Selvoptimaliserende hierarkiske systemer

Prosessregulering, nasjonaløkonomi, hjerne og maratonløping

Sigurd Skogestad

Institutt for kjemisk prosessteknologi

NTNU

Trondheim

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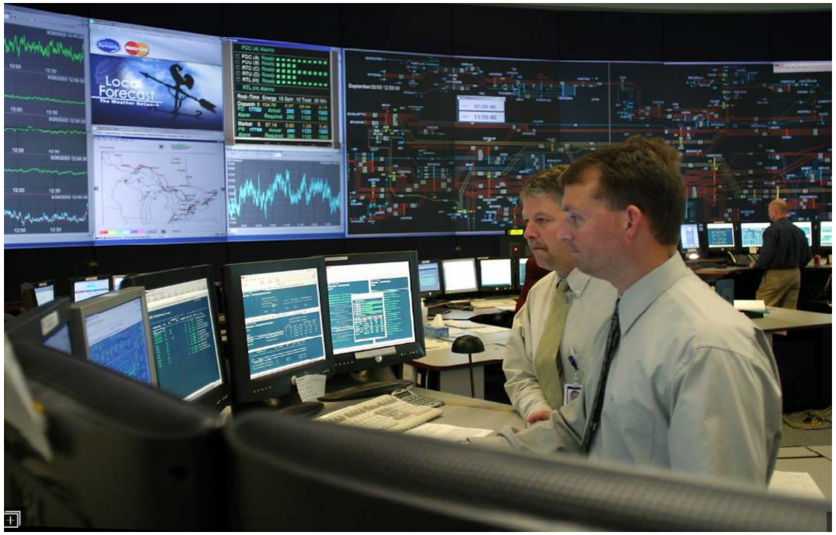
Oversikt

1. Mitt utgangspunkt
2. Styring av virkelige systemer
3. Sentralisert beslutningssystem
4. Hvordan fungerer virkelige styringssystemer?
5. Hvordan designe et hierarkisk system på en systematisk måte?
6. Hva skal vi regulere?
   1. Aktive begrensninger
   2. Selvoptimaliserende variable
7. Eksempler: Biologi, prosessregulering, økonomi, maraton

- Fokus: **Ikke** optimal beslutning
- Men: Hvordan **implementere** beslutning på en enkel måte i en usikker verden

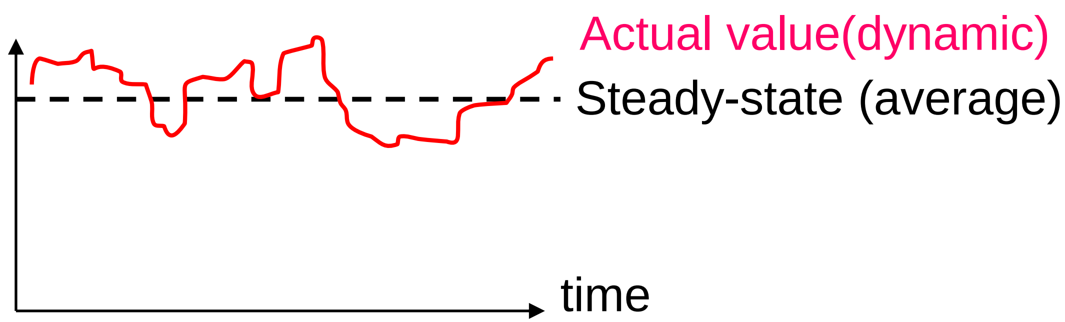
Mitt utgangspunkt: Hvordan skal man regulere et helt prosessanlegg?



Mer generelt: Hvordan designer man komplekse beslutningssystemer?

Why control (*regulering*) ?

- *Operation*



In practice never steady-state:

- Feed changes
- Startup
- Operator changes
- Failures
- …..

} "Disturbances" (d's)

- Control is needed to reduce the effect of disturbances
- 30% of investment costs are typically for instrumentation and control

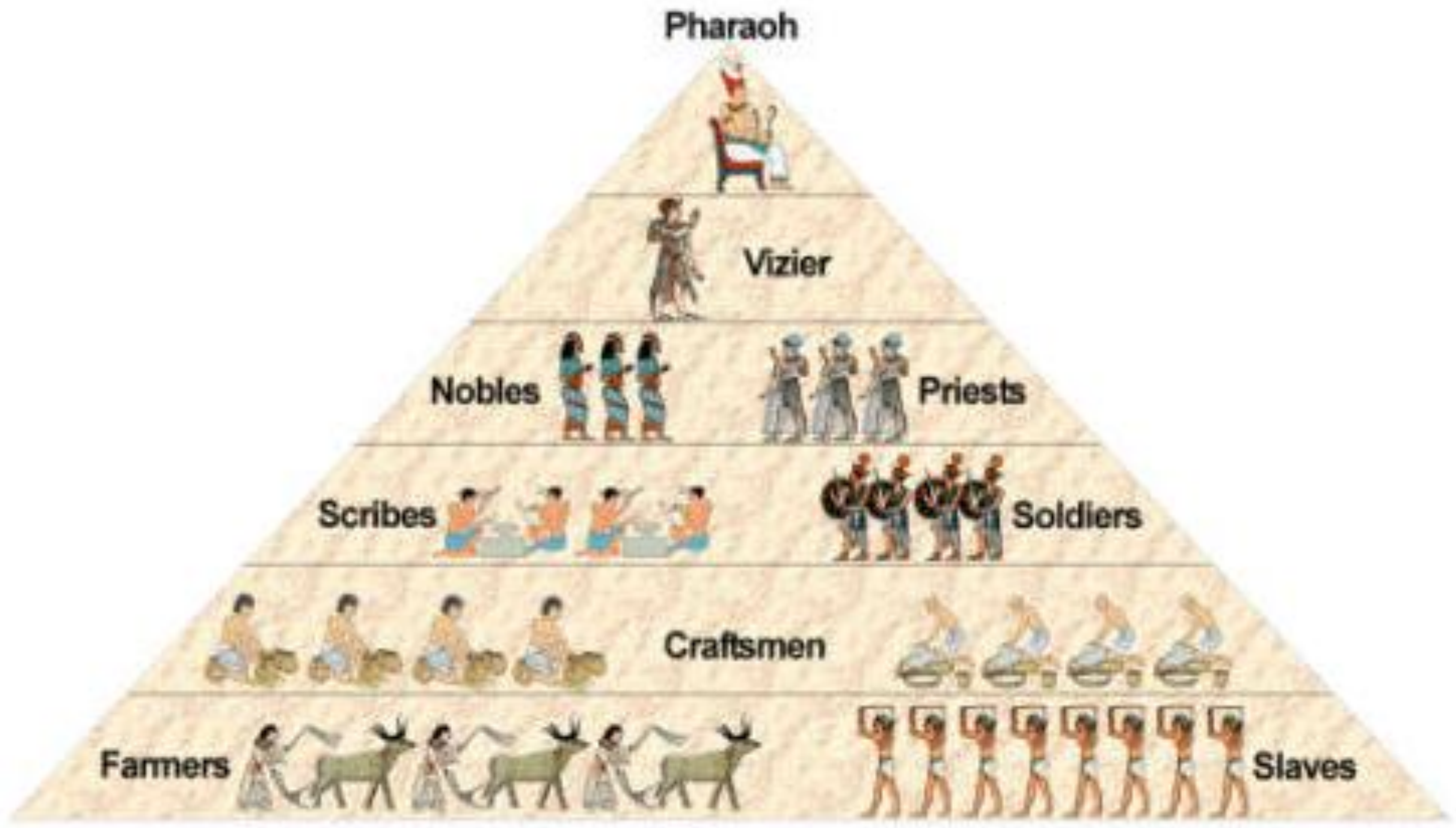
Main objectives control system

1. Stabilization
2. Implementation of acceptable (near-optimal) operation

ARE THESE OBJECTIVES CONFLICTING?

- Usually NOT
  - Different time scales

Alle virkelige beslutningssystemer: Hierarkisk pyramide



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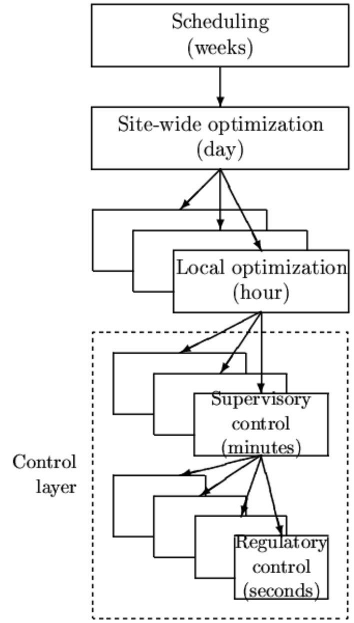
Practice: Engineering systems

- Most (all?) large-scale engineering systems are controlled using hierarchies of quite simple controllers
  - Large-scale chemical plant (refinery)
  - Commercial aircraft
- 1000's of loops
- Simple elements

Same in biological systems

- **Why are real decision systems hierchical and decentralized?**
- **How should such systems be designed?**



Example: Bicycle riding

Note: design starts from the bottom

- ***Stabilizing (regulatory) control*:**
  - First need to learn to stabilize the bicycle
    - CV = y_2 = tilt of bike
    - MV = body position

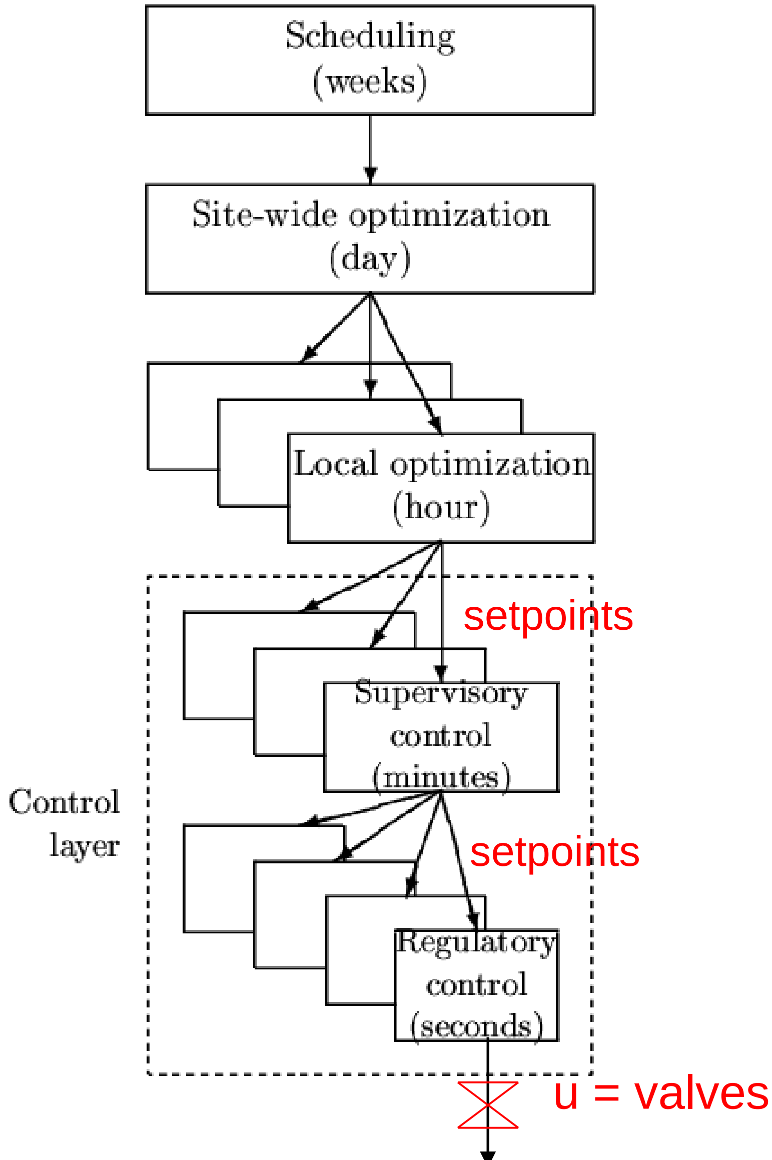
- ***Economic (supervisory) control*:**
  - Then need to follow the road.
    - CV = y_1 = distance from right hand side
    - MV=y_{2s}
  - Usually constant setpoint, e.g. y_{1s}=0.5 m

- ***Optimization*:**
  - Which road should we follow?

MV = manipulated variable
CV = controlled variable

Process control: Hierarchical structure (pyramid)

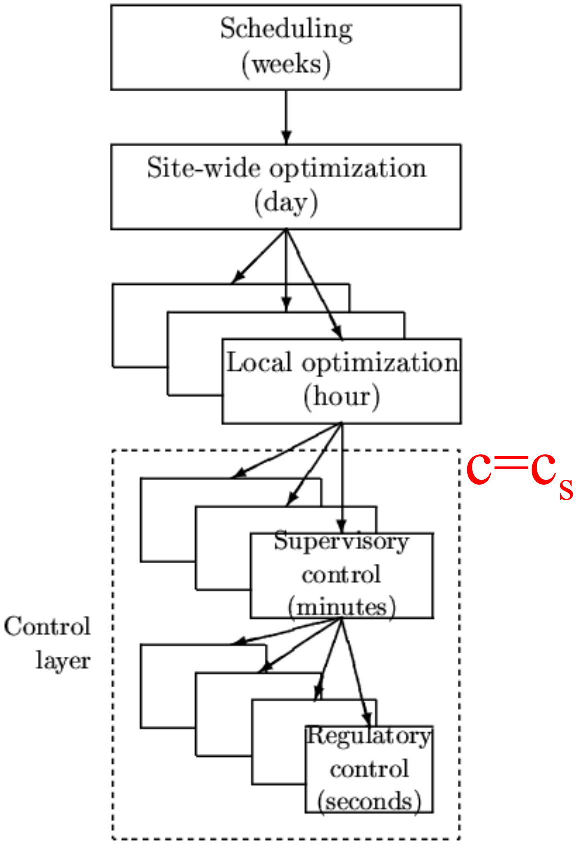
Our Paradigm



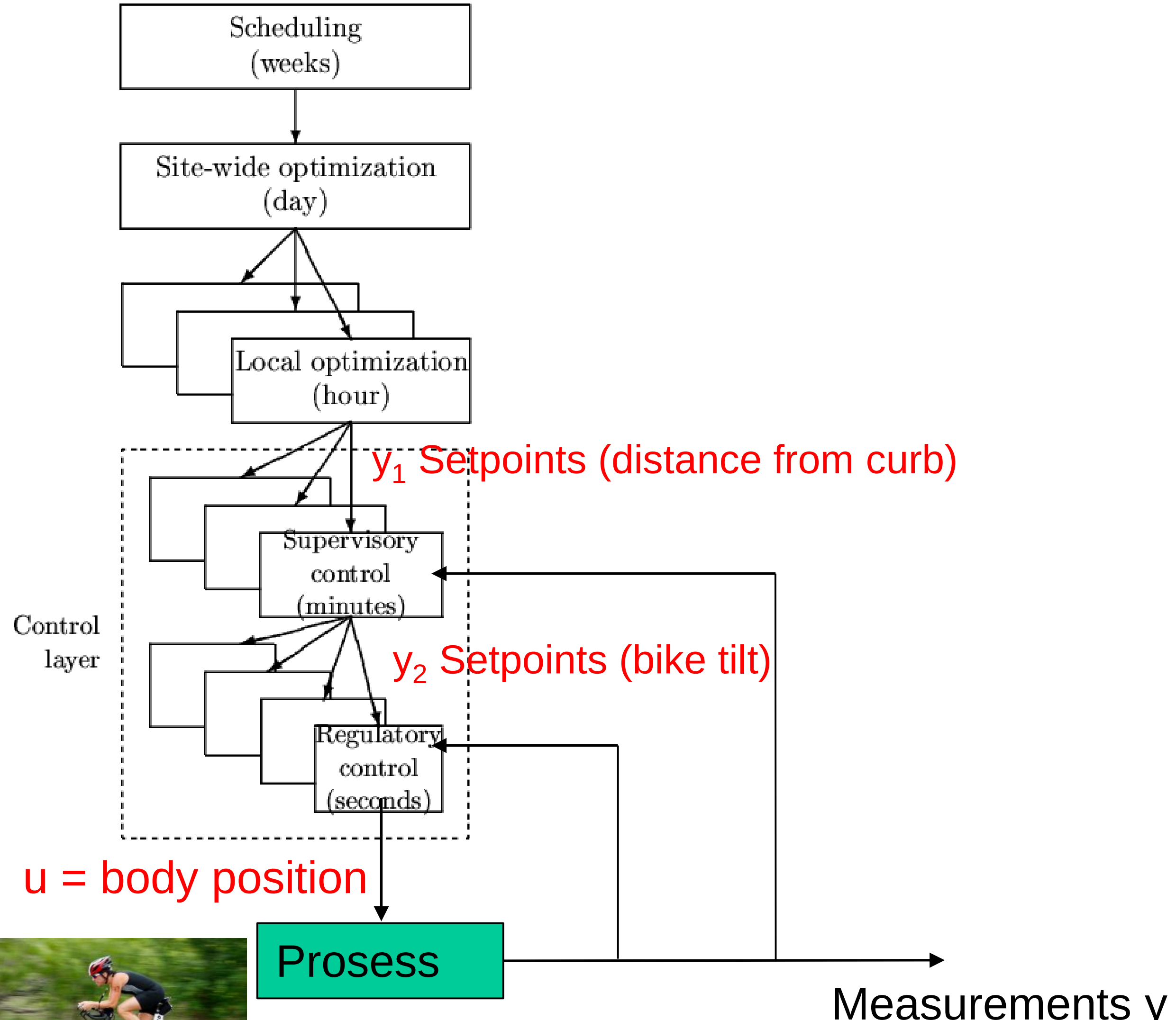
1. Tidsskalaseparasjon
2. Selvoptimaliserende variable
3. Lokal feedback

Self-optimizing Control

Self-optimizing control is when acceptable operation can be achieved using constant set points (c_s) for the controlled variables c (without re-optimizing when disturbances occur).



Håndtere usikkerhet: Lokal feedback



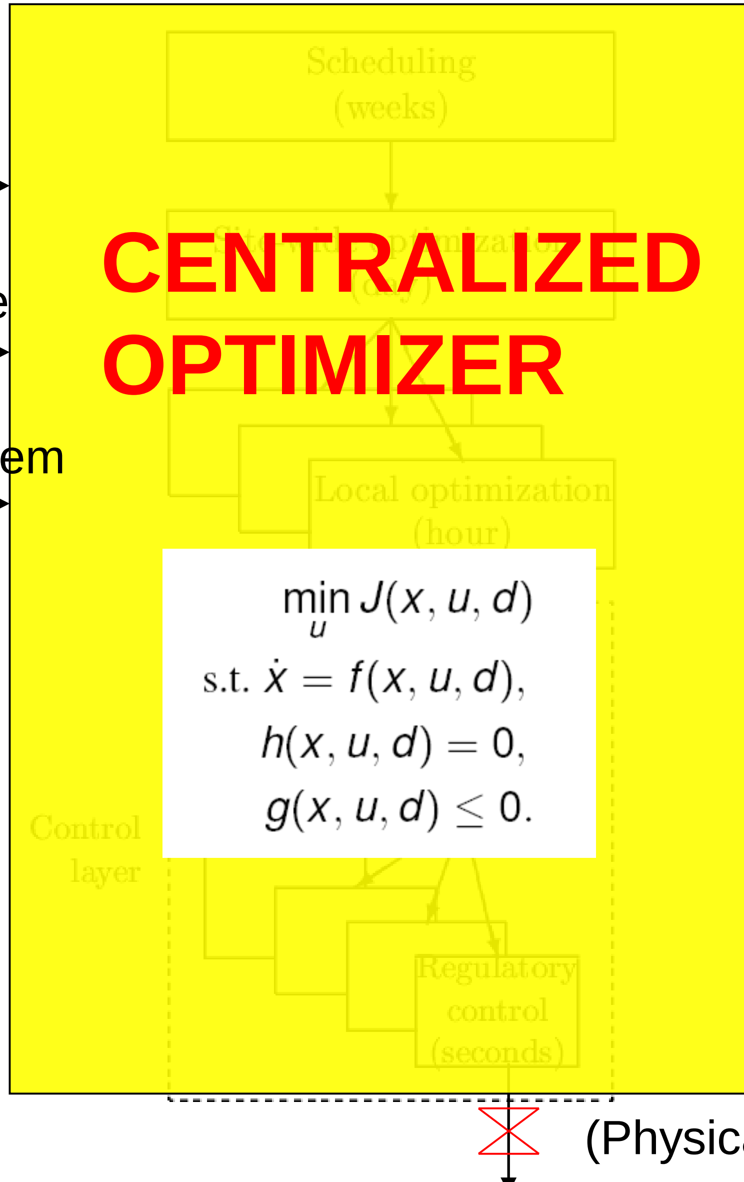
In theory: Optimal control and operation

In theory: Optimal control and operation

Objectives

Present state

Model of system



$$\min_u J(x,u,d)$$
$$\text{s.t. } \dot{x} = f(x,u,d),$$
$$h(x,u,d) = 0,$$
$$g(x,u,d) \le 0.$$

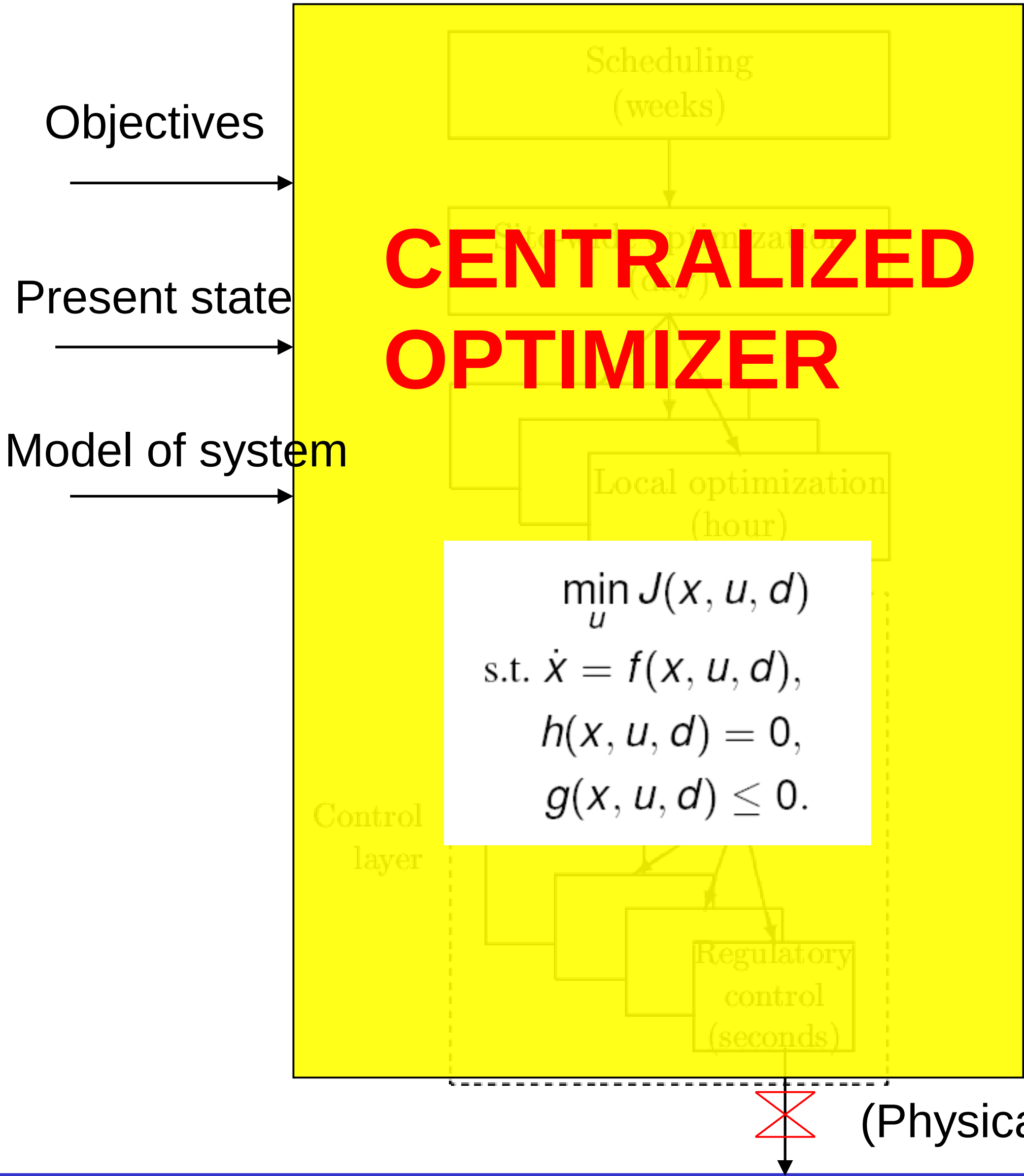
(Physical) Degrees of freedom

Approach:
- Model of overall system
- Estimate present state
- Optimize all degrees of freedom

Process control:
- Excellent candidate for centralized control

Problems:
- Model not available
- Objectives = ?
- Optimization complex
- Not robust (difficult to handle uncertainty)
- Slow response time

In theory: Optimal control and operation



Approach:
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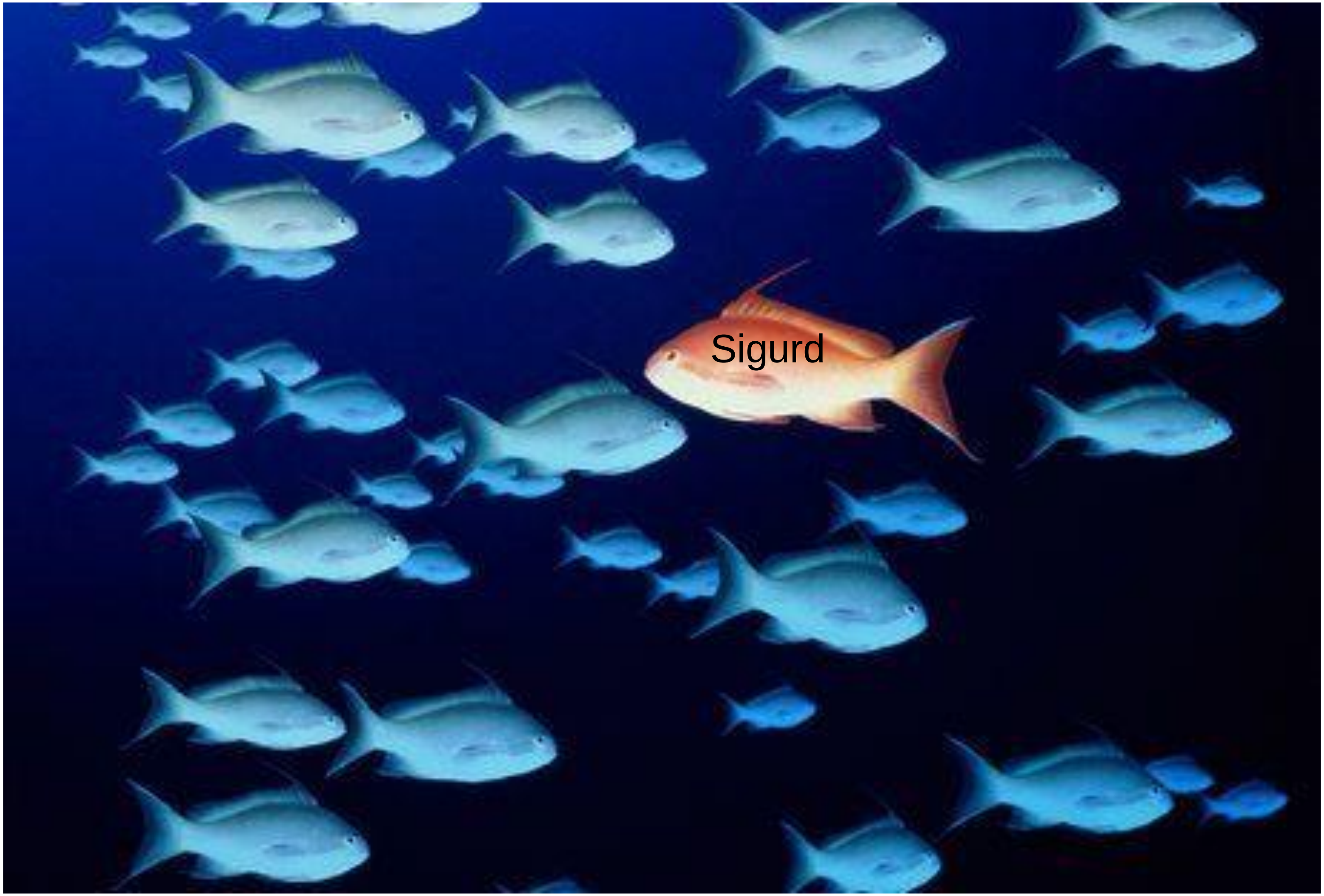
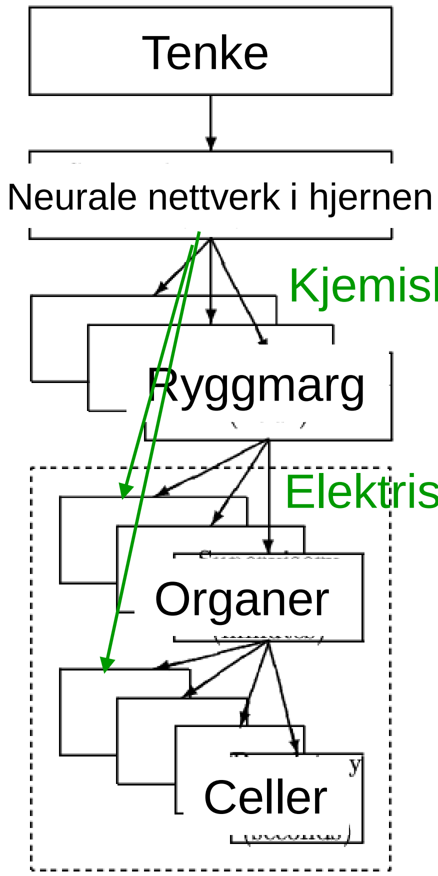
Academic process control community fish pond

Optimal centralized Solution (EMPC)



Menneskets beslutningssystem



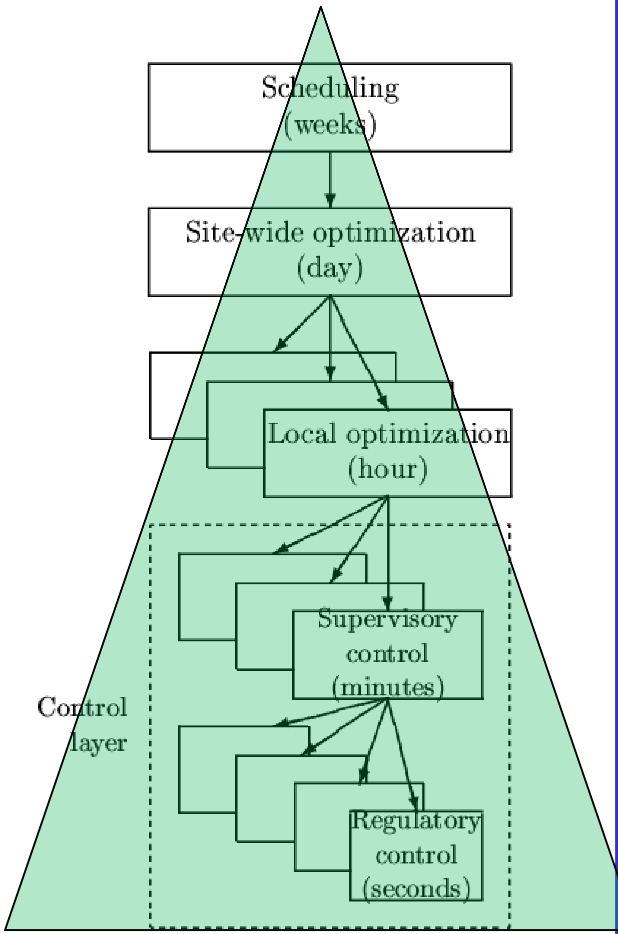
Bevissthet

Intuisjon
Instinkt

Kjemisk signal (hormoner)

Reflekser

Elektrisk signal (nerver)



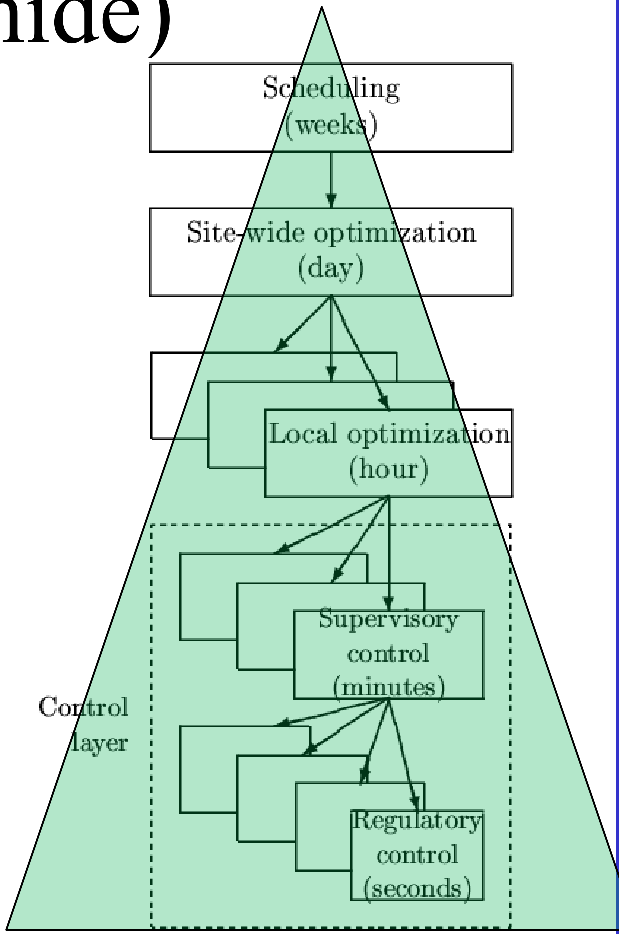
Eksempler:
Temperatur-regulering
Puls-regulering
Puste-regulering

To hovedprinsipper for oppdeling av beslutningssystemer (pyramide)

1. **Tidsskala-separasjon (vertikal oppdeling)**
   - Hierarkisk (Master-slave)
   - Setpunkt sendes nedover
   - Rapport om problemer sendes oppover

   Intet tap dersom:
   - tidsskalaene er separert og man har selvoptimaliserende regulering mellom oppdateringer

2. **Romlig separasjon (horisontal)**
   - Desentralisert
   - Intet tap dersom oppgaver kan utføres uavhengig av andre på samme nivå



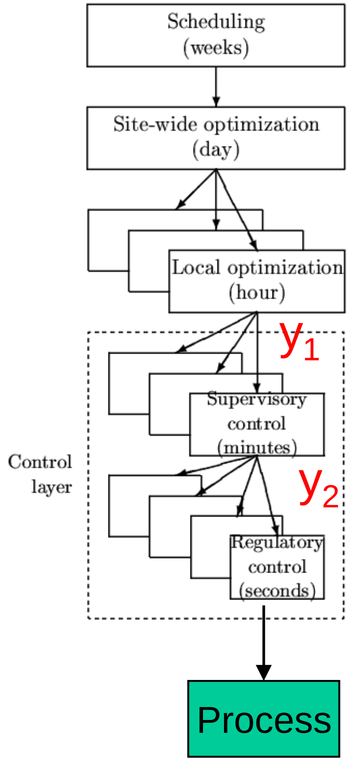
Systematic approach: Control structure design

I Top Down

- **Step 1:** Define optimal operation
  - Cost function J (to be minimized)
  - Operational constraints
- **Step 2:** Identify degrees of freedom and optimize for expected disturbances
  - Identify **Active constraints**
- **Step 3**: Select primary controlled variables y_1
  - **Active constraints + Self-optimizing variables**
- **Step 4:** Locate throughput manipulator (process control only)

II Bottom Up (dynamics, y_2)

- **Step 5**: Regulatory / stabilizing control (PID layer)
  - What more to control (y_2)?
  - Pairing of inputs and outputs
- **Step 6:** Supervisory control
- **Step 7:** Real-time optimization (Do we need it?)



S. Skogestad, ``Control structure design for complete chemical plants'', *Computers and Chemical Engineering*, **28** (1-2), 219-234 (2004).

Step 1. Define optimal operation (economics)

- What are we going to use our degrees of freedom u for?
- Define cost function J and constraints

J = cost feed + cost energy – value products

Step S2. Optimize

(a) Identify degrees of freedom
(b) Optimize for expected disturbances

- Need good model,
- Optimization is time consuming! But it is offline
- Main goal: Identify ACTIVE CONSTRAINTS
- A good engineer can often guess the active constraints

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Step S3: Implementation of optimal operation

- Have found the optimal way of operation. How should it be implemented?
- **What to control ?**
  1. Active constraints
  2. Self-optimizing variables (for unconstrained degrees of freedom)

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Optimal operation of runner

– Cost to be minimized, J=T
– One degree of freedom. Input u (MV)=power
– What should we control?

MV = manipulated variable

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1. Optimal operation of Sprinter

- 100m. J=T
- Active constraint control:
  - Maximum speed (”no thinking required”)
  - CV = power (at max)

CV = controlled variable

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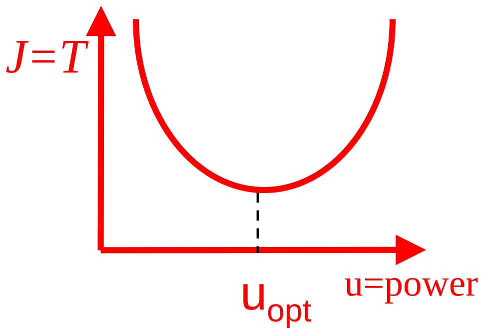
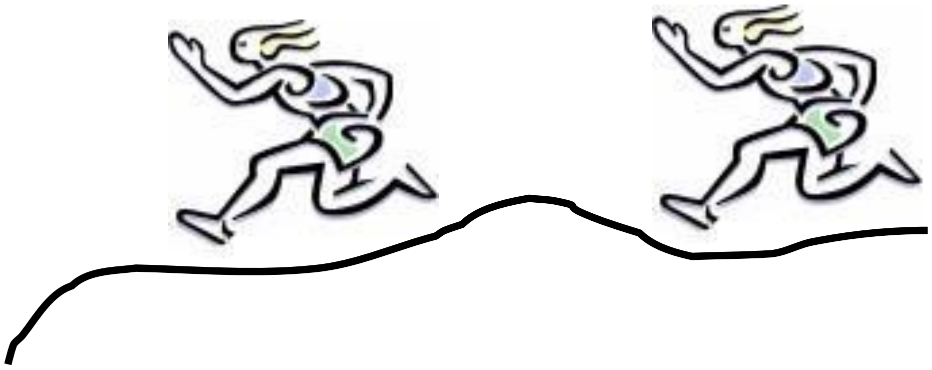
2. Optimal operation of Marathon runner

- 40 km. J=T
- What should we control?
- Unconstrained optimum





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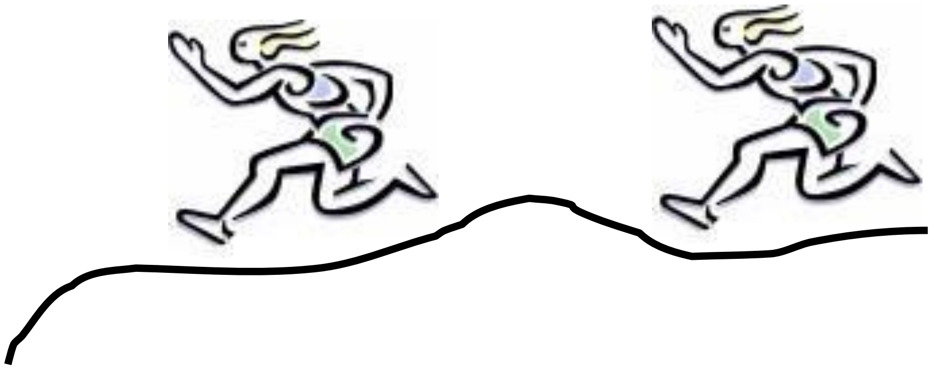
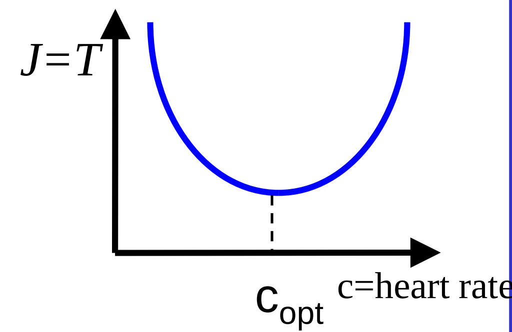
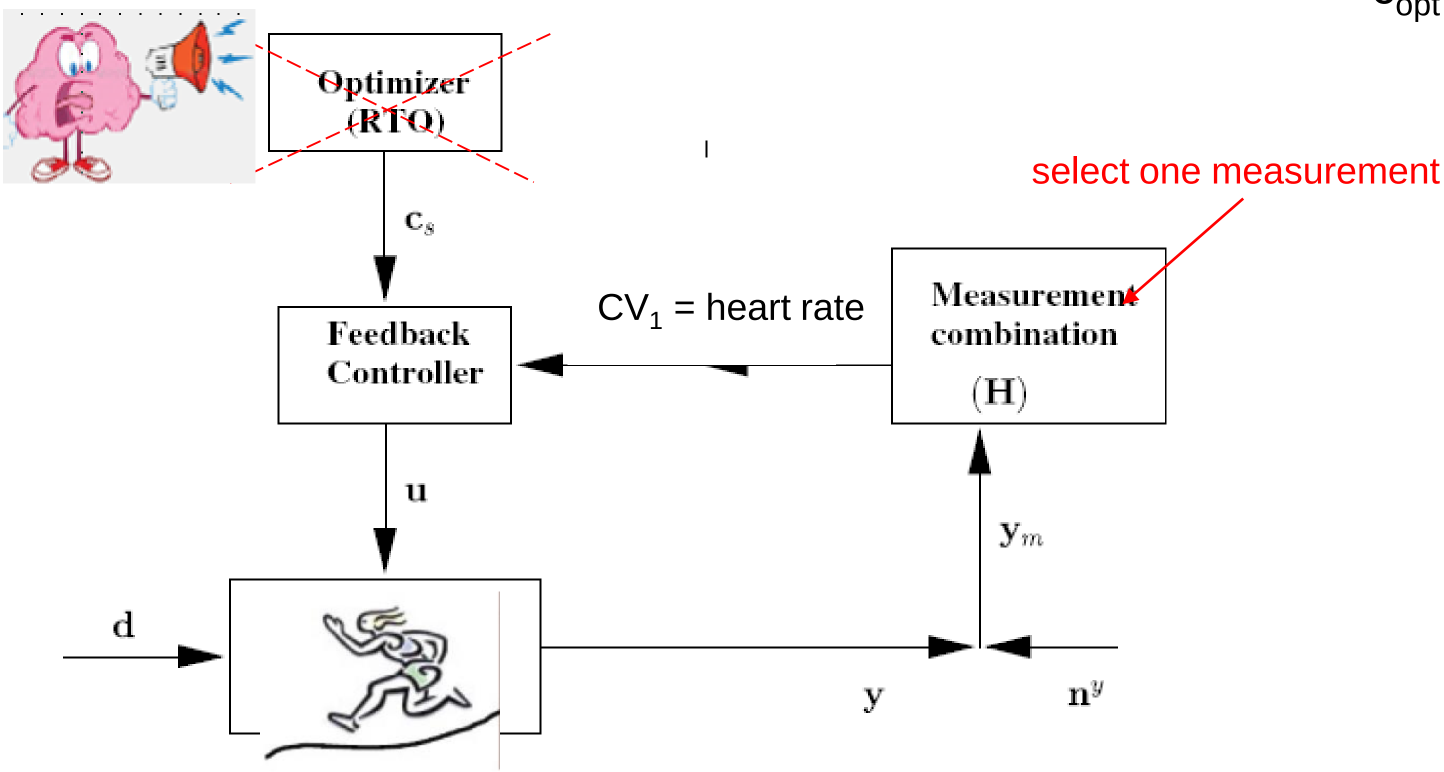
Self-optimizing control: Marathon (40 km)

- Any self-optimizing variable (to control at constant setpoint)?
  - c_1 = distance to leader of race
  - c_2 = speed
  - c_3 = heart rate
  - c_4 = level of lactate in muscles



Conclusion Marathon runner

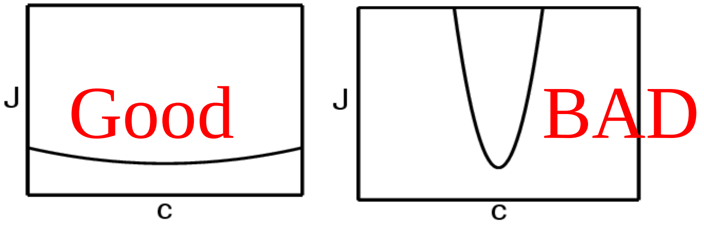




- CV = heart rate is good “self-optimizing” variable
- Simple and robust implementation
- Disturbances are indirectly handled by keeping a constant heart rate
- May have infrequent adjustment of setpoint (c_s)

In practice: What variable c=Hy should we control? (for self-optimizing control)

1. **The *optimal value* of c should be *insensitive* to disturbances**
   - Small HF = dc_{opt}/dd
2. **c should be easy to measure and control**
3. **The *value* of c should be *sensitive* to the inputs** (“**maximum gain rule**”)
   - Large G = HG^y = dc/du
   - Equivalent: Want flat optimum



(b) Flat optimum: Implementation easy

(c) Sharp optimum: Sensitive to implementation erros

Note: Must also find optimal setpoint for $c=CV_1$

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Example: Cake Baking

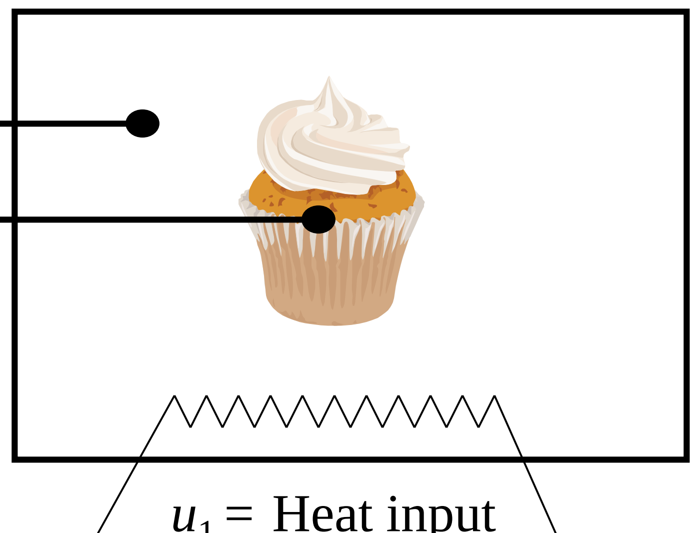
- Objective: Nice tasting cake with good texture

Measurements

$y_1 =$ oven temperature

$y_2 =$ cake temperature

$y_3 =$ cake color



Disturbances

$d_1 =$ oven specifications

$d_2 =$ oven door opening

$d_3 =$ ambient temperature

$d_4 =$ initial temperature

$u_1 =$ Heat input

$u_2 =$ Final time

Degrees of Freedom

Further examples self-optimizing control

- Central bank. J = welfare. u = interest rate. c=inflation rate (2.5%)
- Cake baking. J = nice taste, u = heat input. c = Temperature (200C)
- Business, J = profit. c = "Key performance indicator (KPI), e.g.
  - Response time to order
  - Energy consumption pr. kg or unit
  - Number of employees
  - Research spending

  Optimal values obtained by "benchmarking"
- Investment (portofolio management). J = profit. c = Fraction of investment in shares (50%)
- Biological systems:
  - "Self-optimizing" controlled variables c have been found by natural selection
  - Need to do "reverse engineering" :
    - Find the controlled variables used in nature
    - From this possibly identify what overall objective J the biological system has been attempting to optimize

Define optimal operation (J) and look for "magic" variable (c) which when kept constant gives acceptable loss (self-optimizing control)

Summary Step 3.
What should we control (CV_1)?

Selection of primary controlled variables $c = CV_1$

1. **Control active constraints!**
2. **Unconstrained variables: Control self-optimizing variables!**

- Old idea (Morari *et al.*, 1980):

"We want to find a function c of the process variables which when held constant, leads automatically to the optimal adjustments of the manipulated variables, and with it, the optimal operating conditions."

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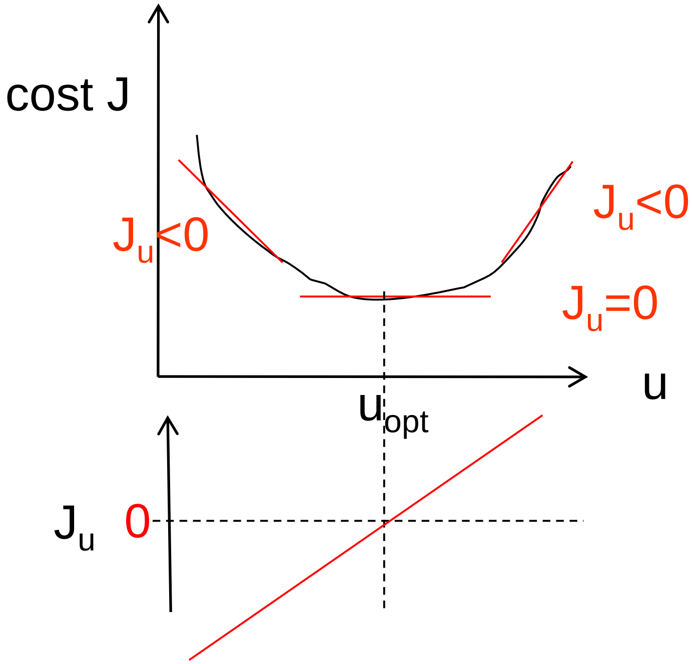
The ideal "self-optimizing" variable is the gradient, J_u

$$c = \partial J/\partial u = J_u$$

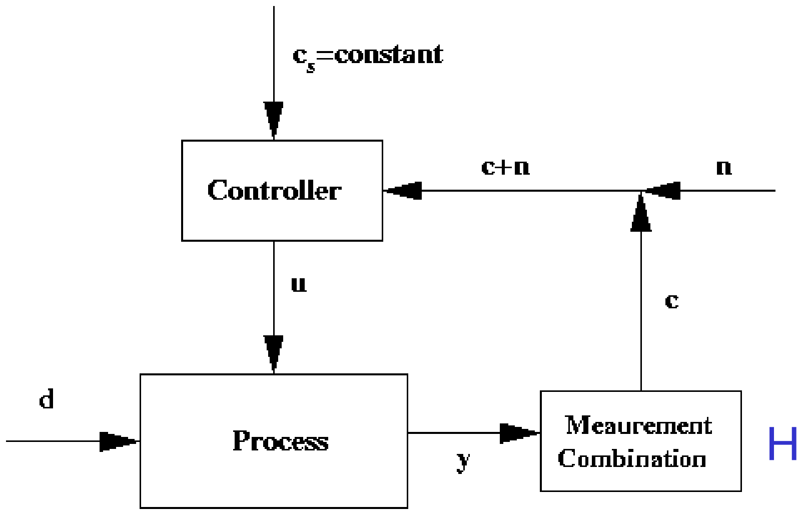
- Keep gradient at zero for all disturbances ($c = J_u = 0$)
- Problem: Usually no measurement of gradient



Ideal: c = J_u

In practise, use available measurements: c = H y.

Task: Determine H!



- Single measurements:

$$\mathbf{c} = \mathbf{H}\mathbf{y} \qquad \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

- Combinations of measurements:

$$\mathbf{c} = \mathbf{H}\mathbf{y} \qquad \mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \end{bmatrix}$$

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"Exact local method"

"=0" in nullspace method (no noise)

$$\min_H \|J_{uu}^{1/2}(HG^y)^{-1}H[FW_d \quad W_{n^y}]\|_2$$

"Minimize" in Maximum gain rule
(maximize S_1 G $J_{uu}^{-1/2}$, G=HG^y)

"Scaling" S_1

Analytical solution:

$$H = G^{yT}(YY^T)^{-1} \text{ where } Y = [FW_d \quad W_{n^y}]$$

- No measurement error: HF=0 (nullspace method)
- With measuremeng error: Minimize GF^c
- Maximum gain rule

Example. Nullspace Method for Marathon runner

u = power, d = slope [degrees]

y_1 = hr [beat/min], y_2 = v [m/s]

$F = dy_{opt}/dd = [0.25 \;\; -0.2]'$

$H = [h_1 \;\; h_2]]$

HF = 0 -> $h_1 f_1 + h_2 f_2 = 0.25 h_1 - 0.2 h_2 = 0$

Choose $h_1 = 1$ -> $h_2 = 0.25/0.2 = 1.25$

Conclusion: **c = hr + 1.25 v**

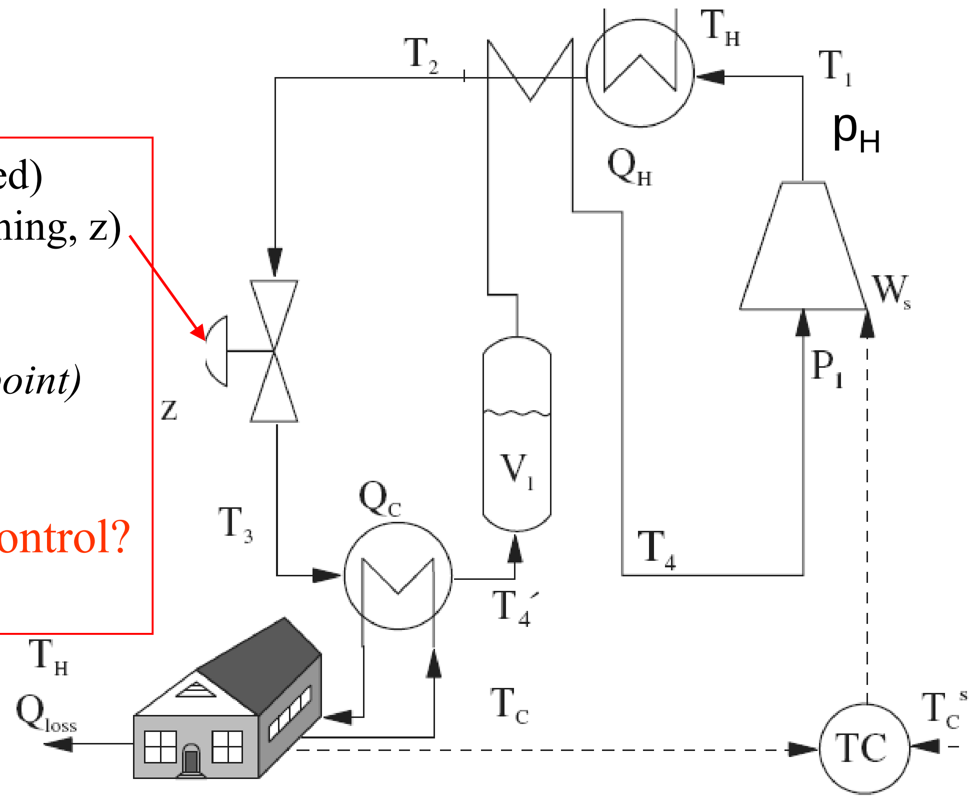
Control **c = constant** -> hr increases when v decreases (OK uphill!)

Example: CO2 refrigeration cycle

$J = W_s$ (work supplied)
DOF = u (valve opening, z)
Main disturbances:

$d_1 = T_H$
$d_2 = T_{Cs}$ *(setpoint)*
$d_3 = UA_{loss}$

What should we control?



CO_2 refrigeration cycle

Step 1. One (remaining) degree of freedom (u=z)

Step 2. Objective function. $J = W_s$ (compressor work)

Step 3. Optimize operation for disturbances ($d_1=T_C$, $d_2=T_H$, $d_3=UA$)

- Optimum always unconstrained

Step 4. Implementation of optimal operation

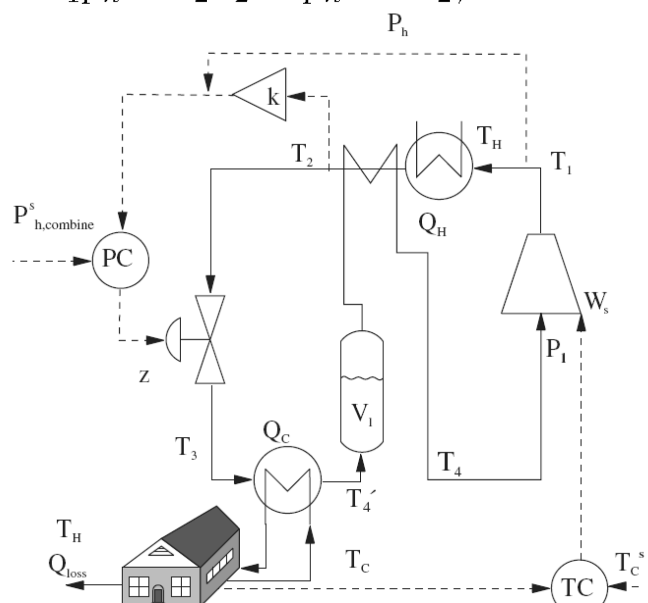
- No good single measurements (all give large losses):
  - p_h, T_h, z, …
- Nullspace method: Need to combine $n_u+n_d=1+3=4$ measurements to have zero disturbance loss
- Simpler: Try combining two measurements. Exact local method:
  - $c = h_1\, p_h + h_2\, T_h = p_h + k\, T_h$; $k = -8.53$ bar/K
- Nonlinear evaluation of loss: OK!

CO2 cycle: Maximum gain rule

Linear "maximum gain" analysis of controlled variables for CO_2 case

Variable (y)	Nom.	$G = \frac{\Delta y}{\Delta u}$	$\lvert\Delta y_{opt}(d_i)\rvert$ d_1 (T_H)	d_2 (T_C)	d_3 (UA_{loss})	$\lvert\Delta y_{opt}\rvert$	n	Span y $\lvert\Delta y_{opt}\rvert + n$	$\lvert G'\rvert = \frac{\lvert G\rvert}{\text{span} y}$
P_h/T_2' (bar °C^{-1})	0.32	−0.291	0.140	−0.047	0.093	0.174	0.0033	0.177	0.25
P_h (bar)	97.61	−78.85	48.3	−15.5	31.0	59.4	1.0	60.4	1.31
T_2' (°C)	35.5	36.7	16.27	−2.93	7.64	18.21	1	19.2	1.91
$T_2' - T_H$ (°C)	3.62	24	4.10	−1.92	5.00	6.75	1.5	8.25	2.91
z	0.34	1	0.15	−0.04	0.18	0.24	0.05	0.29	3.45
V_1 (m^3)	0.07	0.03	−0.02	0.005	−0.03	0.006	0.001	0.007	4.77
T_2 (°C)	25.5	60.14	8.37	0.90	3.18	9.00	1	10.0	6.02
$P_{h,combine}$ (bar)	97.61	−592.0	−23.1	−23.1	3.91	33.0	9.53	42.5	13.9
m_{gco} (kg)	4.83	−11.18	0.151	−0.136	0.119	0.235	0.44	0.675	16.55

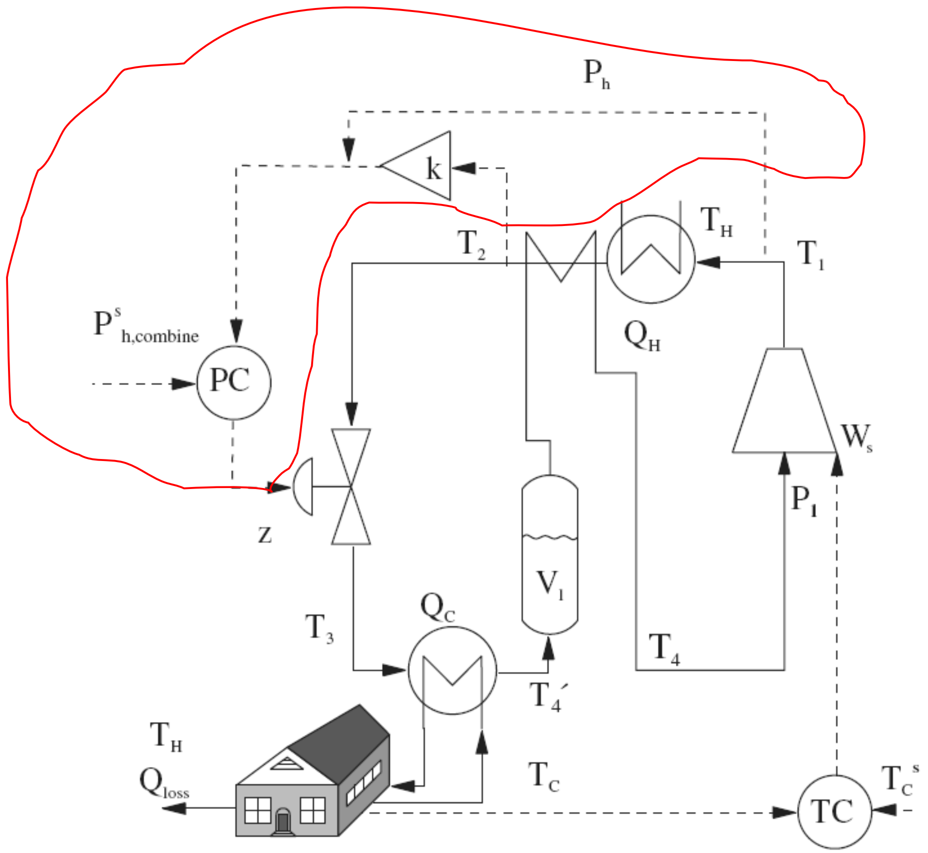
Nullspace method: $c = p_{h,\text{combine}} = h_1 p_h + h_2 T_2 = p_h + kT_2; k = -8.53$ bar/K



J.B. Jensen, S. Skogestad / Computers and Chemical Engineering 31 (2007) 1590–1601

CV=Measurement combination

Refrigeration cycle: Proposed control structure



CV1= Room temperature

CV2= "temperature-corrected high CO_2 pressure"

Oversikt

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5. Hvordan designe et hierarkisk system på en systematisk måte?
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    2. Selvoptimaliserende variable
7. Eksempler: Biologi, prosessregulering, økonomi, maraton

- Konklusjon: Vær systematisk og tenk på helheten når du skal bygge opp et styringssystem
- Enkle løsninger vinner alltid i det lange løp

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References

- The following paper summarizes the design procedure:
  – S. Skogestad, ``Control structure design for complete chemical plants'', *Computers and Chemical Engineering*, **28** (1-2), 219-234 (2004).
- The following paper updates the procedure:
  – S. Skogestad, ``Economic plantwide control'', Book chapter in V. Kariwala and V.P. Rangaiah (Eds), *Plant-Wide Control: Recent Developments and Applications",* Wiley (2012).
- More:
  – S. Skogestad "Plantwide control: the search for the self-optimizing control structure'", *J. Proc. Control*, 10, 487-507 (2000).
  – S. Skogestad, ``Near-optimal operation by self-optimizing control: From process control to marathon running and business systems'', Computers and Chemical Engineering, 29 (1), 127-137 (2004).
- Mathematical details:
  – V. Alstad, S. Skogestad and E.S. Hori, ``Optimal measurement combinations as controlled variables'', Journal of Process Control, 19, 138-148 (2009)
- More information on my home page (Skogestad):

http://www.nt.ntnu.no/users/skoge/plantwide