Preconditions

System definition, quantitative emergence

Objectives

Terminology for self-organization, robustness, and adaptivity

Quantitative approach

Content

- Self-organization and autonomy
- 5 aspects of autonomous systems
- Measuring robustness
- Measuring adaptivity: Configuration space and variability
- Control and degree of autonomy
- Controlled self-organization

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autonomy

robustness

flexibility

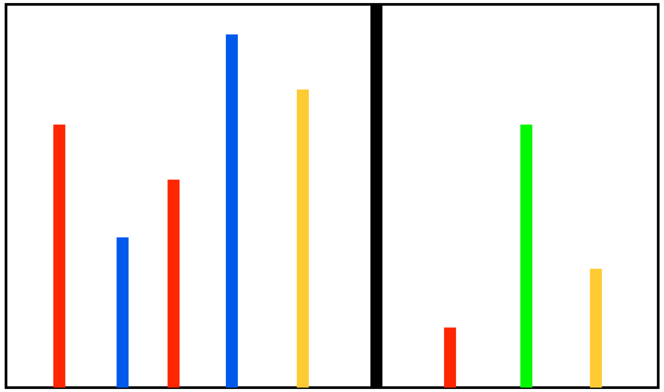
observation

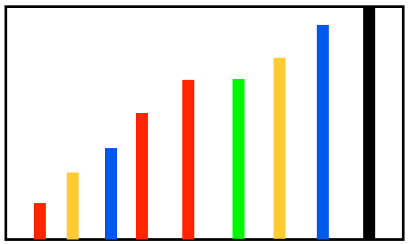
(self-) adaptivity

control

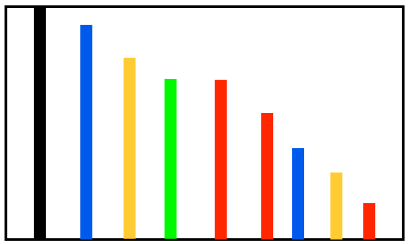
self-organization

ISE SRA

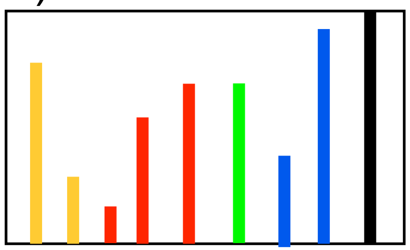




a)



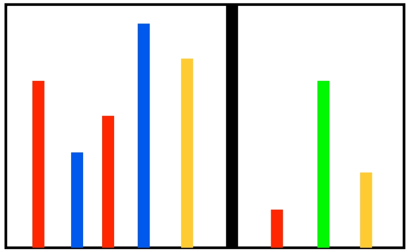
b)



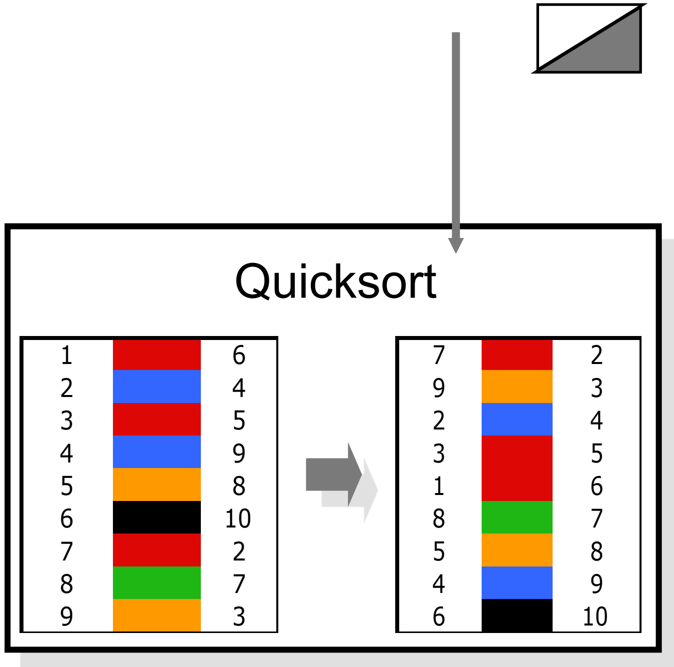
c)

- Properties of each stick:
  - height
  - color
- Ordering objectives
  - a) increasing height
  - b) decreasing height
  - c) color clusters
- Ordering process?

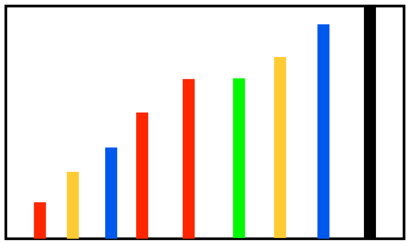
Global objective a := increasing height

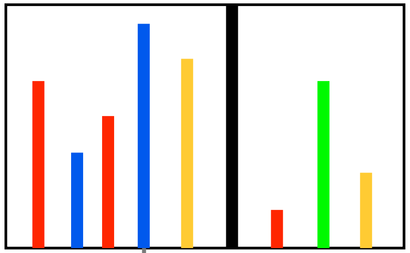


1 Observation
2 Model building
3 Simulation

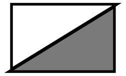


4 Enactment

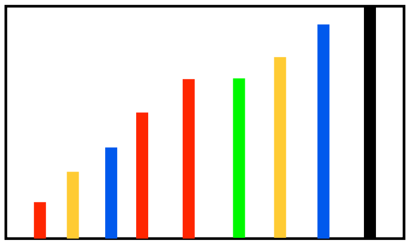




Global objective a := increasing height

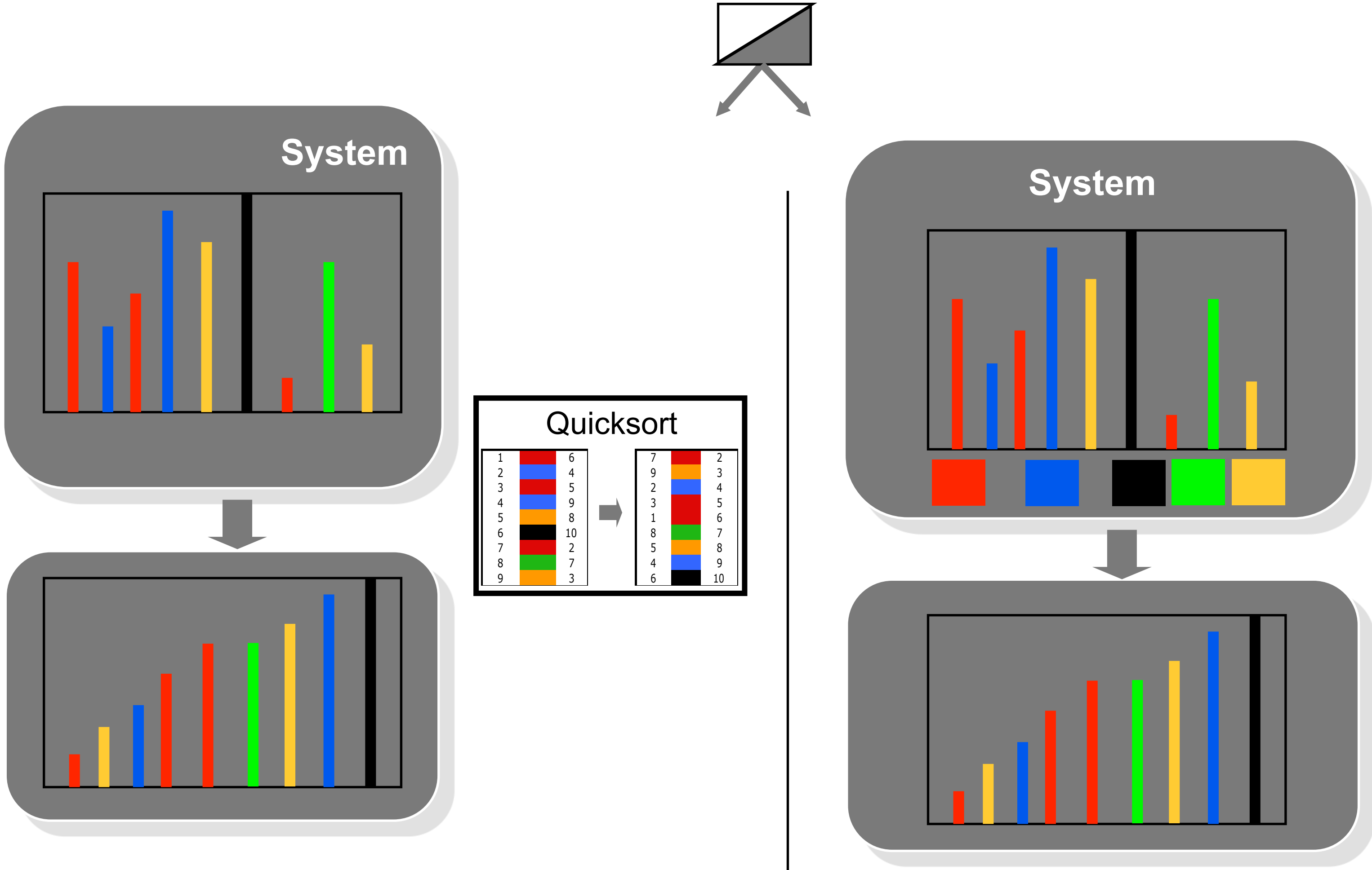


1. Local objective: right > myself
2. Local observation: right < myself
3. Local decision:
   if right < myself then Switch places; else: nil
4. Local enactment
5. Go to 2



enactment = Ausführung, Umsetzung

Global objective := increasing height

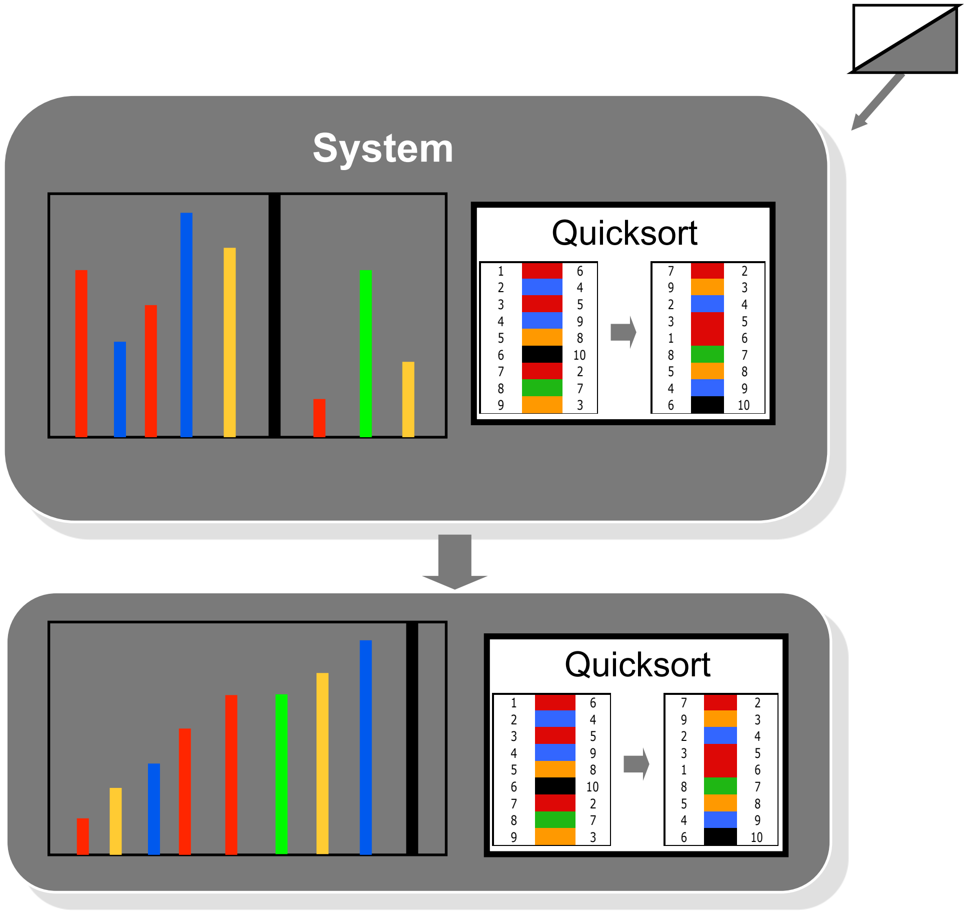


Autonomy? No
SO? No

Autonomy? Yes
SO? Yes

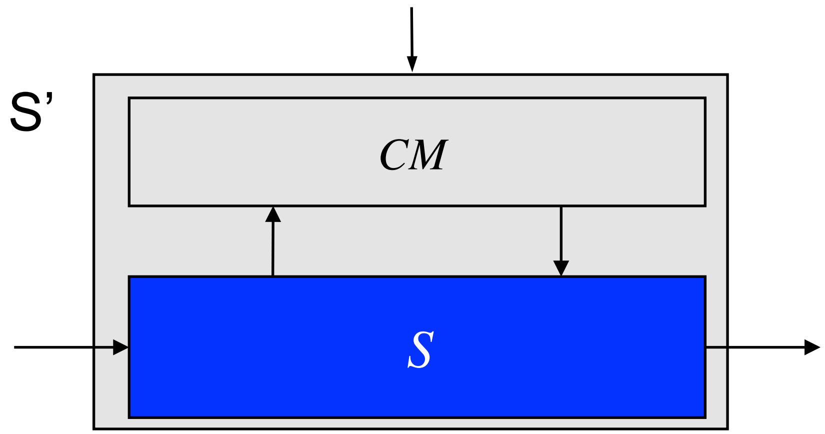
Autonomy? Self-organization? (2)

Global objective := increasing height



Autonomy? yes
Self-organization? Maybe

- Autonomy: A system S' changes its structure without explicit external control.
  - There must be some kind of internal control mechanism CM!
- Self-organization: The internal control mechanism is distributed (to a certain degree).
- Adaptivity: A system S allows to be changed (passive property).



These definitions have to be refined and formulated quantitatively!

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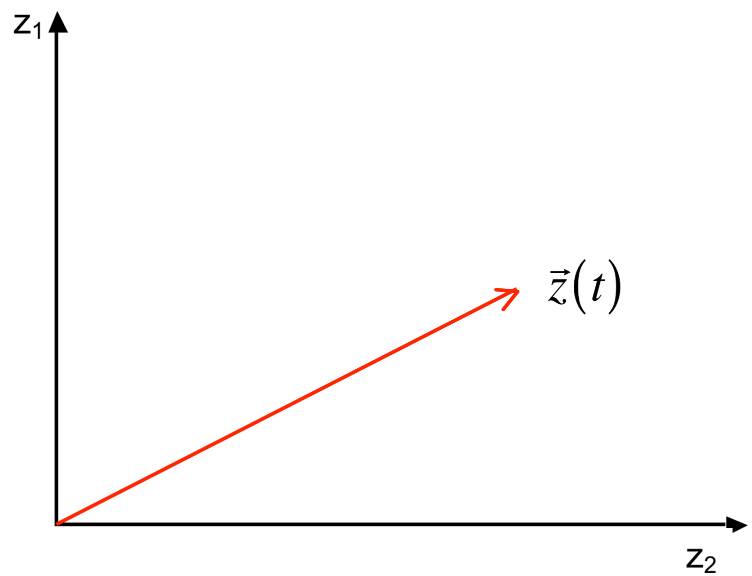
- An autonomous system S is characterized by 5 aspects:
    1. System state
    2. Utility and Acceptance space
    3. Disturbance
    4. Control mechanism
    5. Recovery (process)

- At any given time t, the system S is in state z (t).
- If there are *n* attributes used to describe the state of *S*, **z** (t) is a vector in *n*-dimensional state space Z^n.



- We assign a utility **U** to each state **z** by the evaluation functions η_i:

  $\mathbf{U} = \boldsymbol{\eta}(\mathbf{z})$. $U_i \in R$

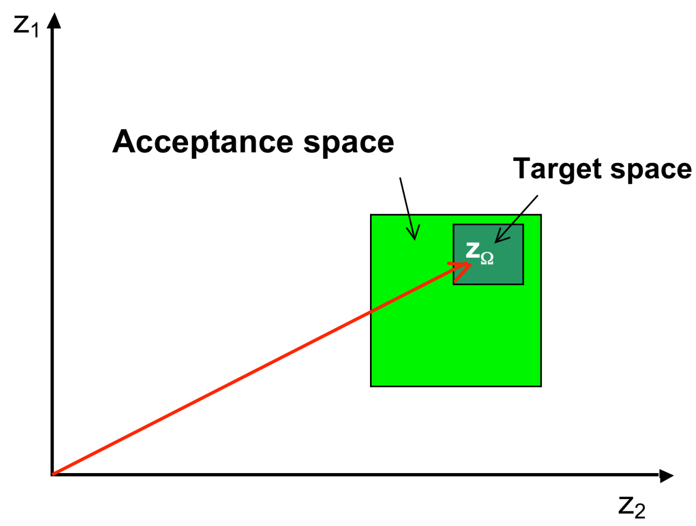
- The set of acceptable states (the acceptance space) corresponds to a minimal acceptable utility

  $U_{i,\ acceptable} = \eta_i(z_{acceptable})$ **and** $U_{i,\ acceptable} \geq U_{min}\ \forall\ \mathbf{z}_{acceptable}$.

- The set of ideal states (the target space) is denoted by Z_Ω. In some cases, it might be a single state $\mathbf{z}_\Omega$.

- The target space is a subset of the acceptance space.

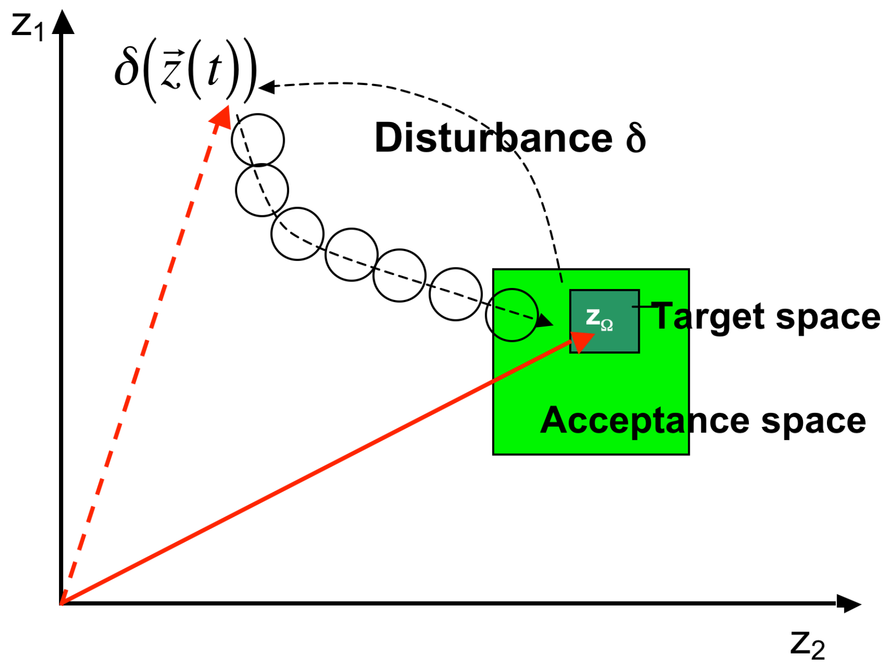
cf. Objective function



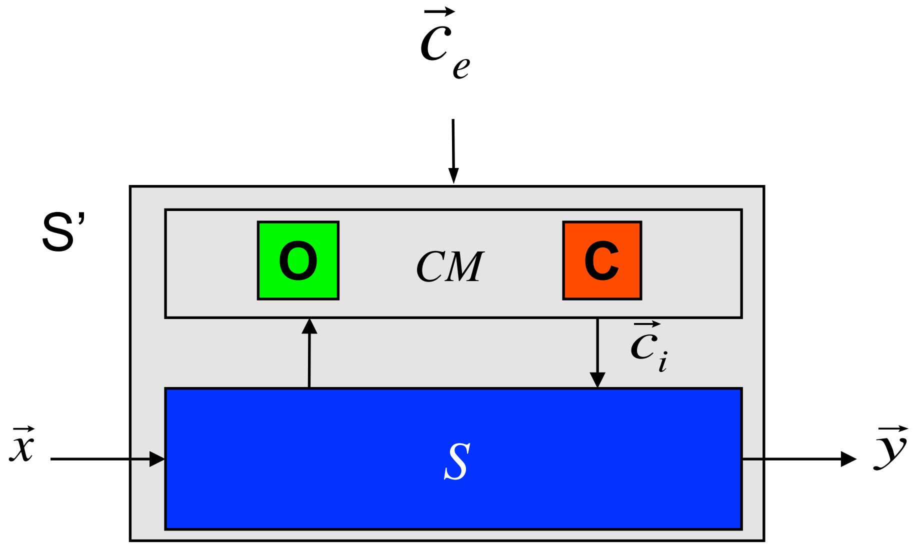
- The system might be disturbed by environmental influences or disturbances δ.
- A disturbance δ changes the state $\mathbf{z}(t)$ into the disturbed state

  $\mathbf{z}_\delta(t) = \delta(\mathbf{z}(t))$.
- Consequently the utility changes to

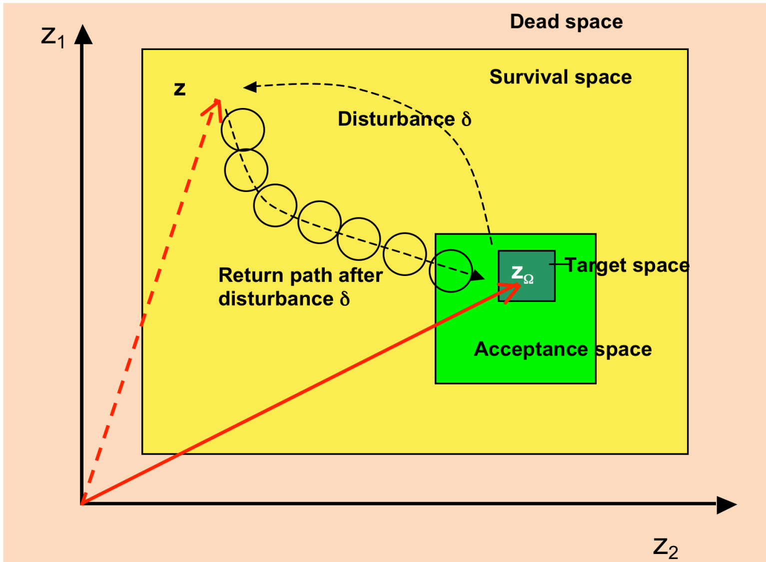
  $\mathbf{U}_\delta = \boldsymbol{\eta}\ (\mathbf{z}_\delta(t)$
- If $\mathbf{U}_\delta < \mathbf{U}_{acceptable}$ the system is outside the acceptance space.



- An internal control mechanism CM to controls the behavior of the system S by changing some of its attributes $\mathbf{c}_i$.
  - See: Configuration space
- The control mechanism CM consists of an Observer O and a Controller C.
- S’ can be controlled via $\mathbf{c}_e$.



- Disturbance and recovery behavior in state space
  - Phase I: A disturbance of strength δ is applied to the system, which changes its state to $\mathbf{z}_\delta$ and its utility to $U_\delta < U_{acceptable}$.
  - Phase II: A control mechanism (which in the case of an adaptive self-organizing system is part of the system itself) actively guides the system back into the acceptance space (recovery process).
  - The time needed for this recovery is t.rec.



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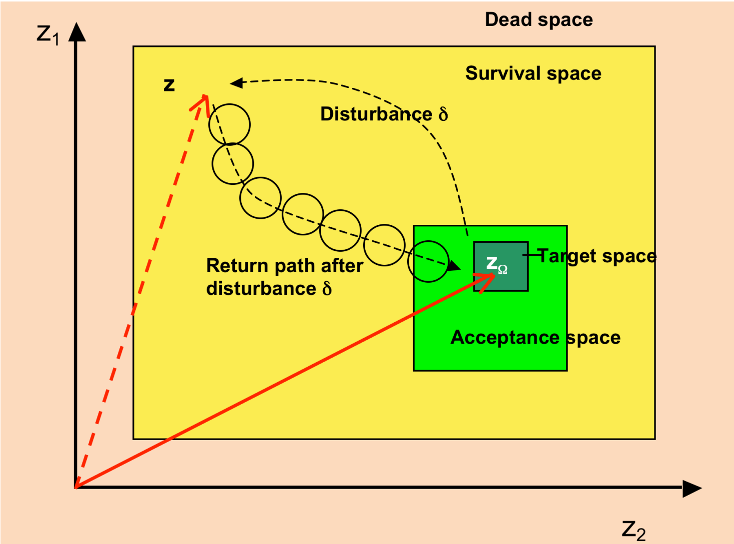
- An adaptive system S will always try to return to the acceptance space.
- Such a recovery is possible only from a certain subset of states, the Survival space.
- Any disturbance δ moving **z** outside the survival space will be lethal for *S:* Dead Space.



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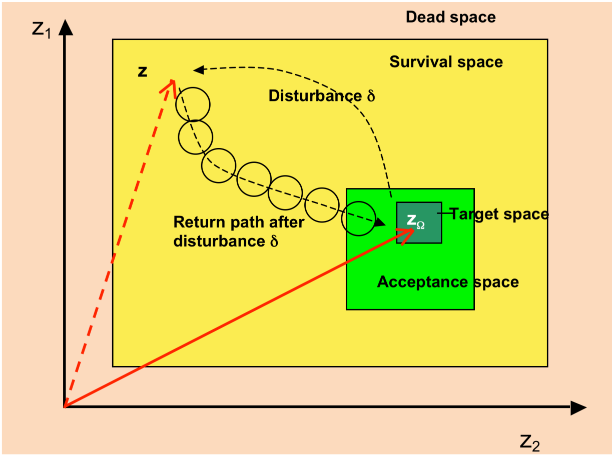
- It is a common misunderstanding that the goal of building OC systems is primarily the construction of (self-) adaptive or self-organizing systems or that OC systems generally have a higher performance (more general: utility) than conventional systems.
- OC systems are not per se faster than conventional systems.
  - But they return to a certain accepted utility in the presence of internal and/or external disturbances. We call this property “robustness”.
  - Or they adapt to new goals (a new acceptance space). We call this property “flexibility”.
- Active correction mechanisms (such as an observer/controller) counteract the temporary deviation of a system from an acceptable state (or in case of a multi-dimensional state space: the acceptance space).

- Robustness
  - The system S' is expected to maintain a required behavior or functionality in spite of certain disturbances.
  - The standard notion for this behavior is robustness.
- Flexibility
  - The requirement to modify the behavior because of changed objectives corresponds to the notion of flexibility.
- Both capabilities, robustness and flexibility, are enabled by the (self-) adaptivity of the system.



- We call a system more robust if it has a large number of states that do not lead to a permanently reduced utility.
- Definition: Let D be a non-empty set of disturbances.
  a) A system S is called strongly robust with respect to D, iff all the disturbances $\delta \in D$ map the target space into itself.
  b) A system S is called weakly robust with respect to D, iff all the disturbances $\delta \in D$ map the target space into the acceptance space.
- Flexibility can be treated like robustness if we define a change of goals (i.e. a change of acceptance space) as a special case of a disturbance.

- Observations
  - The (degree of) robustness of a system increases with the size of the set of disturbances D and the strength of the disturbance δ the system can handle (i.e. fulfilling the requirements a or b above).
  - A system A is more robust than a system B if it returns to the target or the acceptance space in a shorter time after the disturbance occurs.
- If we want to quantify robustness (for comparison between different systems) we have to take into account the following observables:
  - the strength of the disturbance, δ
  - the deviation of the system utility U_δ from the acceptable utility $U_{acceptable}$, ΔU, and
  - the duration of the deviation (the recovery time t_{rec}).

❑ Disturbance and recovery behavior in state space

- Phase I: A disturbance of strength δ is applied to the system, which changes its state to $\mathbf{z}_\delta$ and its utility to $U_\delta < U_{acceptable}$.
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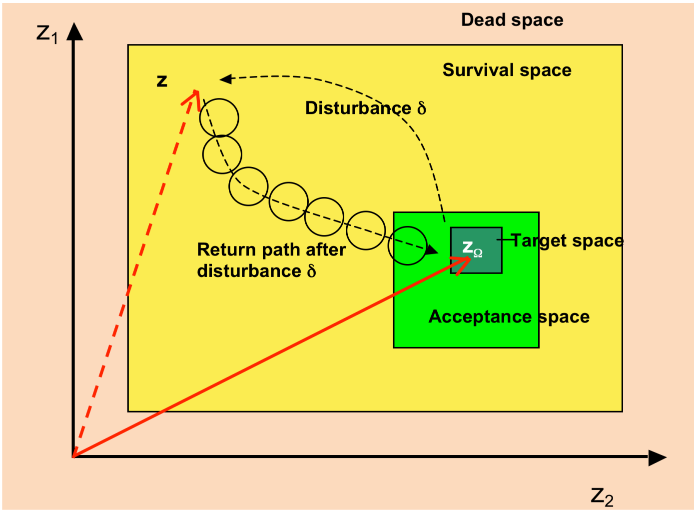
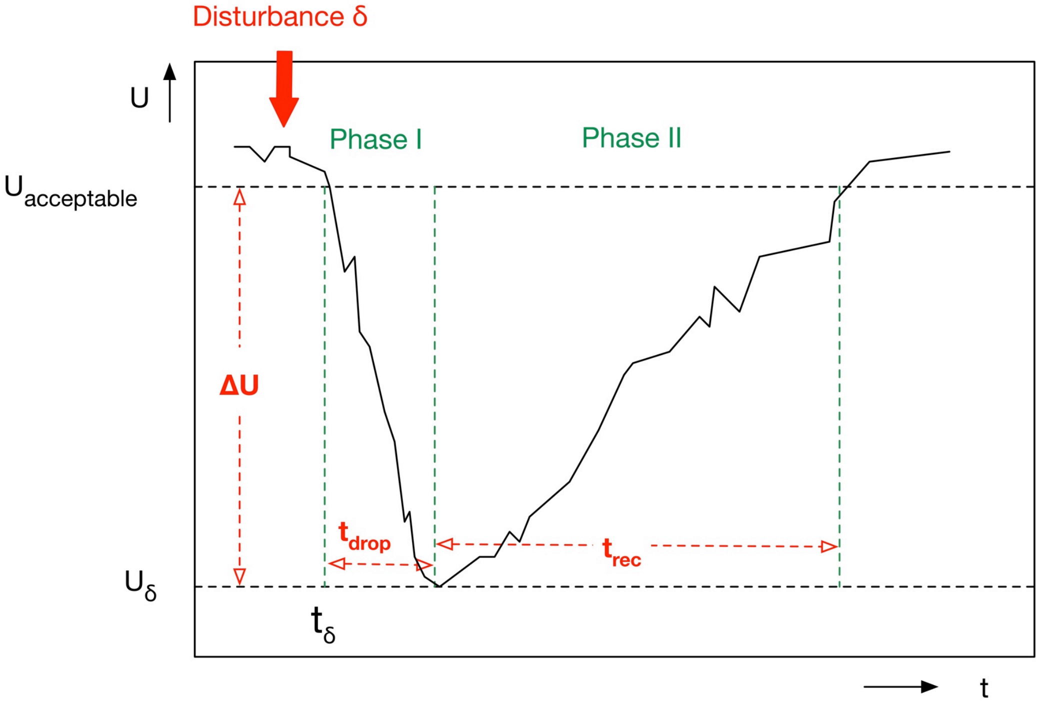
- The time needed for this recovery is t_{rec}.



- Utility degradation behavior over time
  - The deviation begins when the utility drops below $U_{acceptable}$, i.e. at time t_δ (and not when the disturbance occurs).
  - A disturbance taking effect at time t_δ will lead to a utility drop from $U \geq U_{acceptable}$ to U_δ. The drop occurs within t_{drop}.
  - Given an effective control mechanism the system will return back to $U \geq U_{acceptable}$ within time t_{rec}.
  - Phases I and II are called deviation phase.



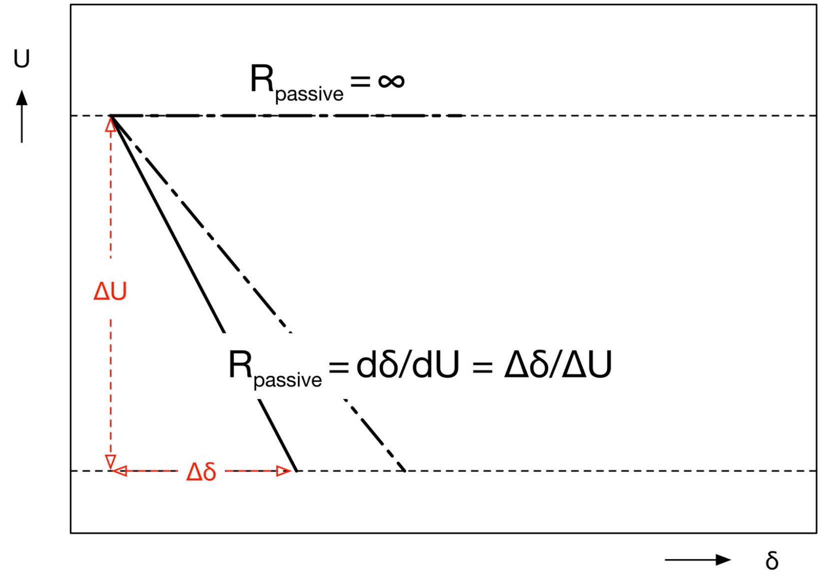
- The deviation phase shows 2 sub-phases:
  - Phase I: Passive robustness (or drop) phase: There is not yet a control mechanism active. The system utility drops by ΔU. The drop ΔU and the time t_{drop} are a function (1) of the strength of the disturbance, δ, and (2) of the structural stability of the system.
  - Phase II: Active robustness phase: The active O/C mechanism tries to reorganize/repair the system.
- It might be difficult to discriminate between the 2 phases, they might overlap.
- Usually t_{drop} is very short, the drop occurs “instantaneously” in many cases.

The utility deviation ΔU is the cost caused by the disturbance.

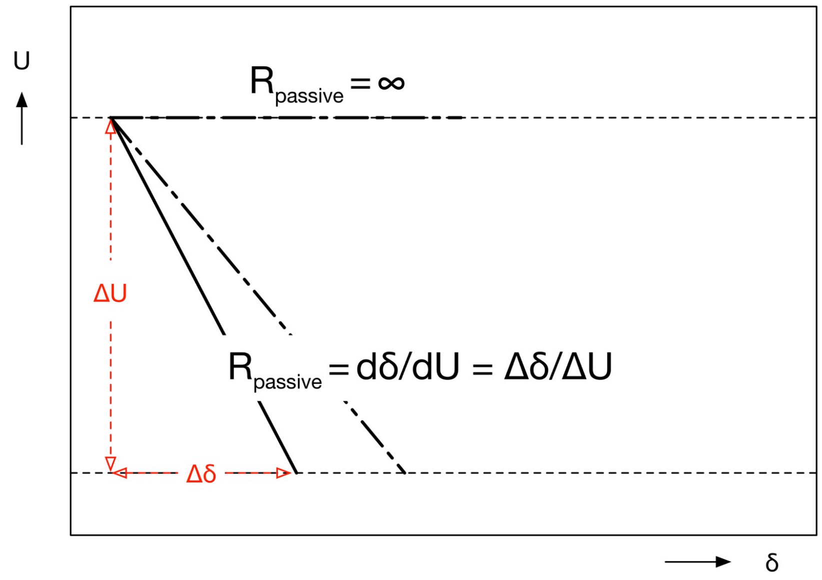
❑ Passive robustness

- Passive robustness $R_{passive}$ is the sensitivity of U against a change of δ, i.e. $dU/d\delta = 1/R_{passive}$
- $R_{passive}$ is a measure of the *structural* stability of a system in the presence of a disturbance δ.
- If δ has no effect on a system ($\Delta U = 0$)

  its structural stability $R_{passive} = \infty$.



- Example 1: A very stable concrete tower, which does not move ($\Delta U = 0$) under a storm of strength δ, is structurally infinitely stable.
- Example 2: A communication link with an error correcting code, which corrects errors up to 3 bits, is structurally infinitely stable under a disturbance of strength $\delta = 1$ bit.



❑ Active robustness R_{active}

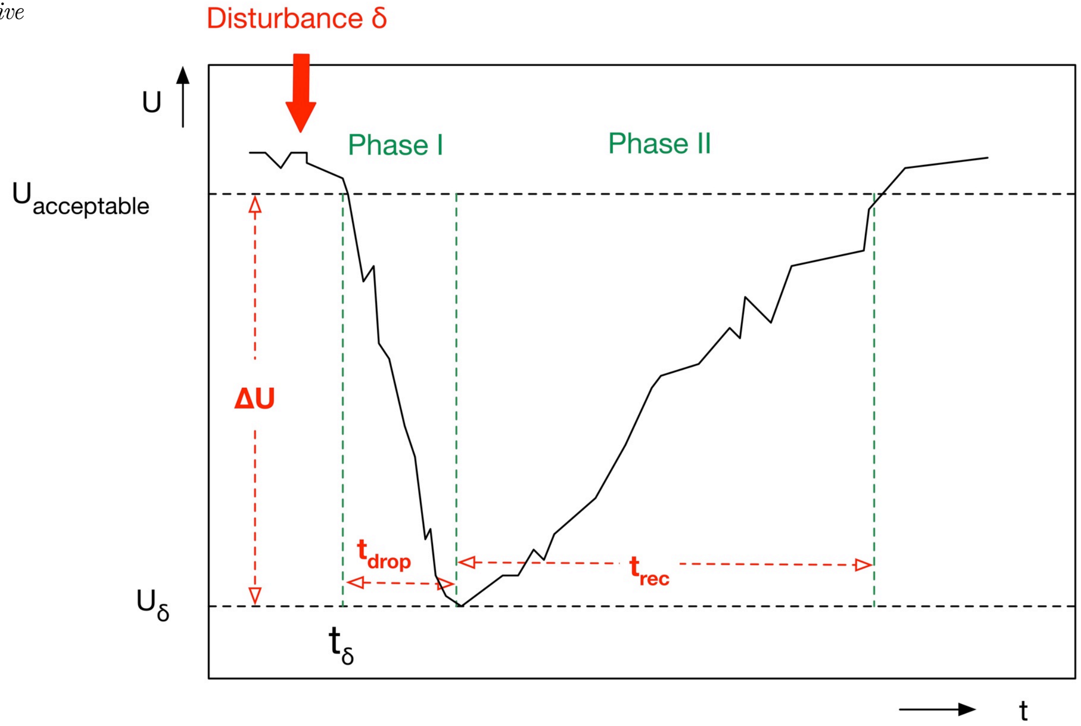
- R_{active} is defined as the (averaged) recovery speed of the system, i.e.

$$R_{active} = \frac{dU}{dt} \; or \; R_{active} = \frac{\Delta U}{t_{rec}} \; (in\ case\ of\ a\ full\ recovery)$$

$$t_{rec} = \frac{\Delta U}{R_{active}}$$

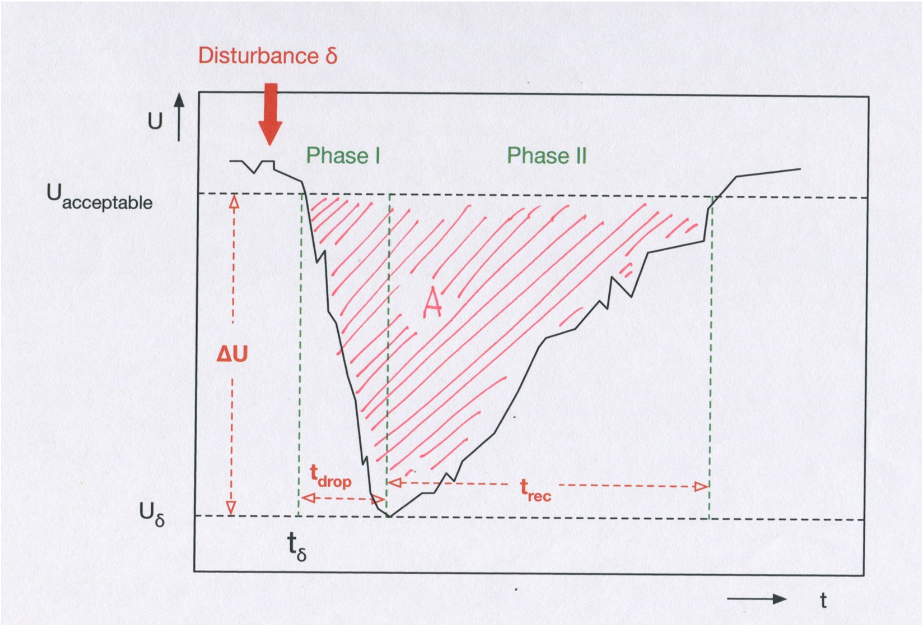
$$t_{rec} = \frac{\delta}{R_{passive} \times R_{active}} \; with \; \Delta U = \frac{\delta}{R_{passive}}$$

- R_{active} is a property of the Observer/Controller
- Without an O/C the system stays at U_δ as long as the disturbance remains.



- The robustness of a system under a given disturbance of strength δ is characterized by the triple (δ, ΔU, t_{rec}) or (δ, $R_{passive}$, R_{active}).
- We can use the area A of the utility deviation from $U_{acceptable}$ until full recovery to $U_{acceptable}$ as a measure for the effective utility degradation:
  - Effective utility degradation [1]) $A = \Delta U \times (t_{drop} + t_{rec}) - \int_{t_\delta}^{t_\delta + t_{rec}} U(t)\,dt$
- To achieve a minimal degradation we have to minimize A (i.e. ΔU and t_{rec}).

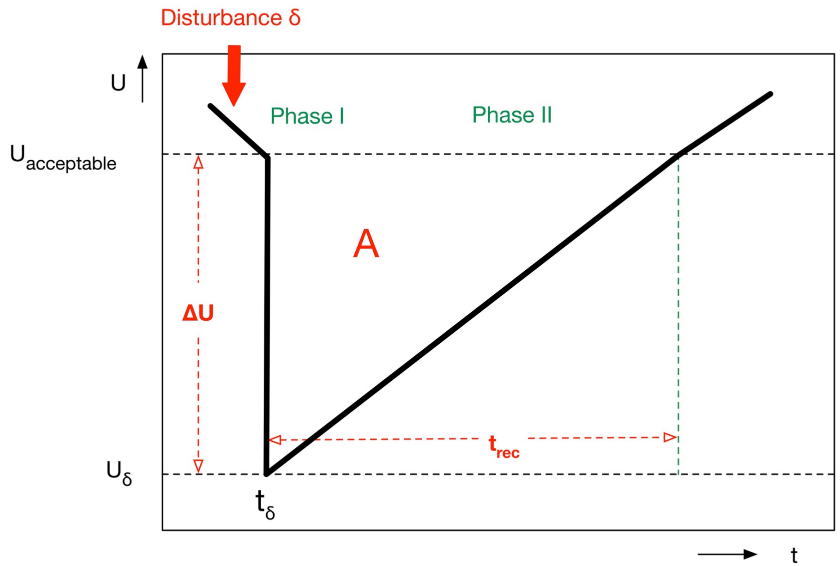
[1]) for $U_\delta = 0$



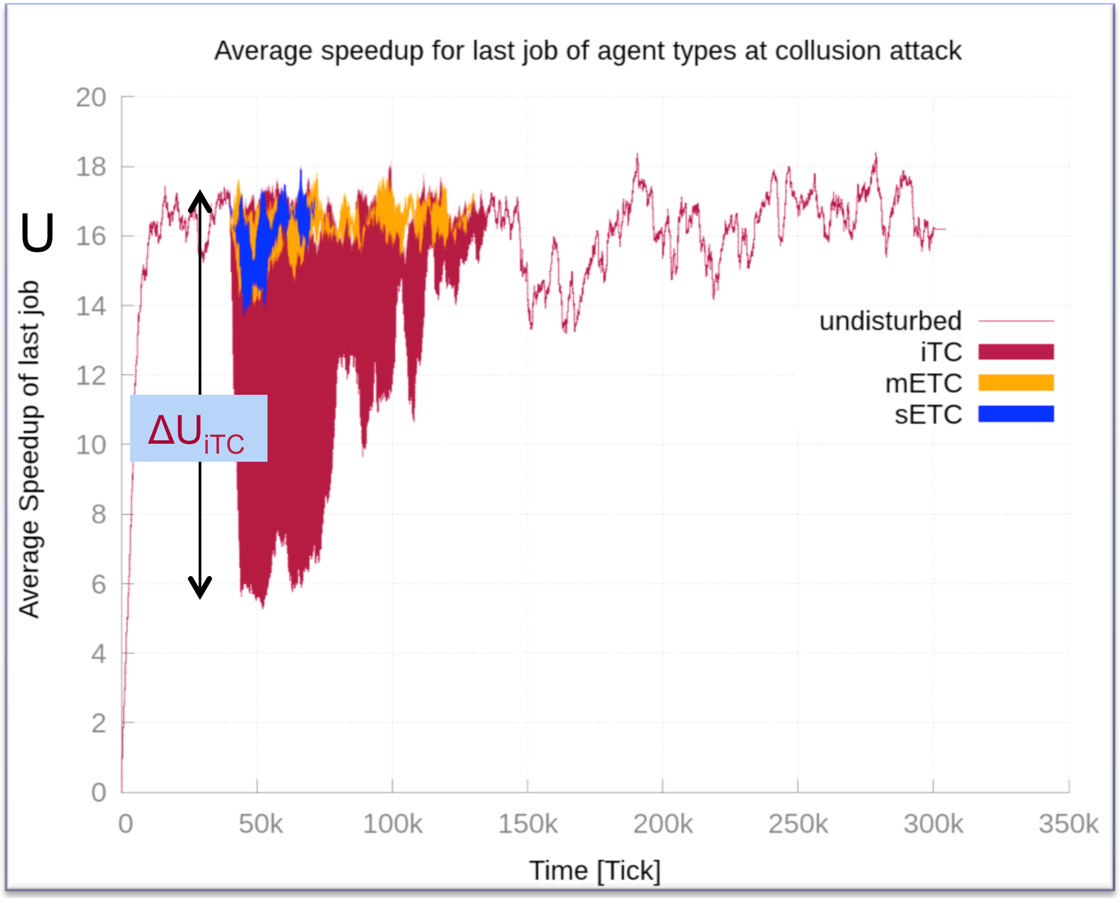
- For simplification we approximate the deviation area by a triangle:
  - The drop occurs very fast, hence $t_{drop} = 0$.
  - The recovery is assumed to be linear.
- Then $A = \frac{\Delta U \times t_{rec}}{2} = \frac{1}{2}\frac{\delta}{R_{passive}} \times \frac{\delta}{R_{passive} \times R_{active}}$
- Effective utility degradation $\boxed{A = \frac{1}{2}\frac{\delta^2}{R_{passive}^2 \times R_{active}}}$

A is a cost x time product

- Observations
  - An increase of $R_{passive}$ decreases A more effectively than a R_{active} increase. The reason is that $R_{passive}$ influences ΔU as well as t_{rec}.
  - There is a trade-off possible between $R_{passive}$ and R_{active} .



Experimental recovery behaviors from TC-enhanced computing grid (1)



- ❑ Trust Community experiments: 3 experimental recovery behaviors
  - with identical δ (attack size)
  - 3 different O/C solutions
- ❑ The O/C solutions mETC and sETC counteract the attack so fast, that ΔU is reduced as well.
- ❑ For the practical comparison of experimental evaluations the determination of A (the colored areas under the 3 curves) seems to be best suited.

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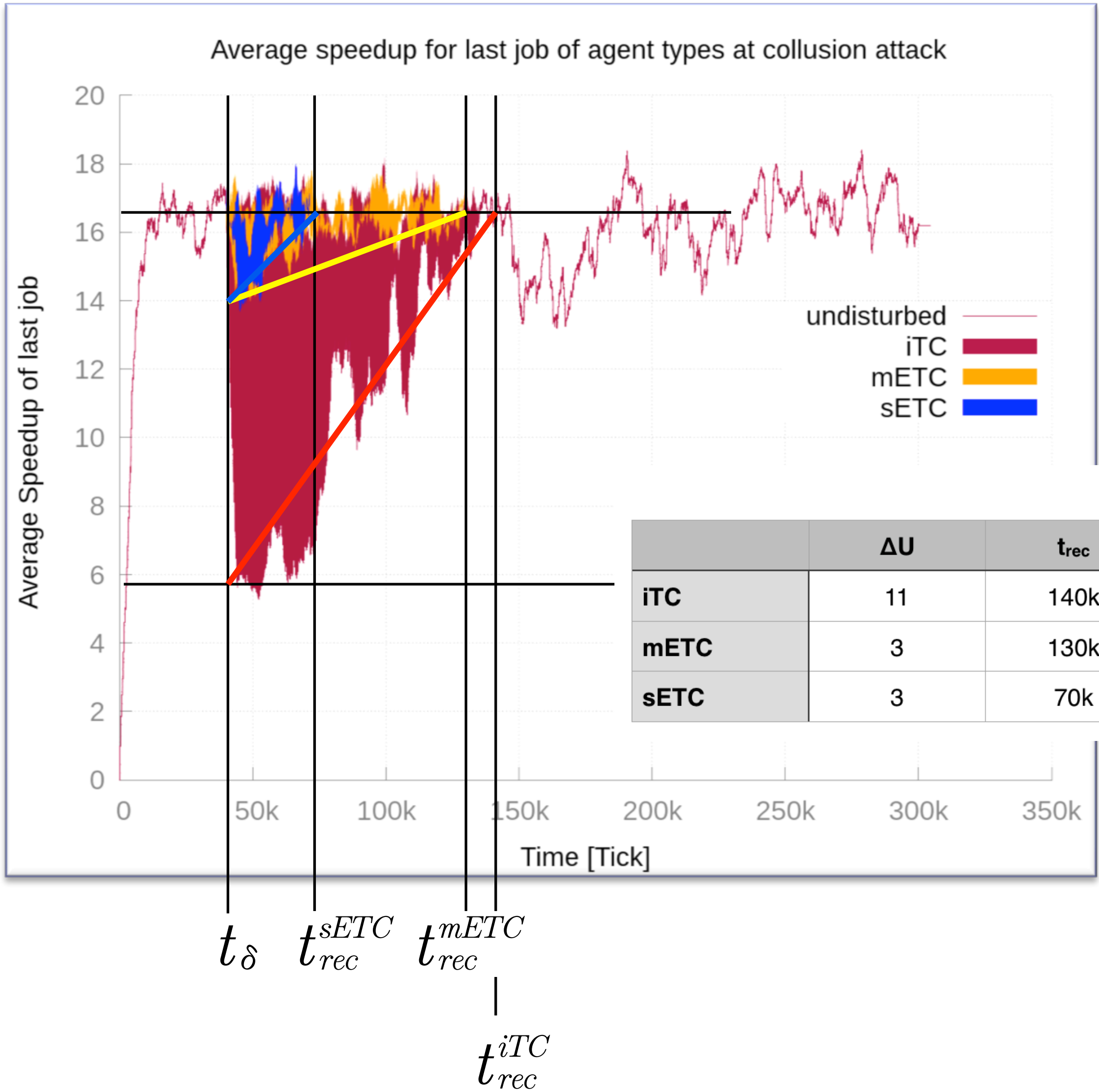
Experimental recovery behaviors from TC-enhanced computing grid (2)



Evaluation

	ΔU	t_{rec}	A [x10³]	$R_{passive}$	R_{active}	δ
iTC	11	140k	770	4.5.	$8 \cdot 10^{-5}$	50
mETC	3	130k	195	17	$2.3 \cdot 10^{-5}$	50
sETC	3	70k	105	17	$4.3 \cdot 10^{-5}$	50

Experimental recovery behaviors from TC-enhanced computing grid (3)

Evaluation

	ΔU	t_{rec}	A [x10^3]	$R_{passive}$	R_{active}	δ
iTC	11	140k	770	4.5.	$8 \cdot 10^{-5}$	50
mETC	3	130k	195	17	$2.3 \cdot 10^{-5}$	50
sETC	3	70k	105	17	$4.3 \cdot 10^{-5}$	50

A is a cost x time product: [A] = [speed-up x time]

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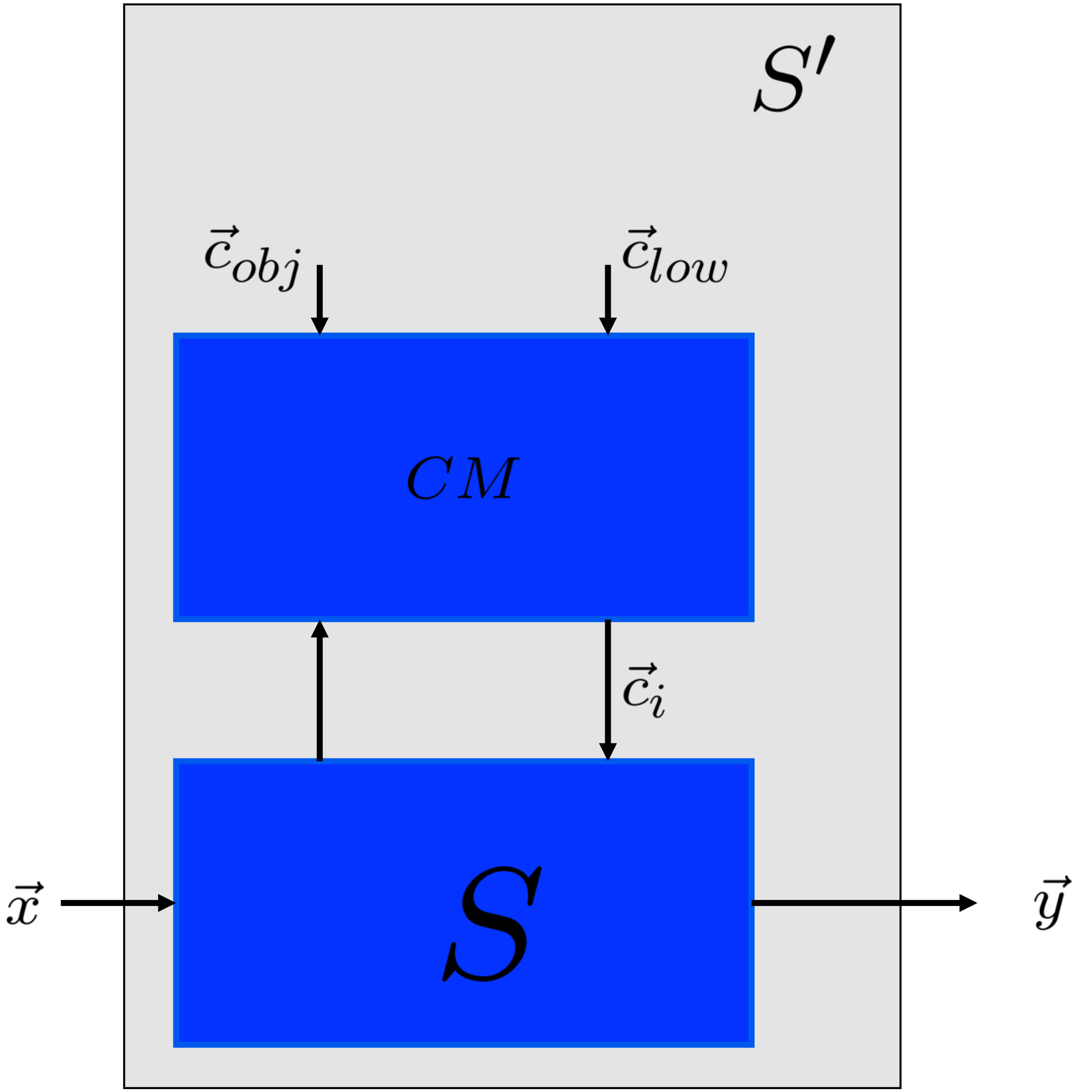


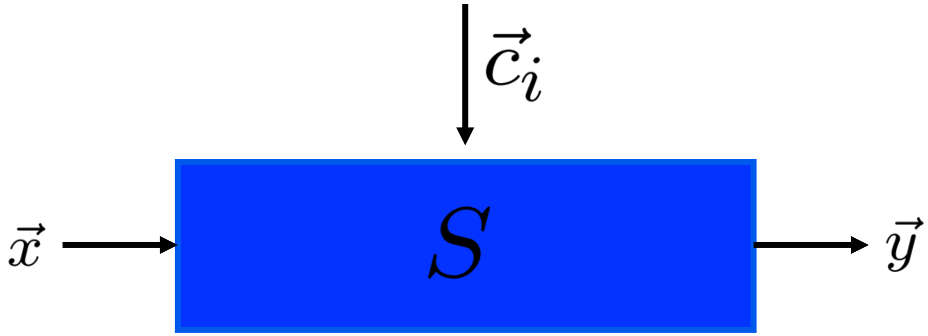
S is adaptable.
S ‘ is adaptive.

- Definition: Let D be a non-empty set of disturbances.
- A system is called (self-) adaptive iff it is capable to move into the acceptance space after any of the disturbances D without* needing external control.
  - That means for a robust system S, if δ transforms state $\mathbf{z}(t)$ of S into state $\delta(\mathbf{z}(t))$ then, after some time interval t_{rec} the state of S will be acceptable.
  - That means for a flexible system S, if δ is a change of goals (i.e. a change of acceptance space) then, after some time interval t_{rec} the state of S will be acceptable.
- The adaptivity of a system is quantitatively specified by its degree of autonomy (see below).

adaptive = robust or flexible!

* "without" must be quantified!

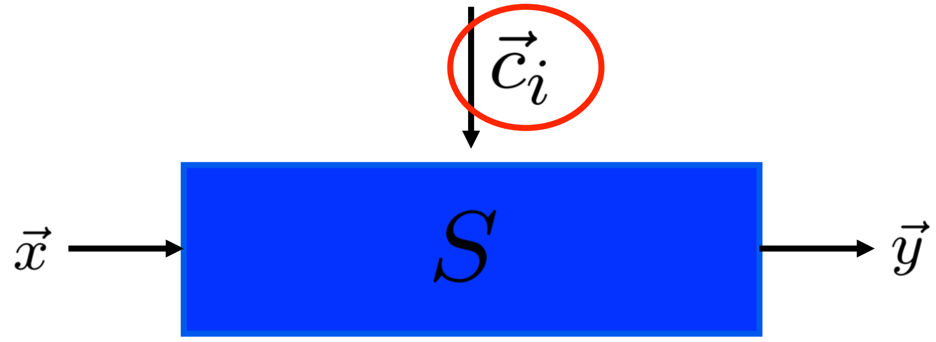
- A system S is called adaptable or controllable iff explicit (external) control actions are possible.
  - The behavior of an adaptable system *S* can be modified from the outside via control inputs $\mathbf{c}_i$ by
    - changing parameters and/or
    - changing its structure (elements and links).



S is adaptable.

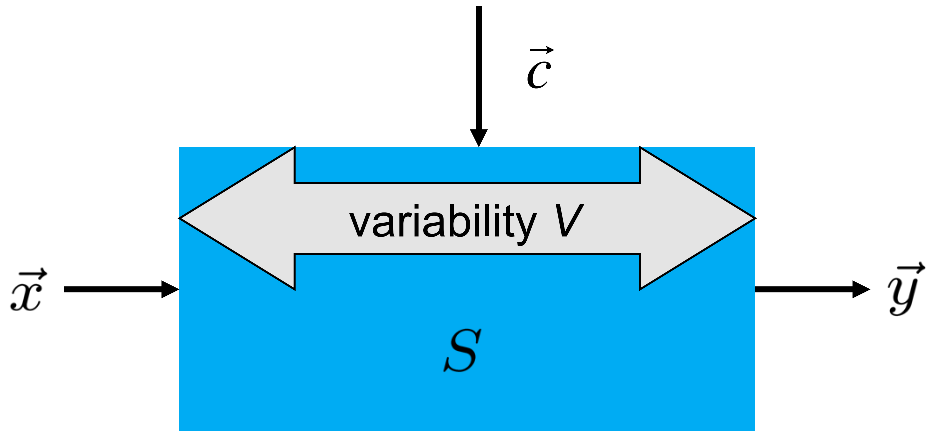
Adaptability is a passive property!

Notation: **c**$_i$ is equivalent to $\vec{c}_i$!



- We have to specify the range of possibilities for influencing the SuOC. This changeability (or plasticity) is described by the configuration space representing the capability of S to be changed (passively!).
- It is determined by the control parameters **c** of the system that can be changed directly by the external control mechanism CM.
  - These control parameters refer to all the components of the system structure and to further parameters.
- A control input **c** selects a certain configuration.
- In the following we assume that S is an adaptable system.

- The configuration space comprises the set of configurations that S can assume.
- Every configuration is specified by the values of a collection of system or environmental parameters **c**, which are open to be modified by control actions.
- These parameters are called configuration parameters.
- **c** can be regarded as a pointer into the configuration space. The dimension of this pointer corresponds to the dimension of the configuration space.



- The Variability *V* equals the number of bits necessary to address all the different configurations in the configuration space.
  - The variability of a system is measured by V = ld (number of configurations). This is the number of bits in **c**.
- The configuration space and the variability represent the possible modifications by CM.
- Every control action modifies the values of a subset of the configuration attributes.
- We denote the number of bits actually modified by a specific control action **c** by #*c*.
  - #c can be less than V (only some attributes are modified).
  - #c can be greater than V (multiple steps of modifications).

Possible modifications ≠ Actual modifications

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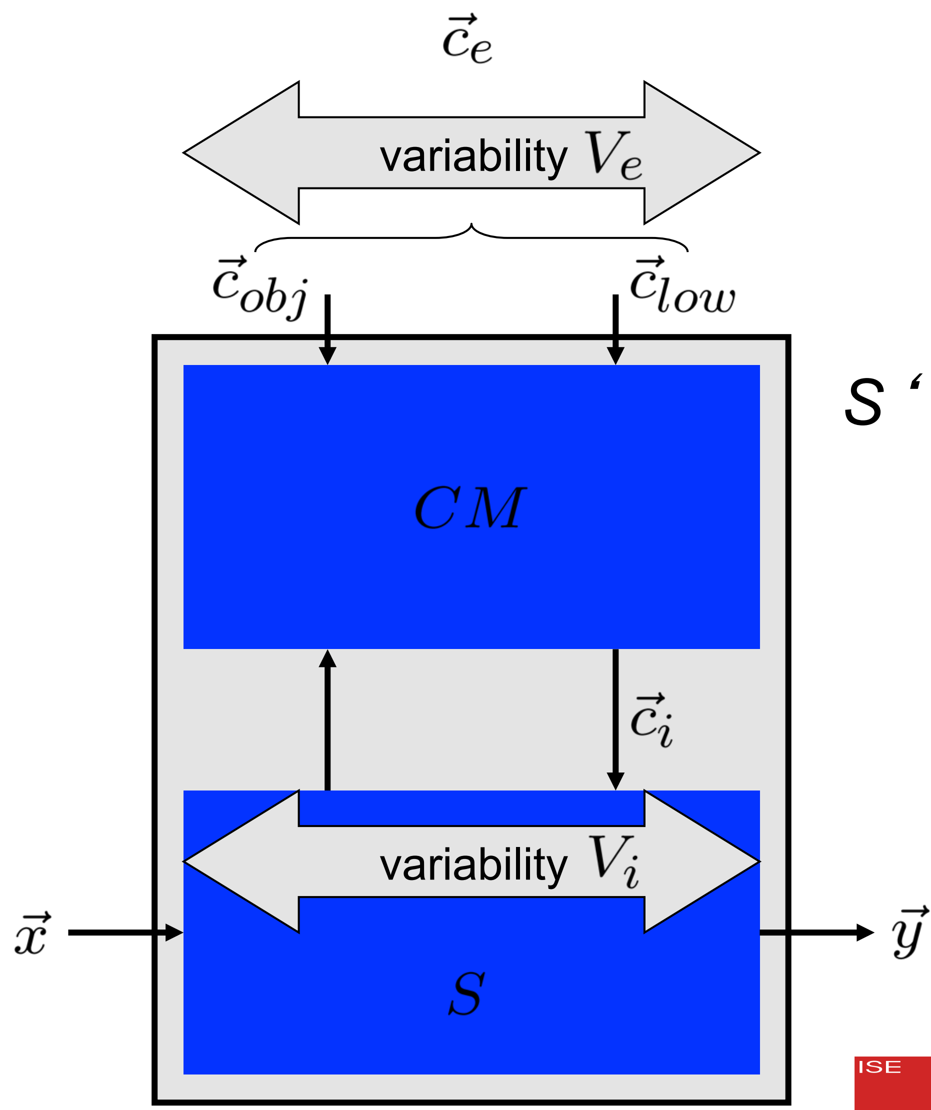
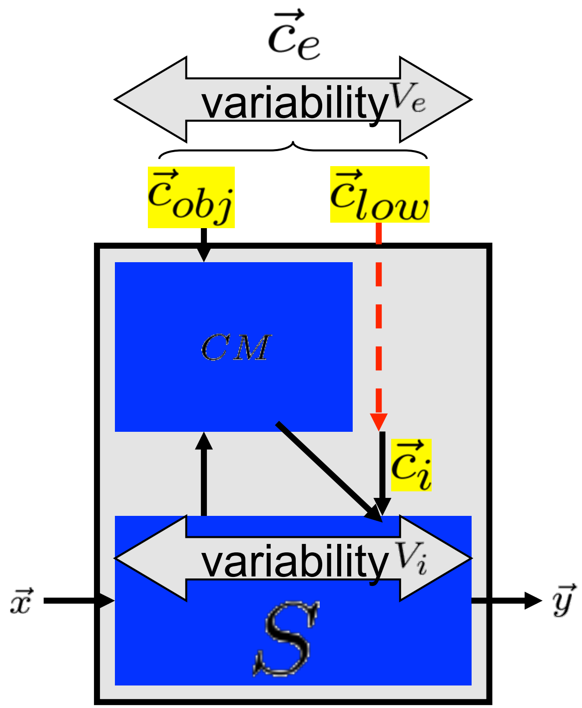
- With respect to S‘ we can distinguish two types of configuration spaces:
  - The internal configuration space is the configuration space of S, its variability is denoted by V_i.
  - The external configuration space is the configuration space of S‘, its variability is denoted by V_e.



- We distinguish between high-level control inputs $\mathbf{c}_{obj}$, specifying system objectives to be followed by the control mechanism *CM,*
- and control actions $\mathbf{c}_{low}$ directly controlling attributes of the internal configuration space (low-level control).

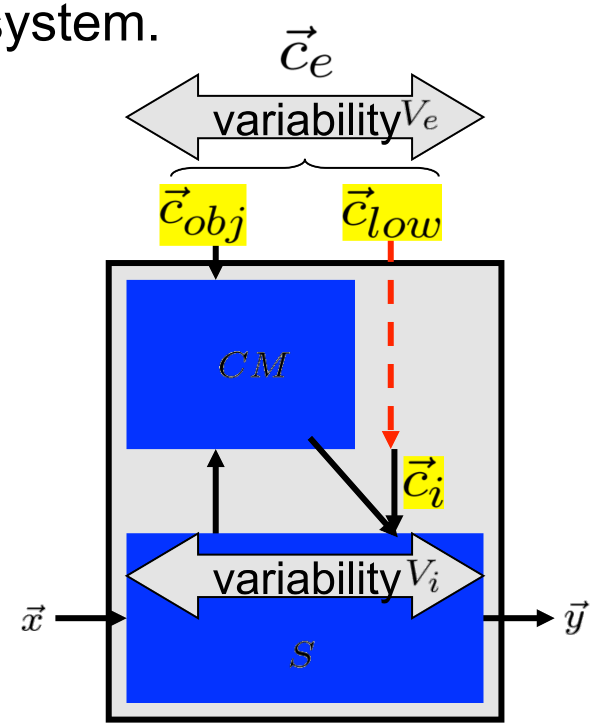


- We use the relation between external and internal control actions to characterize the degree of autonomy.
- The origin of the control actions $\mathbf{c_i}$ determines how autonomous a system is:
  - External origin of $\mathbf{c_i}$, i. e. $\mathbf{c_i} = \mathbf{c_{low}}$: direct control by an external (e. g. human) operator, no autonomy.
  - Internal origin of $\mathbf{c_i}$: *S* is fully controlled by *CM*. *CM* is part of the system S'. Full autonomy.
  - Intermediate: Control actions of type $\mathbf{c_i}$ *and* $\mathbf{c_{low}}$ are both used to control S.

- The autonomy of the system S‘ can be characterized by the complexity reduction R

$$R = V_i - V_e$$

- If the system has been designed with the objective of having increasingly higher levels of abstraction, R will be a positive value.
- A negative value of R would indicate that the control mechanism leads to an additional complexity of the system.



- The (static) degree of autonomy α of system S‘ is defined by

$$\alpha = \frac{R}{V_i} = \frac{V_i - V_e}{V_i}$$

- The value of α will be at most 1 (if V_e = 0).
  - In this case, there is no external variability, i. e. there is no possibility to modify any attributes of S‘ by external control actions.
  - Such a system is called fully autonomous.

- If $\alpha = 0$, the internal and the external variabilities are the same, which indicates that there is no complexity reduction.
- If α drops below zero, we have a situation where the external configuration space contains more controllable attributes than the internal configuration space.

- To characterize the actual degree of autonomy we must consider the total number of bits that have been actually used in all control actions over some time period $[t_1, t_2]$.
- Definition: Let $\#c_e(t_i)$ and $\#c_i(t_i)$ be the number of bits of the external and internal control actions at a certain discrete time t_i.
- The dynamic complexity reduction r in S‘ over some time interval $[t_1, t_2]$ is defined as

$$r = \sum_{t_1}^{t_2} [\#c_i(t_i) - \#c_e(t_i)]$$

- The dynamic degree of autonomy β in S‘ over some time interval $[t_1, t_2]$ is defined as

$$\beta = \frac{\sum_{t_1}^{t_2} [\#c_i(t_i) - \#c_e(t_i)]}{\sum_{t_1}^{t_2} [\#c_i(t_i)}$$

Preconditions

System definition, quantitative emergence

Objectives

Terminology for self-organization and adaptivity

Quantitative approach

Content

- Self-organization and autonomy
- 5 aspects of autonomous systems
- Measuring robustness
- Measuring adaptivity: Configuration space and variability
- Control and degree of autonomy
- Controlled self-organization

- Intuition suggests that a self-organizing system is
  - a multi-element system (consisting of m elements, $m > 1$)
  - which needs no external control to restructure itself (i. e. it has a high degree of autonomy).

- A common assumption is that the control mechanism CM of a self-organizing system is (to a certain degree) distributed over the m elements.

- The control mechanism (CM) can be:
  - centralized (one CM)
  - distributed over the m elements (m CMs)
  - distributed over a hierarchy of CMs

- Definition: Degree of self-organization
  - Count the number of CMs (= k) in relation to the number of elements m of the system (k : m).

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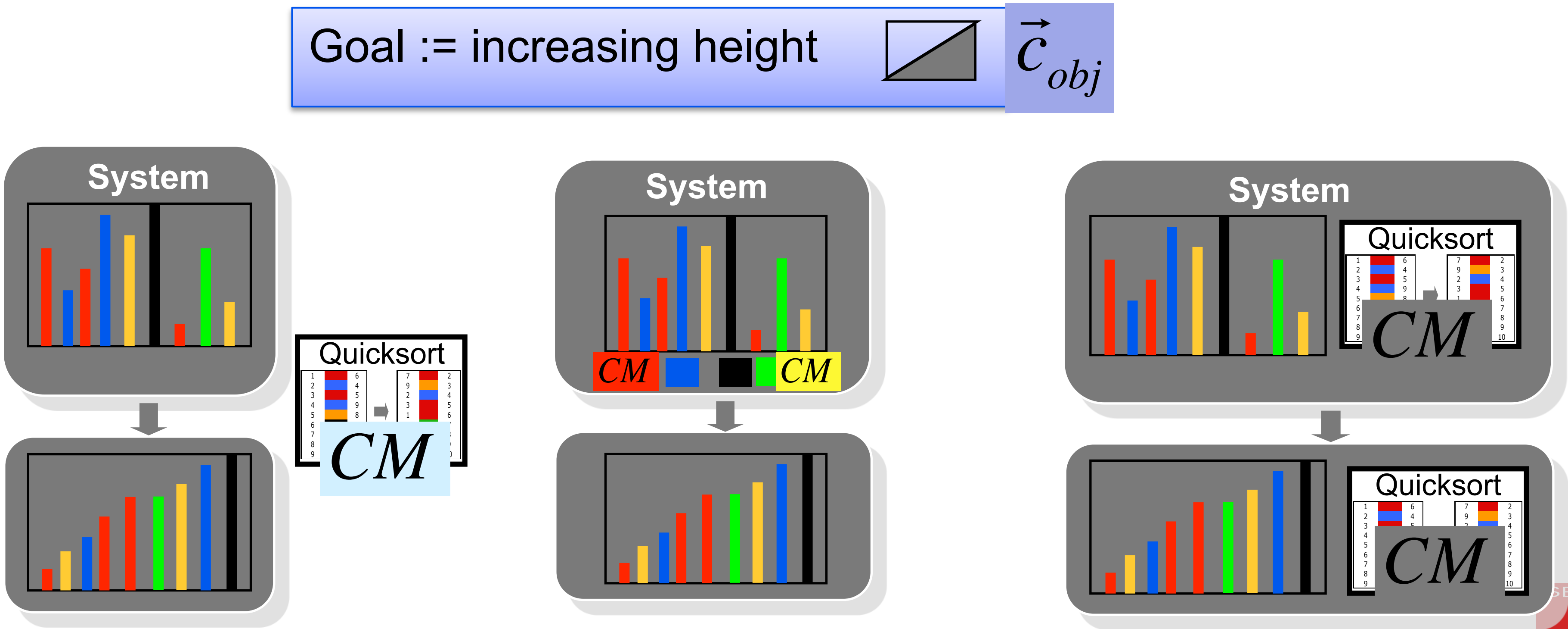
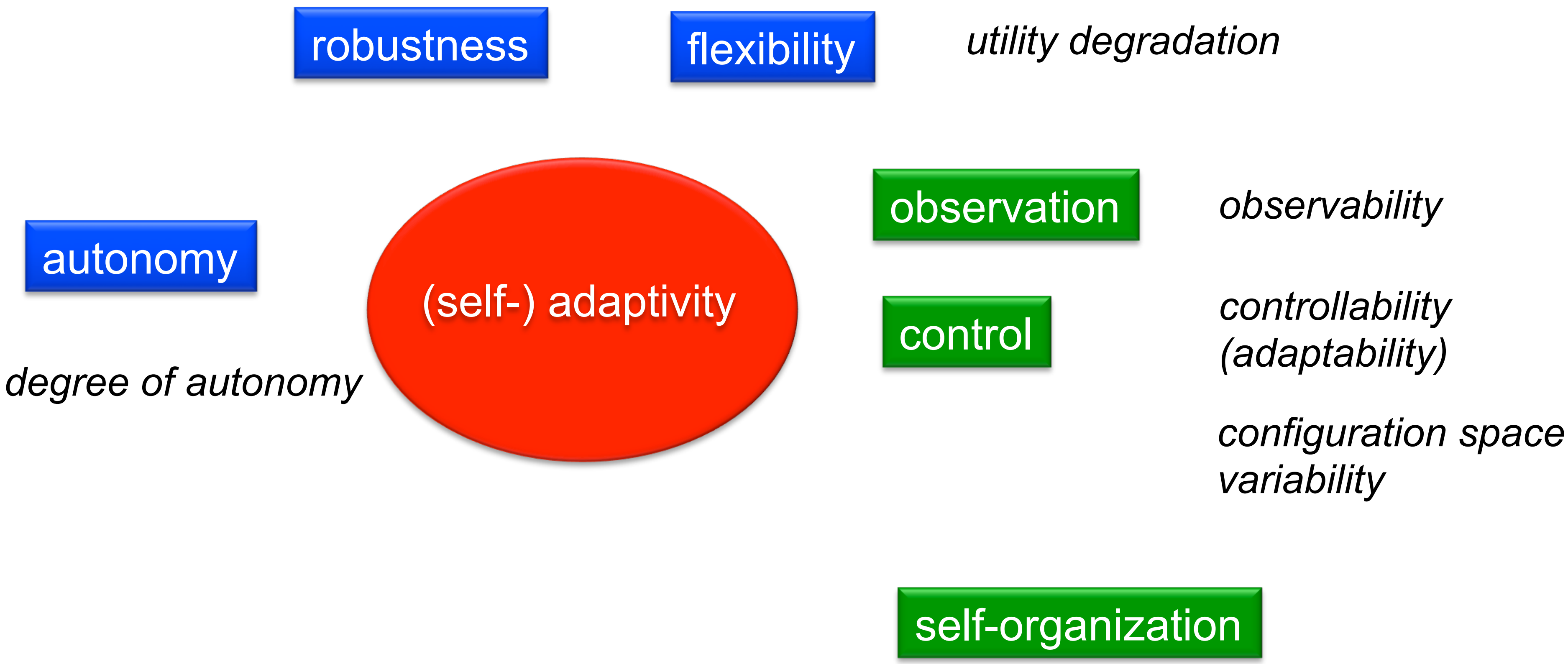
- Definition: Let S be an adaptive system consisting of m elements ($m > 1$) with large degrees of autonomy (α and β) and fully or partially distributed k control mechanisms CM ($k \geq 1$) leading to a degree of self-organization of ($k : m$).
  - S is called strongly self-organised, if $k = m$, i.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

- Definition: A self-organized system S' allows for controlled self-organization, iff:
  - it has a nonempty external configuration space, i. e. we have $V_e > 0$, *and*
  - it allows for external control actions of type $\mathbf{c}_{obj}$. (This implies an internal control mechanism CM!)




robustness
flexibility
utility degradation
autonomy
(self-) adaptivity
degree of autonomy
observation
observability
control
controllability
(adaptability)
configuration space
variability
self-organization