A GENERAL FRAMEWORK FOR MODELING OF SYNTHESIS

- INTEGRATION OF THEORIES OF SYNTHESIS -

Hideaki Takeda
National Institute of Informatics
takeda@nii.ac.jp

Masaharu Yoshioka
Hokkaido University
yoshioka@db-ei.eng.hokudai.ac.jp

Tetsuo Tomiyama
The University of Tokyo
tomiyama@race.u-tokyo.ac.jp

What is Synthesis?

- Examples of Synthesis
  - Scientific Discovery
  - Design
  - Art (Novel, Music)
  - …
- Synthesis is often explained in comparison with analysis
  - Synthesis is defined by using definition of analysis
- Characteristics of synthesis process
  - In process of scientific discovery
    - Many analysis processes and a few synthesis processes
    - Fewer hypotheses are preferred
  - In process of design
    - Many analysis processes and many synthesis processes
    - Many hypotheses are acceptable (or preferred)

Two Viewpoints for Terms "Synthesis" and "Analysis"

- From the viewpoint of "thinking style"
  - Purpose-oriented thought process
  - Synthesis or analysis as the purpose for thinking
    - Synthesis-oriented thought process
      - Process to create or find something
      - ≠ abduction
        - Creative process (abduction) involves examining process (deduction)
    - Analysis-oriented thought process
      - Process to examine something
      - ≠ deduction
        - Examining process (deduction) involves hypothesizing process (abduction)

Two Viewpoints for Terms "Synthesis" and "Analysis"

- Definitions of terms
  - From the logical viewpoint
    - Synthesis → Abduction
    - Analysis → Deduction
  - From the viewpoint of "style of thinking" or naïve definition
    - Synthesis → Synthesis-oriented thought process
    - Analysis → Analysis-oriented thought process
- How can these types of thought processes explained from the logical viewpoint
  - Integration of two viewpoints

Synthesis and Analysis in the Logical Framework

Synthesis/Analysis as a rational thought process based on theories

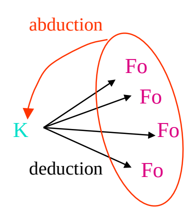
- Theories: Logical relations between foundations and phenomena
- A thought process based on theories: reasoning using theories, i.e., finding foundations to phenomena or finding phenomena for foundations
- Rationality: Consistency to theories

Reasoning with Knowledge: in Science

$K \cup Fd \vdash Th$

- Deduction: Find ***Th*** from ***K*** and ***Fd***
- Abduction: Three types
  1. Find ***K*** and ***Fd*** from (a part of) ***Th***
  2. Find ***K*** from (a part of) ***Th*** and ***Fd***
  3. Find ***Fd*** from (a part of) ***Th*** and ***K***

- In Scientific Thought process
  - Purpose: Discovery of knowledge
  - Abduction is Type 1 or 2
    - Find knowledge with generality from observable facts with individuality
    - Many observable facts
    - Fewer hypotheses
    - Many deduction and fewer abduction
  - ***Deduction is a main process***

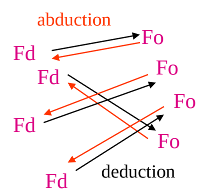


Reasoning with Knowledge: in Design

$K \cup Fd$ |- Th

- Deduction: Find ***Th*** from ***K*** and ***Fd***
- Abduction: Three types
  1. Find ***K*** and ***Fd*** from (a part of) ***Th***
  2. Find ***K*** from (a part of) ***Th*** and ***Fd***
  3. Find ***Fd*** from (a part of) ***Th*** and ***K***

- In Design
  - Purpose: new hypotheses
  - Abduction is Type 3
  - Find defined facts with individuality from observable facts with individuality
    - More knowledge is better
    - Deduction and abduction are equally used
  - ***Abduction is a more important process***



Formalization of Two Types of Thought Processes with Logic

Analysis-oriented Thought Process

(1) Observation of phenomena
A phenomenon is observed as observations ***O***.

(2) Extraction of facts
Observed facts ***Fo*** are extracted from ***O***.

(3) Formation of hypotheses or selection of axioms
Fo can be used to reason out hypothetical axioms ***Kh***. In obvious cases, a set of known axioms ***Ke*** is selected instead.

(4) Assuming definition facts
Initial definition facts ***Fd*** are assumed. Together with ***Ke*** (or ***Kh***), this will be used to derive theorems ***Th***. Usually, ***Fd*** contain such known facts as boundary conditions and initial conditions.

(5) Derivation of theorems from axioms
Theorems ***Th*** are derived from ***Ke*** (or ***Kh***) and ***Fd*** deductively. It may break down the original problem (i.e., derivation of theorems) into smaller subproblems (the “divide-and-conquer strategy").

(6) Verification of theorems against facts
The derived theorems ***Th*** are tested against the observed facts ***Fo*** to check the explicability of the theorems. If $Th \supseteq Fo$, this test is satisfied. Then the theorems are said to explain the extracted facts and the choice of ***Ke*** (or ***Kh***) was appropriate. If $Th = Fo$, then ***Ke*** is complete. If $Th \supset Fo$, then $Th - Fo$ signifies unobserved facts or undiscovered facts in the future or past. If $Fo - Th \neq \emptyset$, then unexplained facts remain.

(7) Verification of theorems against other known axioms
The derived theorems ***Th*** are again tested against other known sets of axioms ***K’***. This test verifies if the theorems are compatible with ***K’*** or at least if they do not violate ***K’***. If the hypotheses obtained in step (3) pass tests (6) and (7), they become axioms.

Synthesis-oriented Thought Process

(1) Describing requirements
Requirements for the synthesis ***R*** are described as theorems.

(2) Extraction of requirements of interest
From ***R***, we only focus on interesting facts as ***Fo***.

(3) Selection of axioms
Axiom to be used is selected. Synthesis requires various viewpoints to be considered. This means that the number or cardinality of ***K*** tends to be large.

(4) Derivation of solutions from requirements and axioms
Solutions ***Fd*** are derived as facts from ***K*** and ***Fo***. The basic reasoning is abduction logically, but other algorithms to arrive at solutions can be also used. The “divide-and-conquer strategy” might be used, but since the number (or cardinality) of ***K*** could be larger than analysis, trade-off and negotiation among different solutions are important.

(5) Derivation of theorems from axioms and facts
Theorems ***Th*** are derived from ***K*** and ***Fd*** deductively. This is the same as in the analysis oriented thought process. Deduction and the divide-and-conquer strategy are central.

(6) Verification of theorems against requirements
The derived theorems ***Th*** are tested against the requirements of interest ***Fo*** to check if the derived ***Th*** subsume the initial requirements ***Fo***; (i.e., $Th \supseteq Fo$). By doing so, we can check if the solutions ***Fd*** are satisfactory.

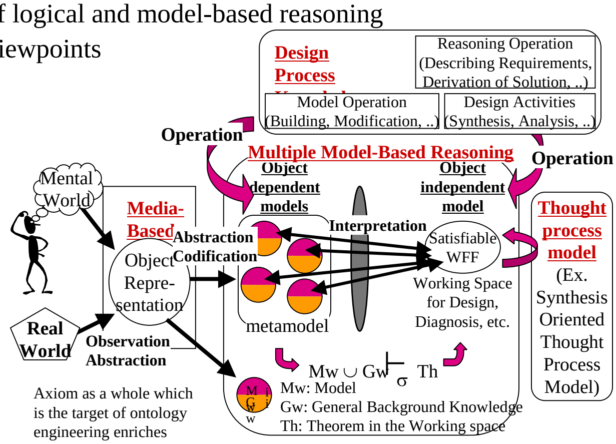
(7) Verification of theorems against other known axioms
The derived theorems are again tested against other known sets of axioms ***K’***. This test verifies if ***Fd*** (and accordingly ***Fo***) is compatible with not only ***K*** but also ***K’***.

Difference between Synthesis and Analysis Processes

- Problem Definition
  - AOTP: Observation
  - SOTP: Enumeration of requirements
  - Arbitrariness of Synthesis
- Setting of viewpoints (Selection of axiom)
  - AOTP: Fewer axioms are preferred
  - SOTP: More axioms are preferred
  - Arbitrariness and complexity of Synthesis
- Roles of abduction and deduction
  - AOTP: abduction in selection of axioms
  - SOTP: deduction in development and evaluation
  - Complementarity of abduction and deduction
- Criteria
  - AOTP: hypothesized knowledge
  - SOTP: hypothesized facts
  - Difficulty of evaluation of synthesis

A Computational Framework of Synthesis

- Requirements: 3 Types of multiplicity
  - Explicit controls for abductive and deductive reasoning processes
  - A variety of knowledge
    - Duality of logical reasoning and model-based reasoning
      - Integration of logical and model-based reasoning
    - Use of multiple viewpoints

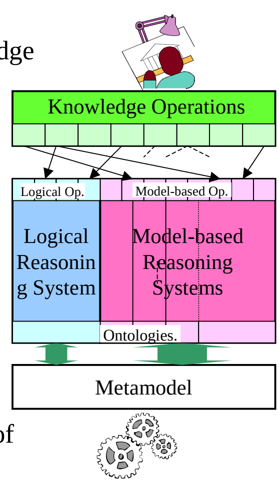


Duality of Logical Reasoning and Model-based Reasoning

- Model-based reasoning:
  - "Modeling": Description of objects and their environments from a specific viewpoint
  - Pros:
    - Knowledge adapted to the real world is provided
      - Knowledge in synthesis: simplicity is not required, but adaptability to the real world is required
  - Cons:
    - Closed in their specific viewpoints
    - Abductive and deductive reasoning are usually indistinguishable
- Integration of logical and model-based reasoning
  - Model-based reasoning: Operations within individual viewpoints
  - Logical reasoning:
    - Orientation of thought process
    - Relationship among viewpoints

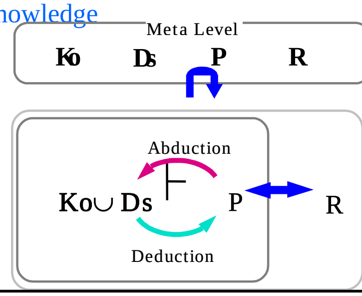
Knowledge Operations in Design

- Activities in design consists of a variety of operations
- Knowledge Operations: a category of operations by viewing design activities as operating designers' knowledge
  - Different types of knowledge resource
    - 1. Knowledge/Information Acquisition
    - 2. Knowledge/Information Reorganization
    - 3. Information Confirmation
    - 4. Conflict Resolution
    - 5. Knowledge/Information Revision
  - Synthesis and analysis
    - 6. Solution Synthesis
    - 7. Object Analysis
- Knowledge Operations as combination and/or selection of model and logical reasoning operations
  - 7 K-Operations = 7 L-Operations + 8 M-Operations



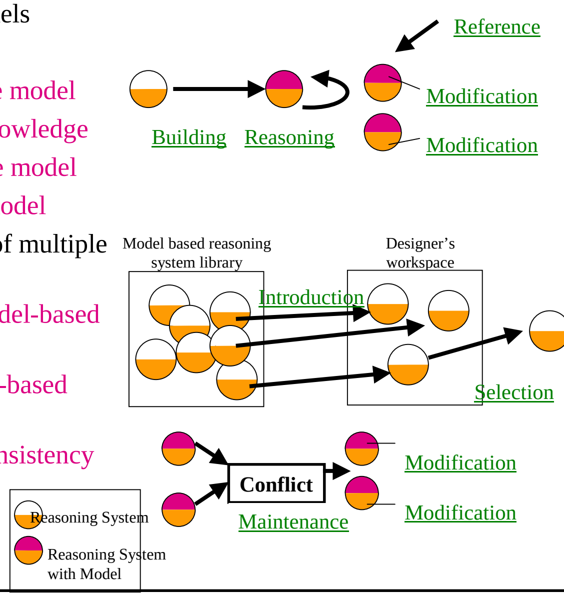
Operations in the Logical Reasoning

- Object level
  - (l-1) Deduction of properties of objects from objects
  - (l-2) Abduction of objects from properties of objects
- Meta level
  - (l-3) Setting of objects
  - (l-4) Setting of requirement specifications
  - (l-5) Setting of design knowledge (selection of axioms)
  - (l-6) Consistency checking of knowledge (axioms)
  - (l-7) Operations on the current set of design knowledge



Operations in Model-based Reasoning

- Operations in individual models
  - (m-1) Building a model
  - (m-2) Reasoning with the model
  - (m-3) Modification of knowledge
  - (m-4) Modification of the model
  - (m-5) Reference of the model
- Operations for maintenance of multiple models
  - (m-6) Introduction of model-based systems
  - (m-7) Selection of model-based systems
  - (m-8) Maintenance of consistency among different models



Knowledge Operations in Design

- (k-1) Knowledge/Information Acquisition
  - (m-6) or (m-3)
  - (l-7)
- (k-2) Knowledge/Information Reorganization
  - (m-7) or (m-8)
  - (l-7)
- (k-3) Information Confirmation
  - (m-5)
  - (l-5)(l-6)
- (k-4) Conflict Resolution
  - (m-8)
  - (l-6)
- (k-5) Knowledge/Information Revision
  - (m-3) or (m-4)
  - (l-5)(l-6)
- (k-6) Solution Synthesis
  - (m-7)(m-1)(m-2)
  - (l-5)(l-2)
- (k-7) Object Analysis
  - (m-7)(m-1)(m-2)
  - (l-5)(l-1)

Conclusion

- Synthesis is defined theoretically
  - Synthesis thought process in the logical framework
- Synthesis is explained computationally
  - A computational framework for synthesis *3 Types of multiplicity*
    - Explicit controls for abductive and deductive reasoning processes
    - A variety of knowledge
      - Integration of logical and model-based reasoning
      - Use of multiple viewpoints
- Synthesis process is also explained computationally
  - Practical synthesis activities are explained in the computational framework
  - Seven knowledge operations each of which is composed of logical and/or model-based operations