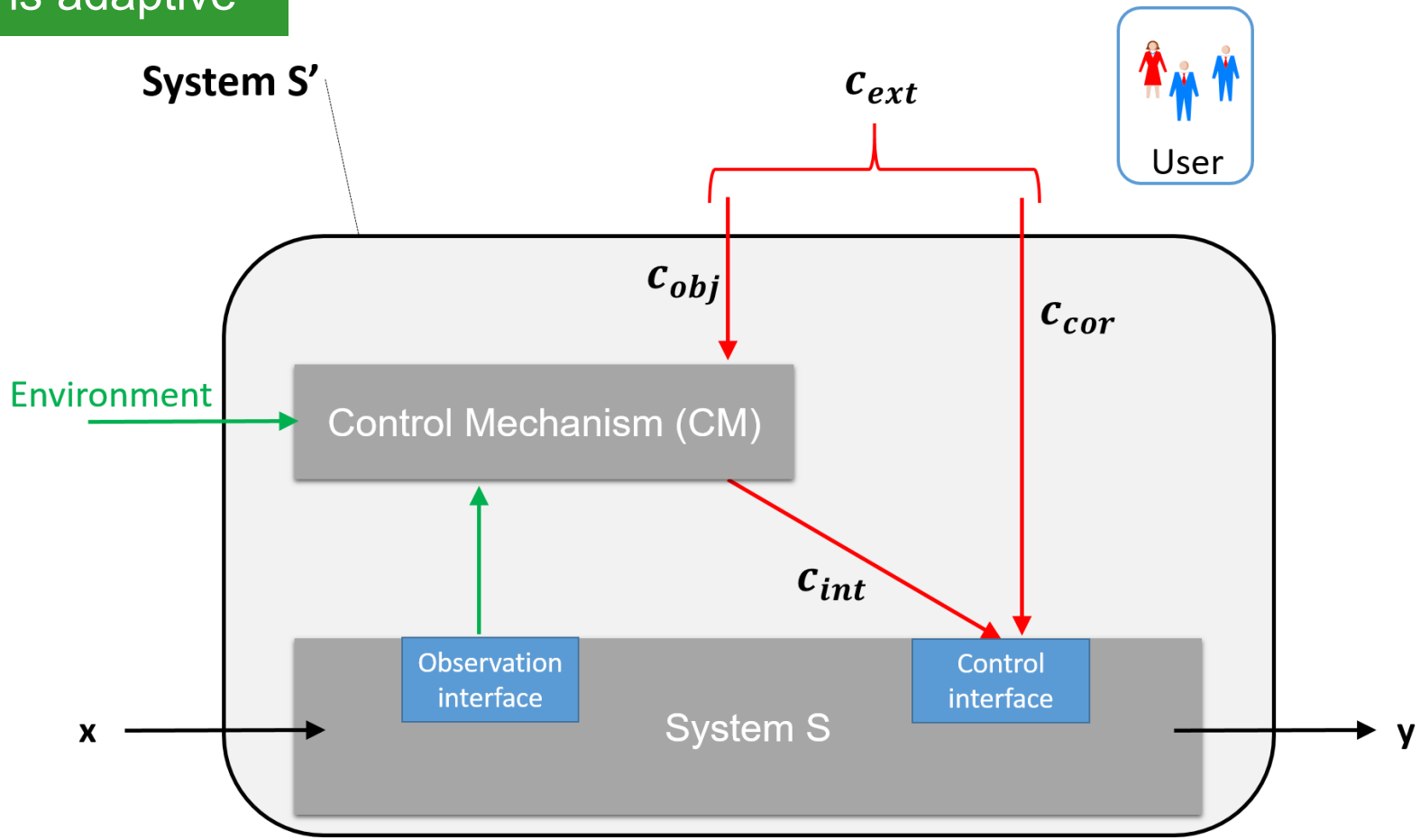
Architecture



- Refine the system architecture.
- Control mechanism
  - Has to observe and influence S.
  - Means: system must provide observation and control interfaces.
  - Observation interface defines certain internal parameters of S as visible for the CM (i.e. for the observer) for monitoring.
  - The control interface exposes certain parameters of S as modifiable by the CM (i.e.: by the controller).
  - A system S, which can be modified via a control interface, is *adaptable*.
  - Apparently, adaptability is a purely passive system property.
- If we add a CM with its active observation and control ability to an adaptable and observable system, we arrive at a system S' which can be called (semi-) autonomous.

Refining the control mechanism (2)

S is adaptable
S' is adaptive



ORGANIC COMPUTING

Distinguish between control influences:

- c_{int} specifies control signals issued from within the system (i.e. from the control mechanism).
- c_{obj} specifies higher-level (and more abstract) goals issued by the user or other higher-layered systems / CMs.
  → These control signals influence *S* only indirectly.
- c_{ext} specifies control signals issued by external sources that influence *S* directly.

→ Obviously: A system S is not autonomous if the system S' adapts its behaviour only in response to control issues c_{ext}!

→ In general, external control signals are less frequently issued.

ORGANIC COMPUTING

- Adaptable system S is influenced by control signals.
- Control parameters accessible for outside modification defines the possible configurations of S.
- A control vector c (comprising the parameters) applied to the control interface is a pointer selecting one possible configuration.
- The size of the configuration space is measured by the total size (in bits) of all control parameters.
- The size of the configuration space is called variability:

$$\text{Variability } V := \#\mathbf{c}$$

(#**c** denotes the number of bits used in **c**.)

ORGANIC COMPUTING

Examples for influencing S:

- Parameter modification can tune certain behaviours of S.
  → E.g. the timing or certain threshold values.
- Parameters can change the system structure of S.,
  → E.g. by adding or deleting edges in the communication graph of a distributed system.
- A system implemented as an FPGA (Field Programmable Gate Array) might be totally redefined by rewriting its control memory.
  → In this case, the configuration space is huge allowing all configurations acceptable by the FPGA.

ORGANIC COMPUTING

Effectiveness of an autonomous system

- $\mathbf{c}_{obj}$ is (1) smaller and (2) less frequently applied than $\mathbf{c}_{int}$.

  (if designed correctly).

- Quantification possible using the difference: count the number of bits necessary to express $\mathbf{c}_{obj}$ and $\mathbf{c}_{int}$, i.e. variabilities:

  $V_{obj} = \#\mathbf{c}_{obj}$ and $V_{int} = \#\mathbf{c}_{int}$.

- The difference of V_{int} and V_{obj} is the complexity reduction CR:

  $$CR = V_{int} - V_{obj}$$

- Positive value of CR: S has a larger configuration space than S';
  → CM achieves the desired complexity reduction.

- Assumption: coding of the parameters in $\mathbf{c}_{int}$ and $\mathbf{c}_{obj}$ is optimal in the sense that no unnecessary information is encoded.
  → Different variabilities are comparable.

ORGANIC COMPUTING

- Perfectly designed OC system:
  - CM is able to translate higher-level control signals (expressed as objectives or goals) into lower-level internal control signals.
  - the prescribed objectives are met.
  - the system stays in or returns to the acceptance space.
- In contrast: CM may need frequent external corrections because it is not able to keep the system within the acceptance space.
- Corrections are applied in the form of additional external control signals $\mathbf{c}_{corr}$.
- $\mathbf{c}_{corr}$ defines an extension of the configuration space of S'.
- The total configuration space of S' is now a combination of $\mathbf{c}_{obj}$ and $\mathbf{c}_{corr.}$
- Combined configuration space is addressed by $\mathbf{c}_{ext}$:

$$\mathbf{c}_{ext} = (\mathbf{c}_{obj} ; \mathbf{c}_{corr})$$

Corrective control (2)

ORGANIC COMPUTING

If external corrections are applied:

- Variability of S' is then $V_{ext} = \#\mathbf{c_{ext}}$.
- Complexity reduction CR is the $CR = V_{int} - V_{ext}$

For frequent use of external corrections:

- Many corrective actions necessary.
- V_{ext} might become even larger than V_{int} .
- Leads to a negative complexity reduction:
  → It is in this case more difficult to control S' than S!

ORGANIC COMPUTING

Quantification of autonomy

- Use the complexity reduction CR
- Goal: define the static degree of autonomy α of a system S' as the complexity reduction CR relative to the internal variability V_{int}.

Static degree of autonomy

$$\alpha = (V_{int} - V_{ext})/V_{int} = CR/V_{int}$$

- with $0 \leq \alpha \leq 1$.

Implications:

- $\alpha = 0$ if there is no complexity reduction, i.e. $V_{int} = V_{ext}$.
- $\alpha = 1$ if $V_{ext} = 0$,
  → S' is a system, which cannot be controlled from the outside; it has a degree of autonomy of 100% (which is clearly undesirable).

ORGANIC COMPUTING

From static to dynamic degree of autonomy

- Static degree of autonomy α is an indicator only of the *possible* control actions for S and S'.
- Does not express the actual control actions applied by CM or by the external authority to S.
- Example: Configuration space with a certain variability V might be used frequently to control or correct S or not at all.
- Goal: measure the control flow, which is actually applied via a control interface during a defined time period from t_1 to t_2.

Dynamic degree of autonomy (2)

Let #c(t_i) be the number of control bits applied at a discrete time t_i. Then we define the dynamic complexity reduction *cr* as

$$Dynamic\ complexity\ reduction\ cr = \sum_{t_1}^{t_2} [\, \#c_{\text{int}}(t_i) - \#c_{ext}(t_i)\,]$$

and the *dynamic* degree of autonomy β as

$$Dynamic\ \deg ree\ of\ autonomy\ \beta = \frac{cr}{\sum_{t_1}^{t_2} [\, \#c_{\text{int}}(t_i)\,]} = \frac{\sum_{t_1}^{t_2} [\, \#c_{\text{int}}(t_i) - \#c_{ext}(t_i)\,]}{\sum_{t_1}^{t_2} [\, \#c_{\text{int}}(t_i)\,]}$$

with 0 ≤ β≤ 1.

Implications:

As above for α, an autonomy degree of β = 0 means that internal and external control are equal, hence all the control originates from the external authority instead of CM. And β = 1 means that there exists no external control.

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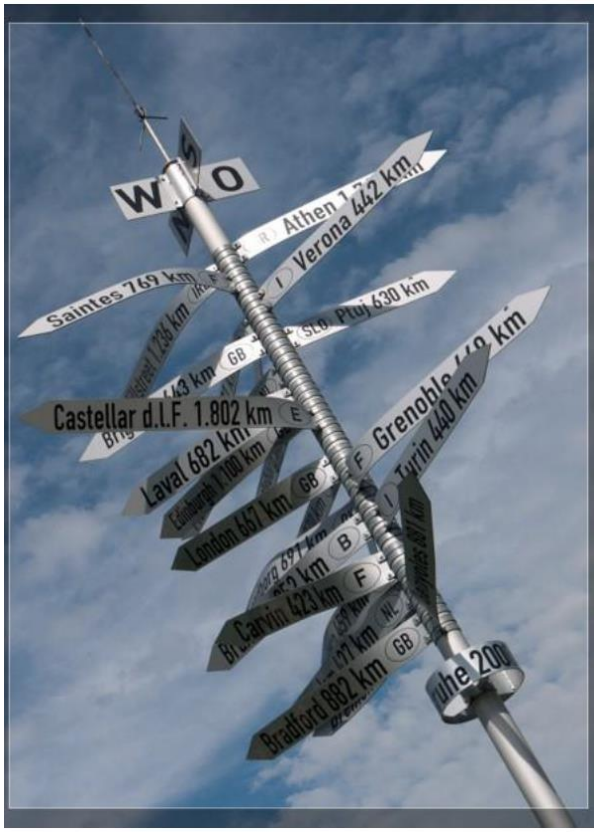

Conclusion

ORGANIC COMPUTING

This chapter:

- Introduced the necessary terminology for OC systems.
- Illustrated the runtime process of an OC system as survival cycle.
- Explained how major aspects of these systems can be quantified.
- Highlighted that the overall goals of organic control mechanisms are:
  - Achieve robustness
  - Reduce complexity

By now, students should be able to:

- Define what the terms self-organisation, autonomy, adaptability, utility, robustness, disturbance, and variability mean.
- Explain the behaviour of an organic system according to a state space model.
- Describe the OC survival cycle.
- Quantify robustness, self-organisation, and autonomy.

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Questions …?