1 The Topic
2 Tasks
3 Modeling

Goal:
• Modeling methods and systems in AI
• Conceptual modeling
• Modeling techniques and behavior prediction
• for model-based systems
• Script: Ch. 10.3
Requirements on Modeling

- conceptual modeling
- executable behavior models
- qualitative models
- (automatic) model composition
- behavior prediction
- multiple modeling

Conceptual Model

Model Composer

Behavior Model

Inconsistency

inconsistent

Solution

consistent

Criterion

mathematical

Predictor
Knowledge-based Systems for Industrial Applications

1 The Topic
2 Tasks
3 Modeling
  3.1 Component-oriented Modeling

Goal:
- Ontology
- Relational Behavior Models
- Script: Chap. 12.3.2/3 (D)
Motivation – Requirements on Modeling
What Should the Model Do? - Prediction

Blocked-closed

Model-Based Systems & Qualitative Reasoning
Group of the Technical University of Munich
(Partial) Result of Model-based FMEA

Blocked-closed

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Model-Based Systems & Qualitative Reasoning
Group of the Technical University of Munich
What Should the Model Do? – Diagnostic Reasoning

Models

- explicit conceptual and structural model
- Behavior models
- Compositional („context-free“)
- (possibly) qualitative models
What Should the Model Do? – Detecting Inconsistencies

- Inconsistent partial models: „conflict“
- combined evidence from conflicts
- Pump OR pressure sensor OR container defect
- OR mechanical drive AND flow sensor
- logical theory: consistency-based diagnosis
Representation of Structure
Conceptual Modeling - Fundamentals

- Perceivable objects and relations
  - e.g. valves, pipes, connections,
- Behavioral constituents (“laws”)
  - e.g. “valve law”, flow through a pipe, effect of a pump, ...
- Associations between perceivable and behavioral constituents
  - e.g. a valve implies the “valve law”, ...
  - if it is working correctly

Modeling languages (“ontologies”): primitives for describing constituents
Compositional, Component-oriented Model
Components

- Physical objects with a characteristic behavior

- **Components** have
  - terminals (Ports)

- **Terminals**
  - are channels to other components

- **Connections** (Conduits)
  - are special components
  - share terminals with components

![Diagram of Components](attachment:image.png)
Exercise Stupid System - Structure

- Components?
- Terminals?
Knowledge-based Systems for Industrial Applications

Representation of Behavior
Models – Capture Behavior

- Inferences about quantities that characterize the behavior
**Variables**

- **Physical objects with a characteristic behavior**

- **Components** have
  - terminals (Ports)
  - parameters (constant)
  - state variables (dynamic)

- **Terminals**
  - are channels to other components
  - have “interface” variables

- **Connections** (Conduits)
  - are special components
  - share terminals with components

---

![Diagram](image-url)
Behavior Models - E.g. Ohm‘s Law

- Ohm‘s Law
  \[ R \times i = \Delta v \]

- What does it mean?
  - Constrains the possible tuples of values
  - For instance \( R=1\Omega \)
    \[ 1\Omega \times i = \Delta v \]
  - For instance,
    - (5, 1, 5) is possible
    - (5, 1, 2) is not
  - A relation \( R_{\Omega,1} \)
Ohm’s Law - Essential Distinctions

- Ohm’s Law
  \[ R \times i = \Delta v \]

- Models that make the
  - essential and
  - possible distinctions only

- What is essential?
- Depends on the task

- For consistency-based problem solvers:
  - Distinctions are essential, if they can contribute to the detection of inconsistencies
Exercise Stupid System – Behavior

- Variables?
- Behavior?
Models – Variable Domains

- What kind of predictions?
- What kind of observations?
- Numerical?
- Qualitative?
- Symbolic?
Qualitative Models
Qualitative Modeling - Goals

• What can be observed?

- hydraulic unit
- front left wheel
- rear right wheel
- brake pedal

under-braked

over-braked

harder

brake pedal
Qualitative Modeling - Goals

- What needs to be distinguished?
Qualitative Modeling - Goals

- Inferences about system behavior with partial knowledge/information:
  - Only rough understanding
  - Inaccurate, missing data
  - Only qualitative statements required
  - Handle classes of systems and conditions

- Expected utility:
  - Finite representation
  - Efficiency
  - Intuitive (re)presentation
Qualitative Modeling - Tasks

• Models, that represent only
  - essential and
  - possible distinctions
• Calculi for qualitative domains and interdependencies
• Formal relations between models of different granularity
Ohm’s Law - Essential Distinctions

- Ohm’s Law
  \[ R \times i = \Delta v \]

- Models that make the
  - essential and
  - possible
distinctions only

- What is essential?
- Depends on the task

- For consistency-based problem solvers:
  - Distinctions are essential,
    if they can contribute to the detection of inconsistencies
Ohm’s Law - Essential Diagnostic Distinctions

- Ohm’s Law
  \[ R \times i = \Delta v \]

- Open resistor:
  \[ i = 0 \]

For discrimination of the two behavior modes:
- which distinctions are essential?
- Distinguish 0 from positive and negative numbers
Ohm’s Law - Qualitatively

- Ohm’s Law
  \[ R \cdot i = \Delta v \]

- Open resistor:
  \[ i = 0 \]

- Qualitative values:
  
  - "-" := \((-\infty, 0)\)
  
  - "0" := [0, 0]
  
  - "+" := (0, \(\infty\))

- \(R_{\Omega,1} = \{(\text{-, -}), (0, 0), (+, +)\}\)

- \(R_{\text{open}} = \{(0, -), (0, 0), (0, +)\}\)
Domain Abstraction for the Pedal Position Sensor

Electronic Control Unit

Potentiometer

Switch

Mechanical connection

Battery

gnd  batt

grd  \ldots  v_{\text{switch}}  \ldots  \text{batt}

\begin{align*}
V_{\text{pot}} & \\
V_{\text{switch}} & \\
\end{align*}

Electronic Control Unit

low  betw  high
Domain Abstraction - Formally

General:
• \( \tau_i: \text{DOM}_0(v_i) \rightarrow \text{DOM}_1(v_i) \)

Aggregation of values (P: the power set):
• \( \tau_i: \text{DOM}_0(v_i) \rightarrow \text{DOM}_1(v_i) \subseteq \text{P(\text{DOM}_0(v_i))} \)

(Generalized) Intervals (I: space of intervals):
• \( \tau_i: \text{IR}_\infty \rightarrow \text{DOM}_1(v_i) \subseteq \text{I(\text{IR}_\infty)} \)

Real landmarks and intervals between them:
• \( L \subseteq \text{IR}_\infty \)
• \( \tau_i: \text{IR}_\infty \rightarrow \text{DOM}_1(v_i) \subseteq \text{I}_L(\text{IR}_\infty) \)
### Interval Arithmetic

- **Addition** of intervals
  \[(\alpha_1, \omega_1) \oplus (\alpha_2, \omega_2) = (\alpha_1 + \alpha_2, \omega_1 + \omega_2)\]

- **Subtraction**
  \[(\alpha_1, \omega_1) \ominus (\alpha_2, \omega_2) = (\alpha_1 - \omega_2, \omega_1 - \alpha_2)\]

- **Multiplication**
  \[(\alpha_1, \omega_1) \otimes (\alpha_2, \omega_2) = (\min(\alpha_1 \cdot \alpha_2, \alpha_1 \cdot \omega_2, \alpha_2 \cdot \omega_1, \omega_2 \cdot \omega_1), \max(\alpha_1 \cdot \alpha_2, \alpha_1 \cdot \omega_2, \alpha_2 \cdot \omega_1, \omega_2 \cdot \omega_1))\]

- **Division**
  \[(\alpha_1, \omega_1) \oslash (\alpha_2, \omega_2) = (\min(\alpha_1/\alpha_2, \alpha_1/\omega_2, \omega_1/\alpha_2, \omega_1/\omega_2), \max(\alpha_1/\alpha_2, \alpha_1/\omega_2, \omega_1/\alpha_2, \omega_1/\omega_2))\]
  
  - for \(0 \not\in (\alpha_2, \omega_2)\)!
  - Because … ?
Properties of Interval Arithmetic

- Associative
- Commutative
- Sub-distributive:
  \[ i_1 \otimes (i_2 \oplus i_3) \subset (i_1 \otimes i_2) \oplus (i_1 \otimes i_3) \]
- \( \rightarrow \) intervals may include spurious real-valued solutions

Solutions of interval equations

- \( x_1 = i_1, x_2 = i_2, \ldots \)
- satisfies
- \( f_l(x_1, x_2, \ldots, x_n) \approx f_r(x_1, x_2, \ldots, x_n) \)
- iff
- \( f_l(i_1, i_2, \ldots, i_n) \cap f_r(i_1, i_2, \ldots, i_n) \neq \emptyset \)
Spurious Solutions in Interval-based Qualitative Modeling

- \( x+y = y+z \rightarrow x \oplus y \cong y \oplus z \)
- \( x=(1,2), y=(0,1), z=(0,1) \)
- satisfies all constraints
- BUT
- contains no real-valued solution:
- \( x+y = y+z \Rightarrow x = z \)

Solutions of interval equations
- \( x_1=i_1, x_2=i_2, \ldots \)
- satisfies
- \( f_l(x_1, x_2, \ldots, x_n) \cong f_r(x_1, x_2, \ldots, x_n) \)
- iff
- \( f_l(i_1, i_2, \ldots, i_n) \cap f_r(i_1, i_2, \ldots, i_n) \neq \emptyset \)
Special Case: Arithmetic on Signs

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Exercise Stupid System – Qualitative Behavior Models

• Qualitative behavior models
Behavior Models –
General Representation, Model Abstraction
Relational Behavior Models

• **Representational space:** \((\mathbf{v}, \text{DOM}(\mathbf{v}))\)
  - \(\mathbf{v}\): Vector of local Variables and Parameters
  - local w.r.t Model fragment or Aggregat
  - \(\text{Dom}(\mathbf{v})\): Domain of \(\mathbf{v}\)

• **Behavior description:** Relation
  - \(R \subseteq \text{DOM}(\mathbf{v})\)
  - Composition: join of Relations
Valid Behavior Models

- Independently of the syntactical form:
- What set of states is allowed by the model?
- $R_S \subseteq \text{DOM}(v_S)$

A valid model of a behavior:
- $R_S$ covers all states of the behavior
- $\forall \text{sit} \in \text{SIT} \; \text{Val}(v_S, v_{S,0}, \text{sit}) \Rightarrow v_{S,0} \in R_S$
Domain Abstraction - Formally

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- \( \tau_i : \text{IR}_\infty \rightarrow \text{DOM}_1(v_i) \subseteq \text{I}_L(\text{IR}_\infty) \)
Model Abstraction

- Domain abstraction
- \( \tau: \text{DOM}_0(\mathbf{v}_S) \rightarrow \text{DOM}_1(\mathbf{v}_S) \)
- induces model abstraction
- \( R_S \subseteq \text{DOM}(\mathbf{v}_S) \rightarrow \tau(R_S) \subseteq \text{DOM}_1(\mathbf{v}_S) \)

Theorem:
- If the base relation is a valid model of a behavior
- then so is its abstraction
- Important for consistency check
Deviation Models
Models – Behavior Deviations

- Potential scenario:
  - Command normal (no deviation)
  - Flow sensor signal: higher than expected
  - Pressure sensor signal: lower than expected
  - Not absolute, but relative
  - “Deviation”

![Diagram showing a pump, drive, cmd, p down, sensors, f up]
Qualitative Deviations

hydraulic unit
front left wheel
rear right wheel
brake pedal

under-braked
over-braked

harder

braked
over-braked

hydraulic unit
Qualitative Modeling with Deviations

Deviations
\[ \delta x := \text{sign}(x_{\text{act}} - x_{\text{ref}}) \]

Equations
\[ Q_1 + Q_2 = 0 \]

Model Fragments
\[ \delta Q_1 \oplus \delta Q_2 \simeq [0, 0] \]

- \[ \delta(x + y) \simeq \delta x \oplus \delta y \]
- \[ \delta(x - y) \simeq \delta x \ominus \delta y \]
- \[ \delta(x \times y) \simeq (x_{\text{act}} \otimes \delta y \oplus y_{\text{act}}) \otimes (\delta x \ominus \delta x \otimes \delta y) \]
- \[ \delta(x / y) \simeq ((y_{\text{act}} \otimes \delta x) \ominus (x_{\text{act}} \otimes \delta y)) \ominus (y_{\text{act}} \otimes (y_{\text{act}} \ominus \delta y)) \]
- \[ y = f(x) \text{ monotonic} \Rightarrow \delta x = \delta y \]
- Reference can be unspecified!
Exercise Stupid System – Qualitative Deviation Models

- Qualitative deviation models of hydraulic components
- Potential scenario:
- Command normal (no deviation)
- Flow sensor signal: higher than expected
- Pressure sensor signal: lower than expected
Stupid System – Not that Stupid

- Basis for Volvo Demonstrator: Turbo Control System
Example – Model Library for Hydraulic Components

- FMEA of a braking system (material page)
Knowledge-based Systems for Industrial Applications

Modeling Process
Reusable Model Fragments

- Relational Model of Composite System
- Join of the component models
- with shared terminal variables
- $R_{Res1} \bowtie R_{Wire} \bowtie R_{Res2}$

- Library of component models
- Reuse!
  $\rightarrow$ Requirement on behavior description
Context-independent Behavior Descriptions

- Reusability of model fragments
- → Local, context-free descriptions
  - Local variables only!
  - No assumption about other components!

\[
\text{Resistor}_1 \quad R=R_0
\]
\[
\text{Wire} \quad R=0
\]
\[
\text{Resistor}_2 \quad R=R_1
\]
Context-independent Behavior Descriptions

- Reusability of model fragments
- → Local, context-free descriptions
  - Local variables only!
  - No assumption about other components!

E.g. switch

state  current
OPEN  0
CLOSED  +

• Assumes closed circuit!
Context-independent Behavior Descriptions (Cont’d)

• Reusability of model fragments
• → Local, context-free descriptions
  • Local variables only!
  • No assumption about other components!

Switch 2\textsuperscript{nd} attempt

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<tr>
<td>CLOSED</td>
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<td>OPEN</td>
</tr>
<tr>
<td>CLOSED</td>
<td>+</td>
<td>CLOSED</td>
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• Assumes sw2!
Decision-based Model-Building Steps - Example

Resistor

terminal1

$r_0$

terminal2

\{ r_0, i, v \}  \rightarrow \{ r_0, \text{temp, \ldots} \}  \rightarrow \{ i, v, k, \alpha \}

r, \text{temp}  \rightarrow \Delta r, \Delta \text{temp})

<table>
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<th>R1</th>
<th>$\Delta v$</th>
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<tbody>
<tr>
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<td>*</td>
<td>0</td>
</tr>
<tr>
<td>+</td>
<td>*</td>
<td>+</td>
</tr>
</tbody>
</table>

$\Delta v = i \cdot R$

$i_1 - i_2 = 0$

...
Mixed Model-Building Processes

- Ideal: top-down
  - but unrealistic …
- Bottom up
  - e.g. build overhead“ for Matlab model
- „Outside in“ …