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Technical University of Applied Sciences

Systems Engineering - SySe
Chapter 3 – CLDs and DSM

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Content

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Causal Loop Diagrmas and Design Structure Matrix (DSM)

1. What is a causal loop diagram and what is it used for?
2. How to define a causal loop diagram and visualize feedback loops.
3. What is a DSM and what is it used for?
4. How to define a DSM and identify inter relationships.

What is system dynamics?

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- Change of perspective: from structural modelling to modelling of dynamic processes
- Methodology for the analysis of dynamics in complex systems
- Based on systems theory, control theory and cybernetics
- Goal: Understand and control the combination of structure and dynamic changes of systems
- Focus: Feedbacks, Delays, Nonlinearity

Motivation for system dynamics:

- Cause-and-effect relationships are often delayed or indirect
- Intuitive decisions (short term) often lead to undesirable results (longterm)
- System Dynamics makes these challenges/problems visible and understandable.

System Dynamics

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- System dynamics focuses on
  - Feedback Loops (Rückkopplungen) determine the behaviour
  - Stocks (Bestände) accumulate flows
  - Simulation show system behaviour over time
- Systems thinking → understanding of sys elements and relationships
- System Dynamics → simulation & mathematics & scenario analysis

Causal Loop Diagrams (CLD)

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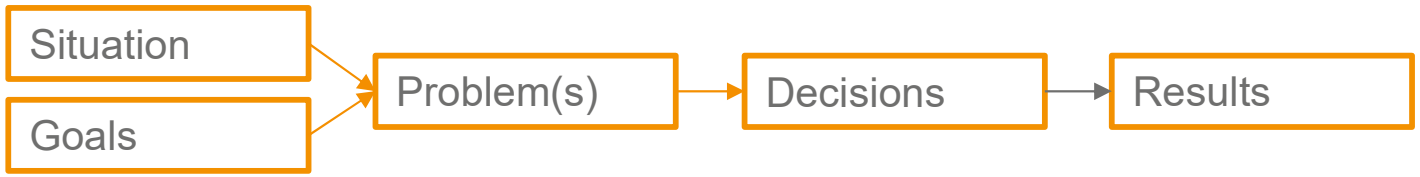
- Causal Loop Diagrams form the bridge between system thinking and system dynamics.
- It shows how variables influence each other – qualitatively, without numbers.

  - **Reinforcing** (verstärkende) processes: Positive feedback that promotes the growth of a variable (~ growth, escalation)
  - **Balancing** (ausgleichende) processes: Negative feedback that stabilizes the system (~ stabilization, control)
  - **Determine Feedback Loops**
  - Feedback loops beeing reinforcing or balancing are shown in **Causal Loop Diagrams**

Basic Idea of Feedback Loops

- Using the example of languages or linear systems:
  - Language German: we construct sentences and use them to make statements: x → y
  - These are basically one-way relationships: x → y and y → z



Linear thinking: We find solutions to problems

(1) Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

→ Basisliteratur: Sterman, J.B. (2006): Business Dynamics; Senge, P.M. (2006): Die fünfte Disziplin

System Dynamics: Basic Idea

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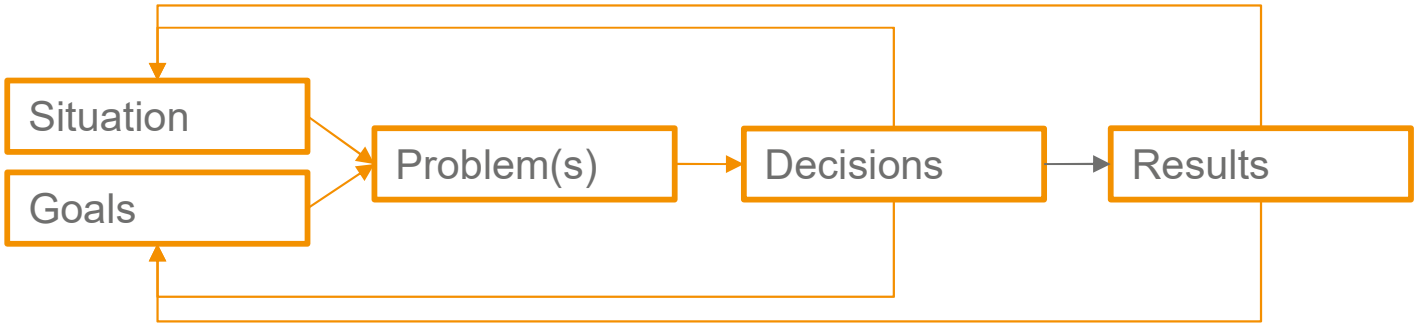
- But what happens to loops?



Iterative thinking: We take care of problems that arise as a result of solutions.

-- Causal Loop Diagrams

(1) Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

→ Basisliteratur: Sterman, J.B. (2006): Business Dynamics; Senge, P.M. (2006): Die fünfte Disziplin

Creating CLDs

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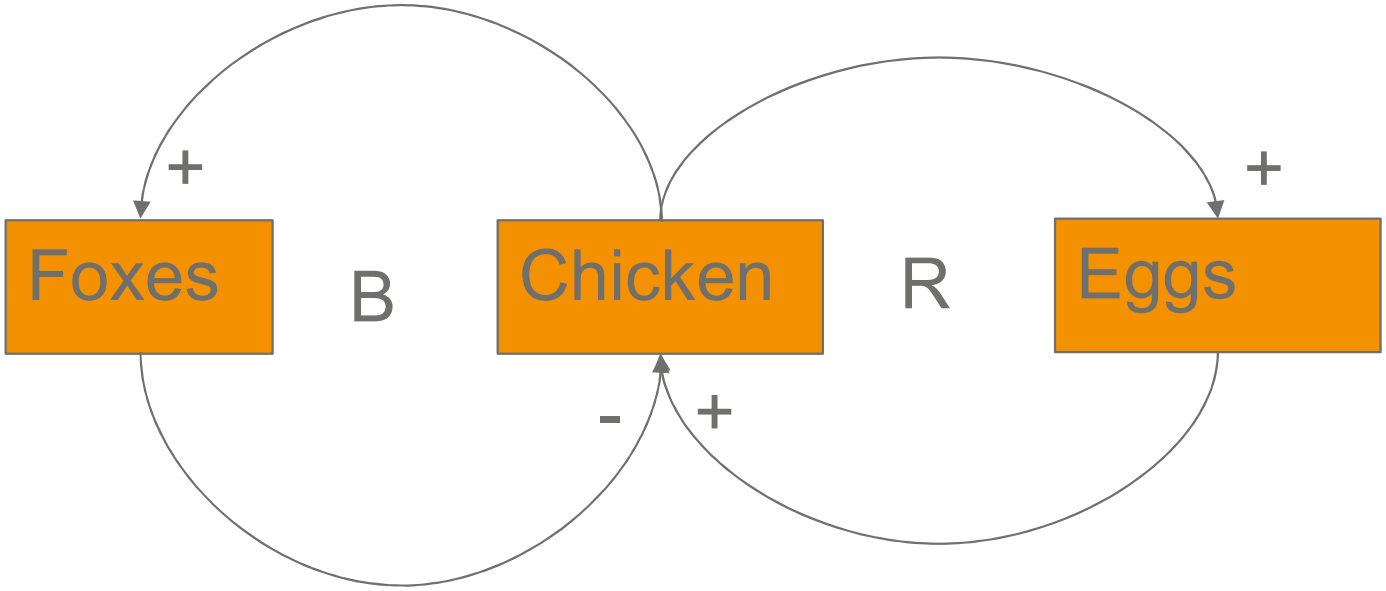
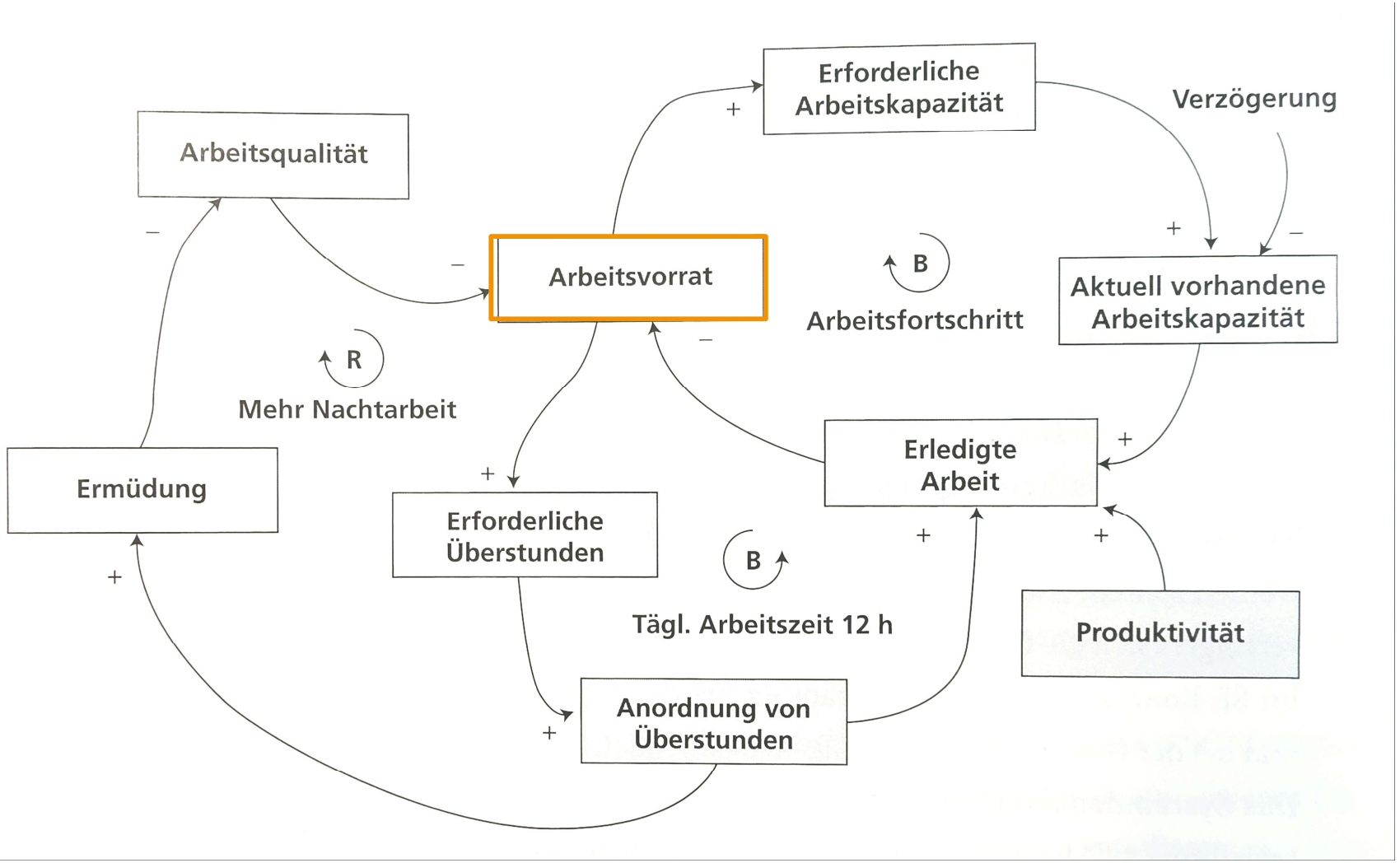
1. Identify elements
2. Establish Relationships of elements
3. Identify loops and add labels (+ , -)
   1. R-Loop (+): Reinforcing Loop: the more eggs, the more chickens
   2. B-Loop (-) : Balancing Loop: Chickens are eaten by the fox, the more chickens, the more the fox can eat. But, the more eaten, the less remain.
4. Check consistency



(1) Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

Sterman, J.B. (2006): Business Dynamics;

A more complex example



Start from Arbeitsvorrat to Arbeitskapazität to vorhandene Arbeitskapazität and so on.

(1) Haberfellner et al., Systems Engineering Grundlagen und Anwendung, orell füssli 2018 (14. Auflage)

Task

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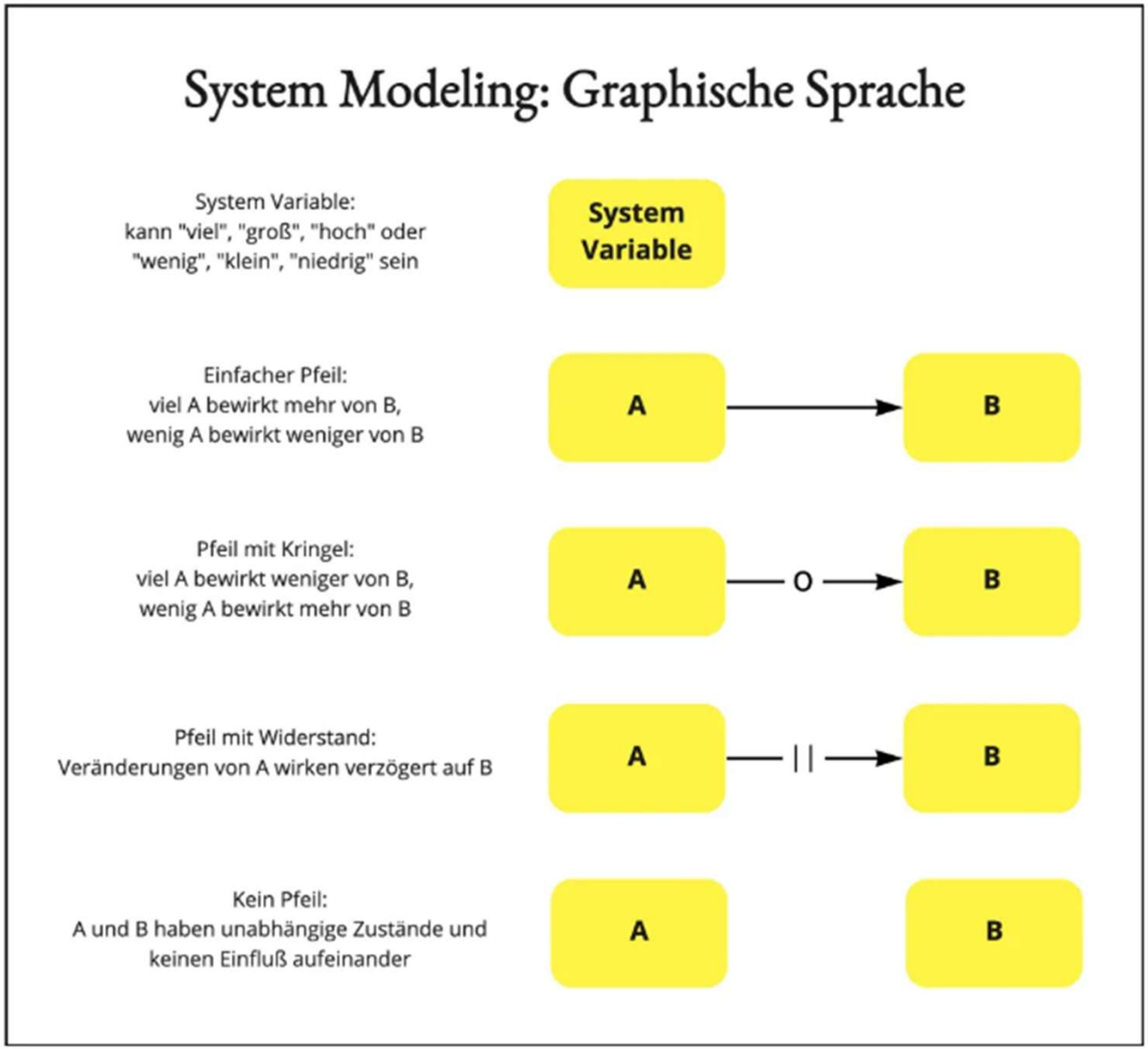
- Create a system dynamics model similar to previous slides on the song:

Fuchs, du hast die Gans gestohlen

- 5 minutes.

Other forms of presentation



Graph: from (1)

- According to https://agilecoach.de/wissen/systems-thinking-mit-causal-loop-diagrammen/ (1) and Senge, P.M. (2006): Die fünfte Disziplin

From CFD to simulation

- Now that we have used a Causal Loop Diagram to understand which variables influence each other, we translate this qualitative model into a stock flow diagram (SFD).

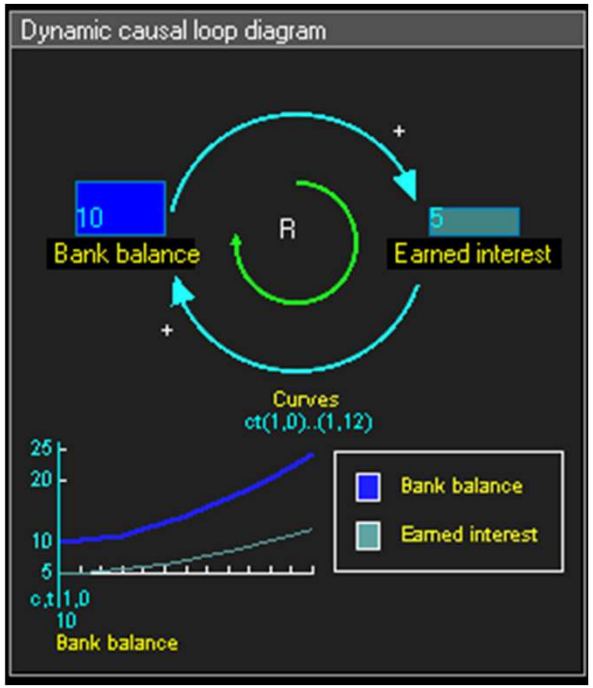
- In the SFD, we distinguish between:
  - **Stocks (Bestände):** States that change over time (e.g. population, capital, temperature)

  - **Flows (Flüsse):** Rates that change inventories (e.g., births, investments, heat supply)

- This makes the model mathematical and simulable

- The simulation then allows:
  - analyze behavior over time,

  - Testing scenarios ("What-if?").



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Summary

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- CLDs are the qualitative introduction to the modelling of dynamical systems and promote system understanding.
- Today, they are actively used in system development, decision support and risk analysis.
- Feedback loops as key to understand the behaviour of the system.
- Fields of application:
  - Economy, ecology, education, health
  - Benefits: System understanding, recognizing side effects, testing strategies
- Further Reading:
  - The Basic Principles of Systems Thinking and System Dynamics (Dangerfield, 2021) [PDF]
  - Leveraging Large Language Models for Automated Causal Loop Diagram Generation: Enhancing System Dynamics Modeling (Liu & Keith, 2025) [Online]
  - Systems Mapping: How to build and use causal models of systems (Barbrook-Johnson & Penn, 2022) (Online)

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Design Structure Matrix

Design Structure Matrix (DSM)

- A Design Structure Matrix (DSM) is an analysis tool used in system development, product design, and project management.
- It presents complex systems and its sub-elements as a matrix in which the relationships between the individual elements of a system are presented:
  - The system is broken down into its individual parts: system, subsystems, elements.
  - The components interact with each other (interfaces), i.e., in form of in- and output
  - DSM shows the interactions and dependencies between the components … is a visual aid for representing dependencies and interactions between elements.
    - → Highlights (critical) interdependencies and potential delays.
    - → Enables reordering to minimize dependencies.
- DSM allows complex structures to be broken down, which creates a better understanding of the system architecture.
- Enables modularity: DSMs support the identification of modular structures, which can reduce development time and maintenance costs.
- Highlights key architectural patterns, i.e., modules, loops

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DSM Construction

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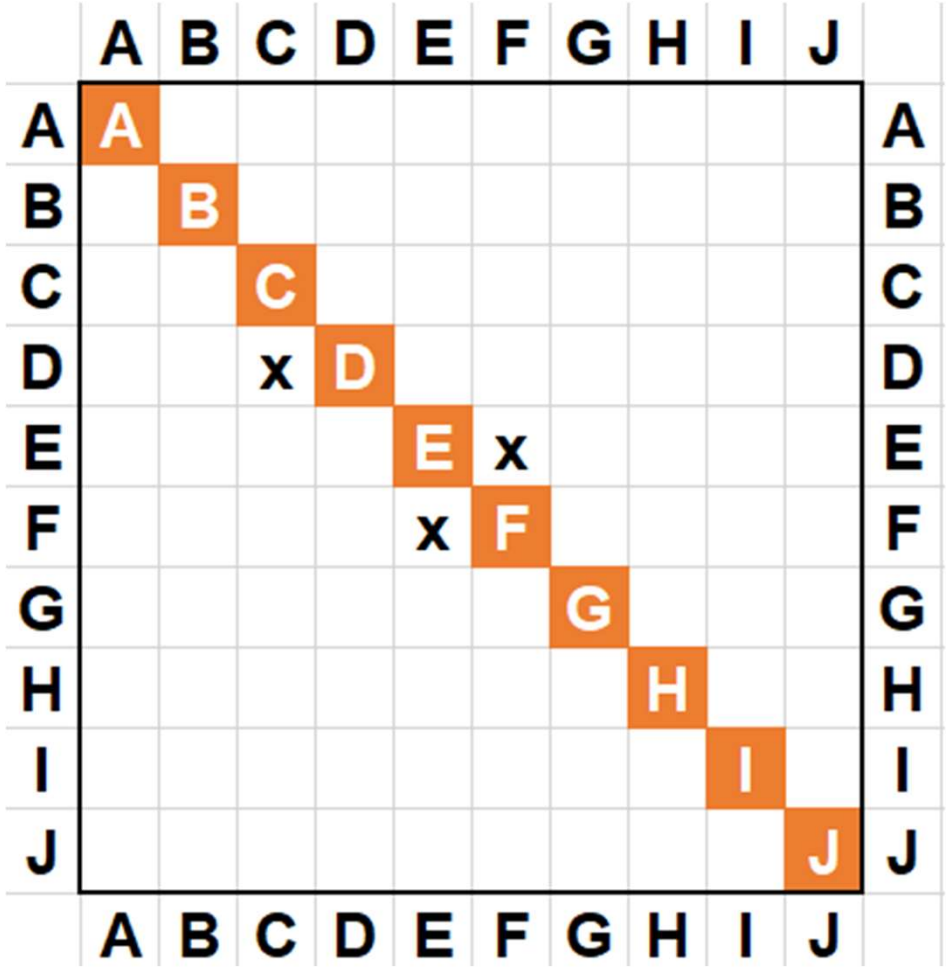

- Square matrix (always square)
- The system components are listed in the rows as well as in the columns (here A, B, C, ...).
- They are listed in the order they occur (for this lecture).
- The interfaces/interactions/relationships of the system component are drawn in the matrix (off-diagonal) (circles, crosses, or weighted, etc.)
- The diagonal, where the (X,Y) columns are the same, is used as a boundary between forward and iterative dependencies.

DSM interpretation

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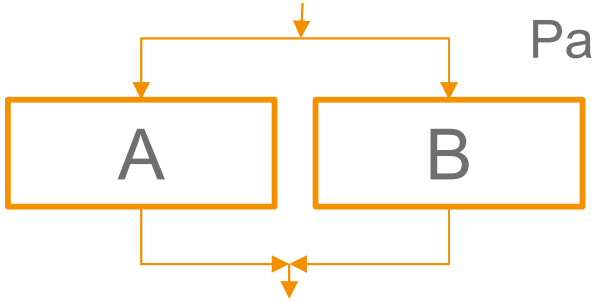
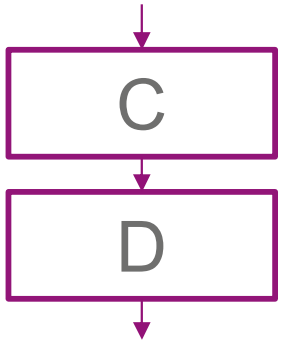
- Binary DSMs represent only the existence of a relation (crosses, dots, etc.)
- Numerical DSMs represent a numerical value (“weight”) to represent the strength of a relation.
- Relation: If there exists a connection between node i and j, the value of element ij (row i, column j) is marked, otherwise ij is zero (or left empty).
- Elements/Tasks are listed in the order they occur, i.e. for processes.
  - Read down the column to see where the element provides sth. to other tasks or components, i.e., output
  - Read across a row to see where the element receives sth., from other tasks or components, i.e., input

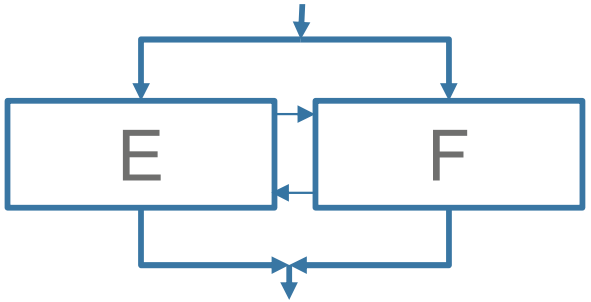
DSM relationships



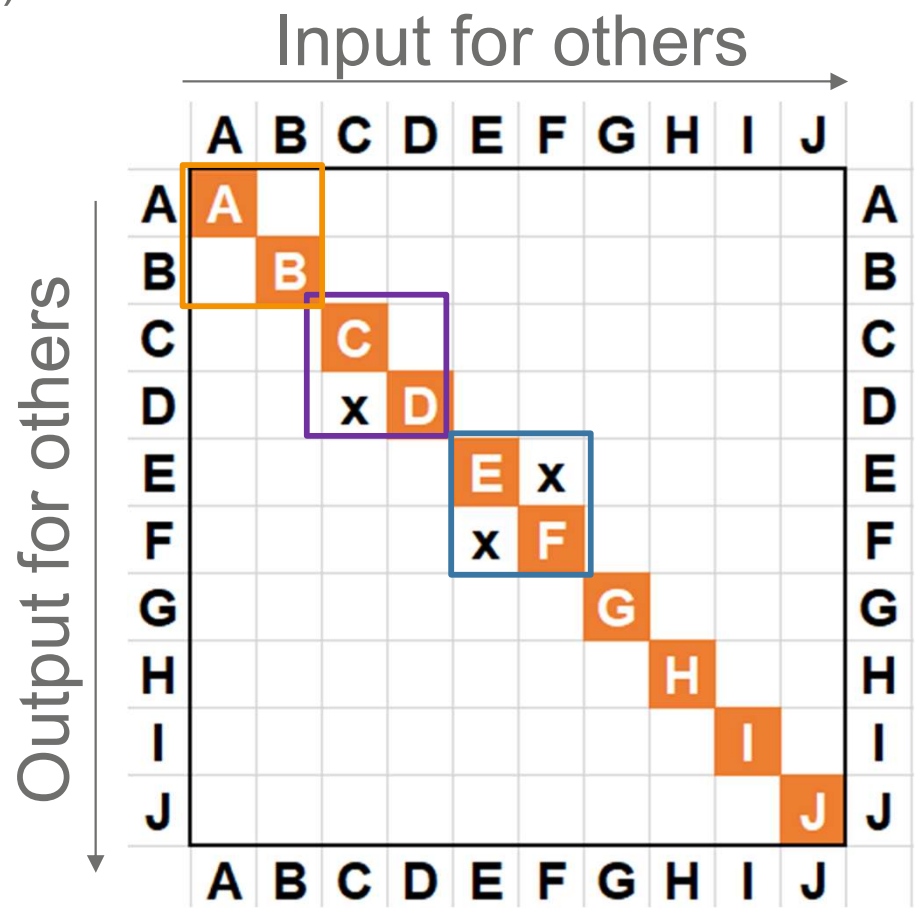
Parallel (independent)



Sequential (dependent)



Coupled (interdependent)



Diagonal elements could be blank, too.

DSM interpretation

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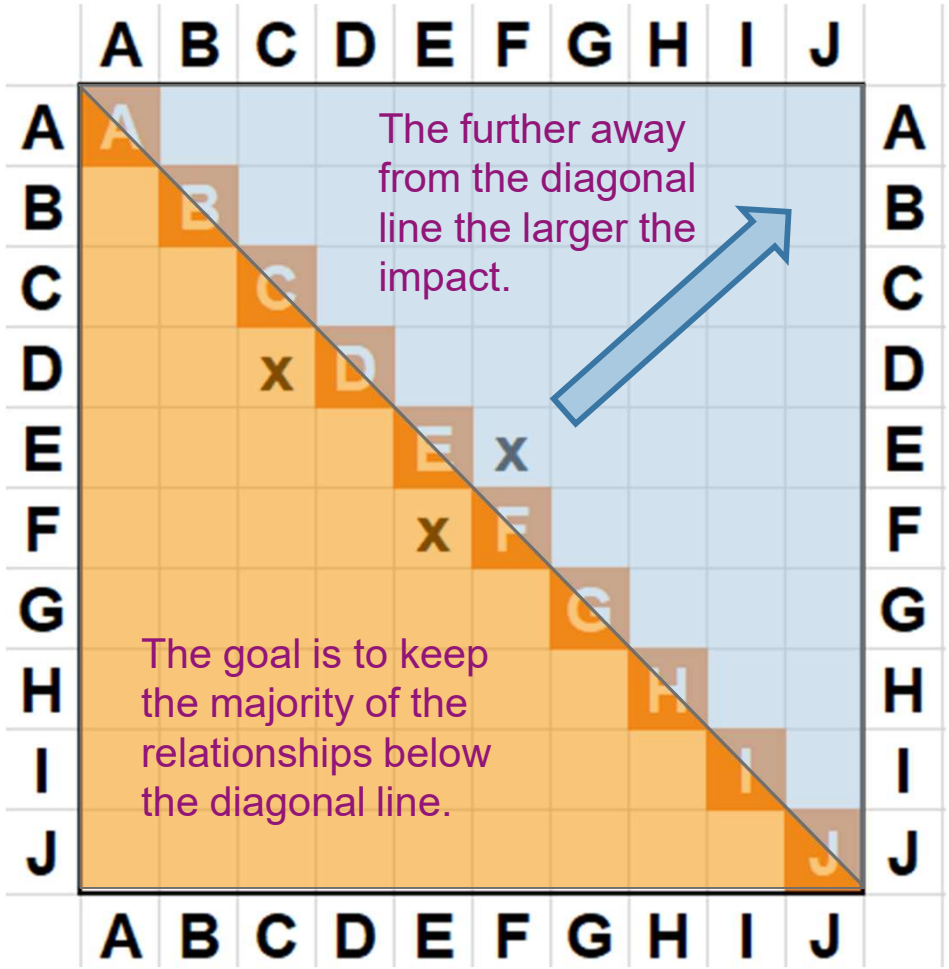
- **Parallel**: tasks / components that can be worked on independently → they can be worked on at the same time and do not rely on input from each other
- **Sequential**: tasks / components that require input from previous tasks/components to complete.

- **Coupled**: tasks / components that require a considerable exchange of information to be completed. These tasks / components might need the rework of previous tasks / components once they are completed. Synonym: iterative tasks.



DSMs are never reflexive, i.e., a relation from an element to the same element is not permissible.

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DSM Applications

Formal or Structural DSM: Used to map the formal/physical interactions among the various components of the system.

Process/Task DSM: Used to identify sequencing and grouping of system tasks or processes.

Organization DSM: Used to map the interactions between people within an organization.

DSM – Step by Step

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1. Decompose the system
2. Document the interactions between components and form a matrix.
3. Analyze the matrix and rearrange the components to optimize information flow.

Source: Browning et al., Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions; IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT, VOL. 48, NO. 3, AUGUST 2001

Decompose the system

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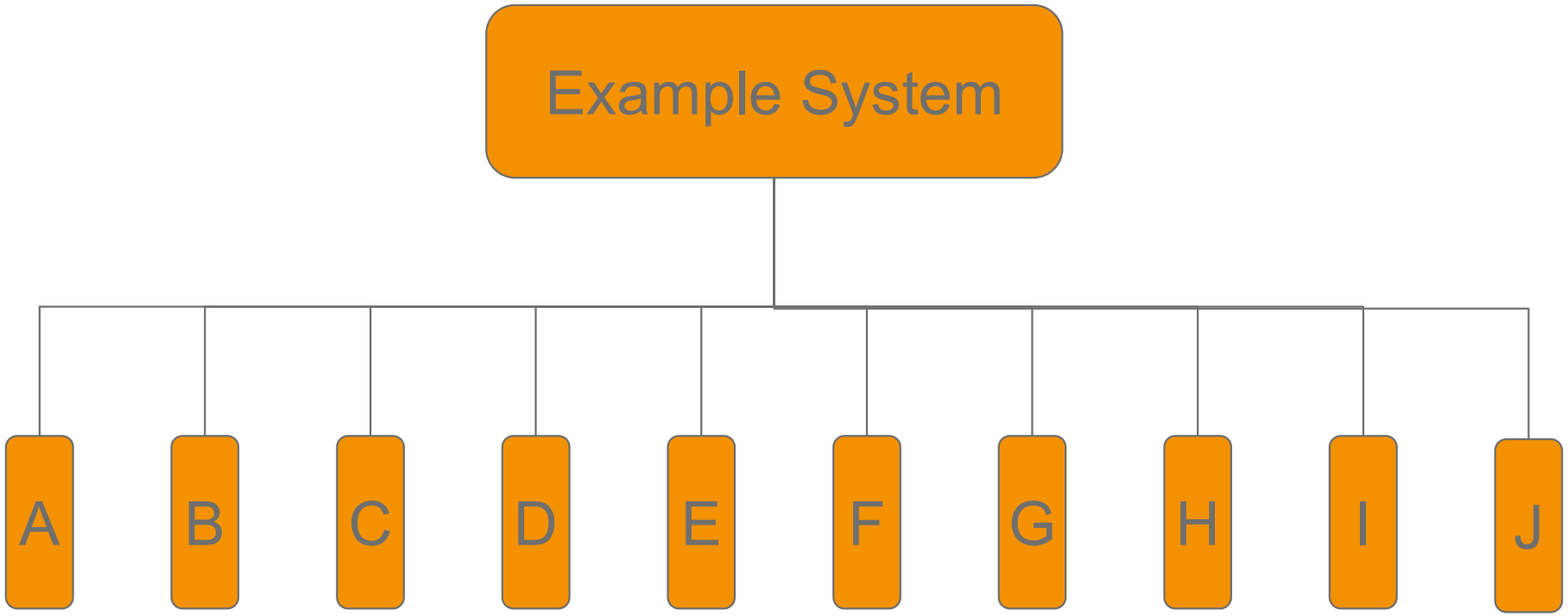
- An imaginary example of a system with A - J sub elements.



Create the DSM

	A	B	C	D	E	F	G	H	I	J
A	A				X				X	X
B	X	B	X			X		X	X	
C			C				X	X		
D			X	D	X					X
E					E					
F	X		X	X		F	X			
G				X			G			X
H					X			H		X
I	X							X	I	
J					X			X		J

Document the interactions between components in a square matrix

- Rows contain the information that components require
- Columns contain the information that components produce

Interpretation examples:
- C produces relevant information for B, D, F
- C requires relevant information from G and H

Other examples?

Analyze the DSM

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- Analyze the matrix and rearrange the components to optimize information flow.
- Sequencing algorithm:

  - Find any empty rows and move them up
    - Empty row is a component that does not receive any input from another component → ideally the first component to be worked on

  - Find any empty columns and move them to the end
    - Empty column is a component that does not produce any output required by other component → ideally the last component to be worked on

Analyze the DSM

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	A	B	C	D	E	F	G	H	I	J
A	A				X				X	X
B	X	B	X			X		X	X	
C			C				X	X		
D			X	D	X					X
E					E					
F	X		X	X		F	X			
G				X			G			X
H					X			H		X
I	X							X	I	
J					X			X		J

Empty rows:

- E
- Move Up

Empty columns:

- B
- Move to the right

Analyze the DSM

	E	A	C	D	F	G	H	I	J	B
E	E									
A	X	A						X	X	
C			C			X	X			
D	X		X	D					X	
F		X	X	X	F	X				
G				X		G			X	
H	X						H		X	
I		X					X	I		
J	X						X		J	
B		X	X		X		X	X		B

Empty rows:

- E
- Move Up

Empty columns:

- B
- Move to the right

Always rearrange to keep diagonal.

Analyze the DSM

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- Now the columns and rows should be shifted in such a way that the crosses/interactions are as close as possible to the diagonal and below the diagonal.

- When we achieve a situation where all the marks are underneath the diagonal, all components are sequenced
  - sequenced interaction only needs input from the previous task
  - no feedback loops.

- Feedback Loop: Feedback loops are processes in which information flows back between different components, which can lead to delays or redundant work steps.

- Steps:
  - Look for feedback loops --- crosses in columns to tasks/components listed earlier.
  - If we find them, we push them up as far as possible. Plan this step earlier.

Analyze the DSM

	E	A	C	D	F	G	H	I	J	B
E	E									
A	X	A						X	X	
C			C			X	X			
D	X		X	D					X	
F		X	X	X	F	X				
G				X		G			X	
H	X						H		X	
I		X					X	I		
J	X						X		J	
B		X	X		X		X	X		B

- G produces output for F and C → F and C happen "before", but need input from something later (G)

→ G moves up.

	E	A	G	C	D	F	H	I	J	B
E	E									
A	X	A						X	X	
G			G		X				X	
C			X	C			X			
D	X			X	D				X	
F		X	X	X	X	F				
H	X						H		X	
I		X					X	I		
J	X						X		J	
B		X		X		X	X	X		B

Analyze the DSM

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	E	A	G	C	D	F	H	I	J	B
E	E									
A	X	A						X	X	
G			G		X				X	
C			X	C			X			
D	X			X	D				X	
F		X	X	X	X	F				
H	X						H		X	
I		X					X	I		
J	X						X		J	
B		X		X		X	X	X		B

- J produces output for H, D, G, A

→ J moves up.

	E	J	A	G	C	D	F	H	I	B
E	E									
J	X	J						X		
A	X	X	A						X	
G		X		G		X				
C				X	C			X		
D	X	X			X	D				
F			X	X	X	X	F			
H	X	X						H		
I			X					X	I	
B			X		X		X	X	X	B

Analyze the DSM

	E	J	A	G	C	D	F	H	I	B
E	E									
J	X	J						X		
A	X	X	A						X	
G		X		G		X				
C				X	C			X		
D	X	X			X	D				
F			X	X	X	X	F			
H	X	X						H		
I			X					X	I	
B			X		X		X	X	X	B

- H produces output for C and J
- → H moves up.

	E	H	J	A	G	C	D	F	I	B
E	E									
H	X	H	X							
J	X	X	J							
A	X		X	A					X	
G			X		G		X			
C		X			X	C				
D	X		X			X	D			
F				X	X	X	X	F		
I		X		X					I	
B		X		X		X		X	X	B

Analyze the DSM

	E	H	J	A	G	C	D	F	I	B
E	E									
H	X	H	X							
J	X	X	J							
A	X		X	A					X	
G			X		G		X			
C		X			X	C				
D	X		X			X	D			
F				X	X	X	X	F		
I		X		X					I	
B		X		X		X		X	X	B

- I produces output for A
- → I moves up.

	E	H	J	I	A	G	C	D	F	B
E	E									
H	X	H	X							
J	X	X	J							
I		X		I	X					
A	X		X	X	A					
G			X			G		X		
C		X				X	C			
D	X		X				X	D		
F					X	X	X	X	F	
B		X		X	X		X		X	B

Analyze the DSM

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	E	H	J	I	A	G	C	D	F	B
E	E									
H	X	H	X							
J	X	X	J							
I		X		I	X					
A	X		X	X	A					
G			X			G		X		
C		X				X	C			
D	X		X				X	D		
F					X	X	X	X	F	
B		X		X	X		X		X	B

- D produces output for G
- → D moves up.

	E	H	J	I	A	D	G	C	F	B
E	E									
H	X	H	X							
J	X	X	J							
I		X		I	X					
A	X		X	X	A					
D	X		X			D		X		
G			X			X	G			
C		X					X	C		
F					X	X	X	X	F	
B		X		X	X			X	X	B

Analyze the DSM

	E	H	J	I	A	D	G	C	F	B
E	E									
H	X	H	X							
J	X	X	J							
I		X		I	X					
A	X		X	X	A					
D	X		X			D		X		
G			X			X	G			
C		X					X	C		
F					X	X	X	X	F	
B		X		X	X			X	X	B

- C produces output for D
- → C moves up.

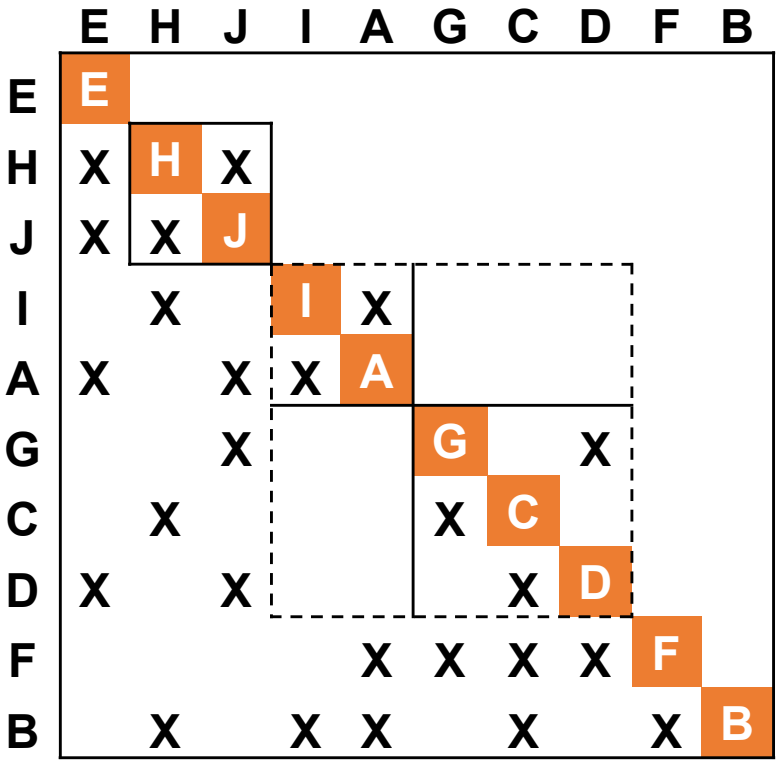
	E	H	J	I	A	C	D	G	F	B
E	E									
H	X	H	X							
J	X	X	J							
I		X		I	X					
A	X		X	X	A					
C		X				C		X		
D	X		X			X	D			
G			X				X	G		
F					X	X	X	X	F	
B		X		X	X	X			X	B

Analyze the DSM

	E	H	J	I	A	C	D	G	F	B
E	E									
H	X	H	X							
J	X	X	J							
I		X		I	X					
A	X		X	X	A					
C		X				C		X		
D	X		X			X	D			
G			X				X	G		
F					X	X	X	X	F	
B		X		X	X	X			X	B

- G produces output for C
- → G moves up.
- Obviously, we can't terminate … there is a causal relationship:
- G needs input from D; D needs input from C and G produces Input for C.
- → these tasks need to be executed together.

DSM interpretation



- Solid boxes: task that needs to be performed together
- Dashed Box: parallel execution of grouped tasks.
- Clustering algorithms with varying foci:
  - Minimize the dependencies (coupling) between the different clusters.
  - Minimize the size of the largest cluster → build sub-cluster
  - The important dependencies and relationships should be as close to the diagonal as possible to allow for easy interpretation and organization of the matrix
  - Negative relationships (e.g. conflicts or unwanted interactions) should be avoided

Tools

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- Commercial tools:
  - https://dsmweb.org/comercial-tools/

- Training tool:
  - https://dsmweb.org/dsmmatrix/

Summary

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- System Dynamics: Analysis of dynamic interactions between elements
  - R-Loop: Reinforcing Loop
  - B-Loop: Balancing Loop
  - Causal loop diagrams

- Design Structure Matrix helps to model interdependency of system components & processes.
  - Used for systems, processes, and institutions
  - Requires typically 3 steps:
    - Decomposition
    - Re-arrange
    - Cluster

Time for questions …

Image from: https://pixabay.com

References

- Youtube Videos:
  - https://www.youtube.com/watch?v=etEZVakaHn4
  - https://www.youtube.com/watch?v=4DCy1mjgOLc
- Online: https://dsmweb.org/dsmmatrix/
- Book: Eppinger et al., **Design Structure Matrix Methods and Applications (Engineering Systems), MIT Press 2016;**