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EXPLORING ANALOGICAL REASONING CAPABILITIES WITHIN A COGNITIVE MODEL

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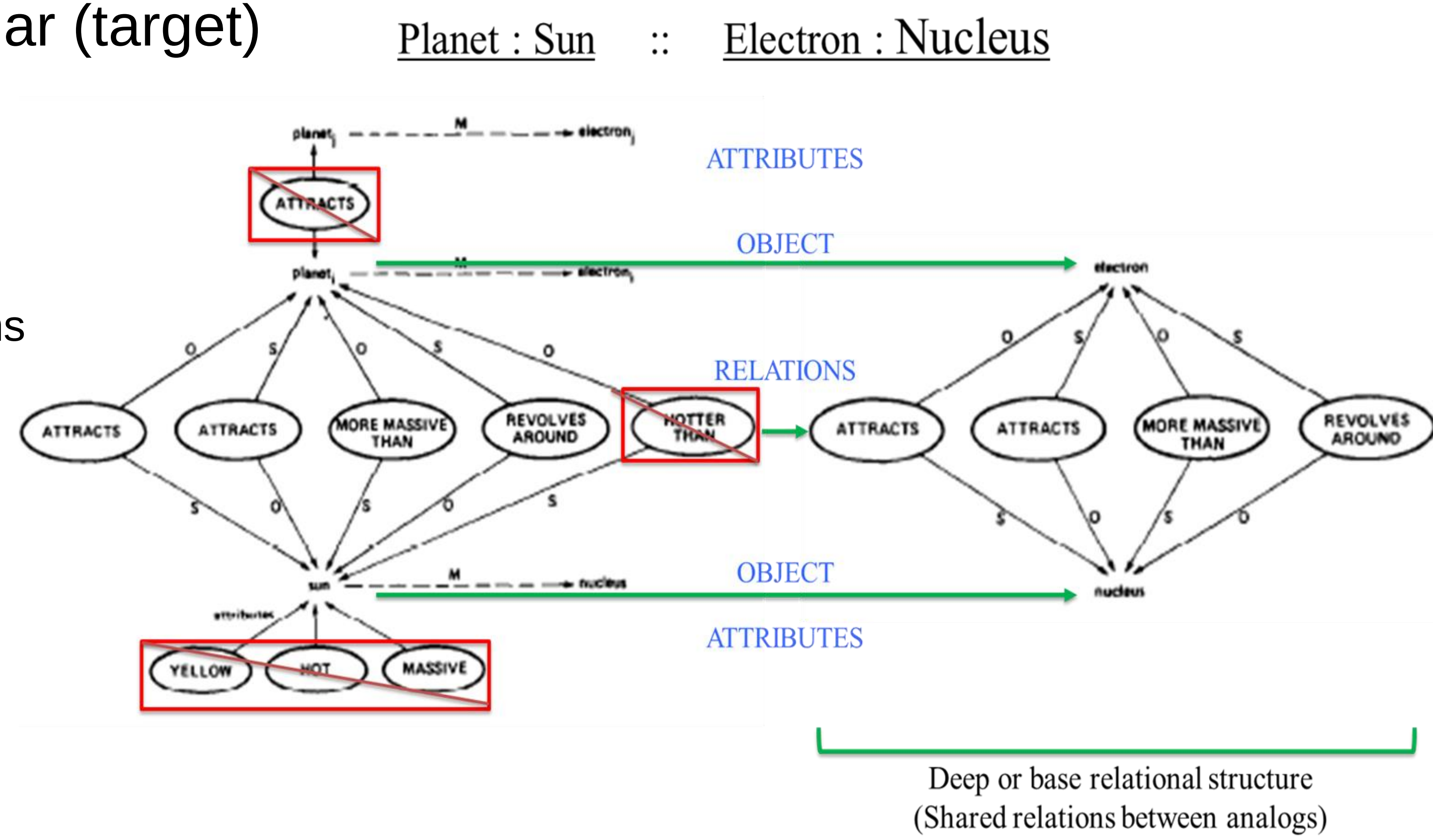
Motivation for Model of Analogical Reasoning

- Intelligent Cognitive Agent Research
  - Deal with incomplete knowledge
  - “Understanding”, knowledge transfer, and generalization
- Technical Questions
  - Build/refine representations?
  - Determine similarity: words, relations, analogs?
  - Scalability and constraints
- Theoretical Questions
  - Representing analogs/systems?
  - Similarity, analogical distance, and relation hierarchies?
  - Exhaustive, partial, or heuristic processes?

ANALOGICAL REASONING THEORY

Analogical Reasoning – What is it?

- Relational system and infer new information (Gentner & Smith, 2013)
- Familiar (source) -> less familiar (target)
- Structure mapping (Gentner, 1983)
  - Situations are systems
    - Objects, attributes, and relations
  - Levels of mapping
    - Literal/surface similarity
    - Abstraction
    - Analogy

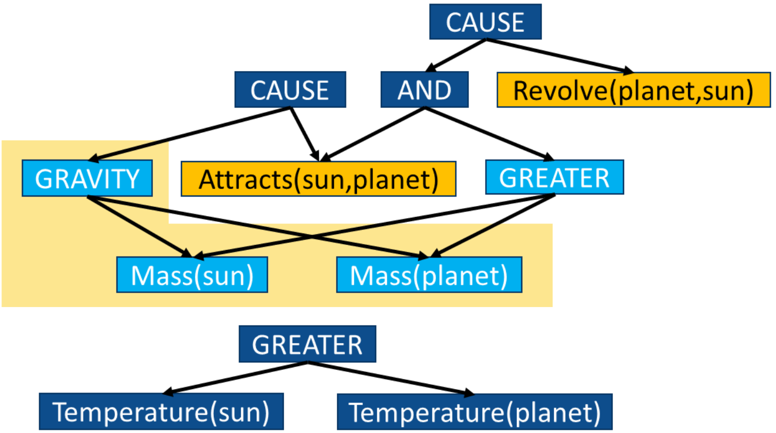


Analogical Reasoning – What is it?

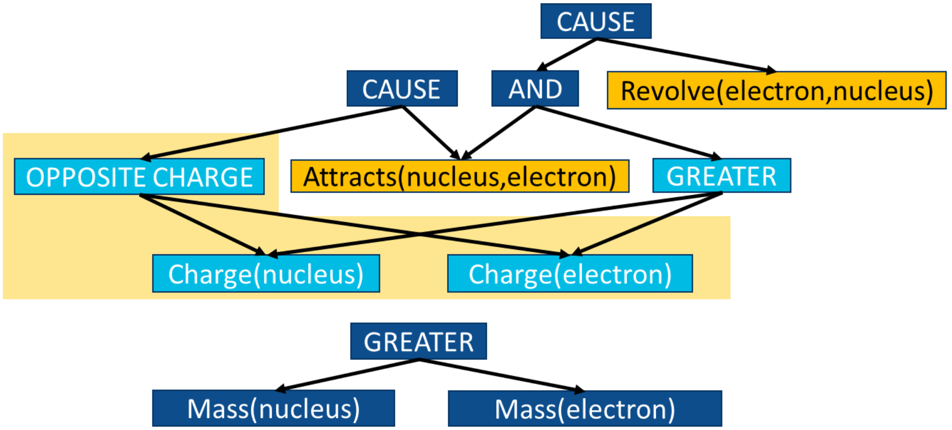
Schemas and transfer in problem solving (Gick & Holyoak, 1983)

- Analogy - partial mapping and extension of attributes/relations
  - Not always noticed, include surface and deep structure
- Schema – deep structure/relations
  - Effort and experience, can transfer

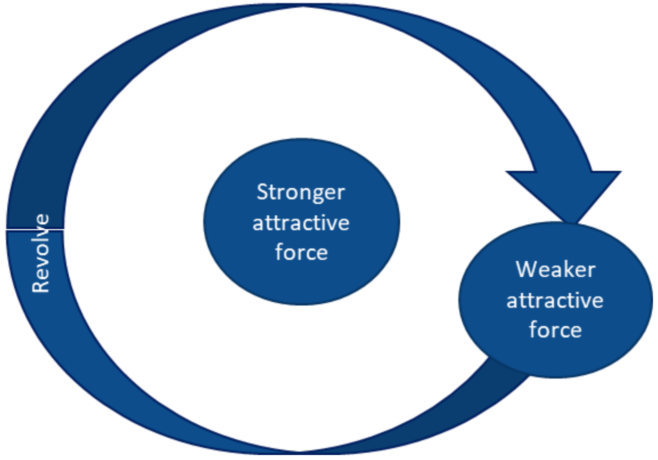
Solar System



Atom



Schema (analogy)

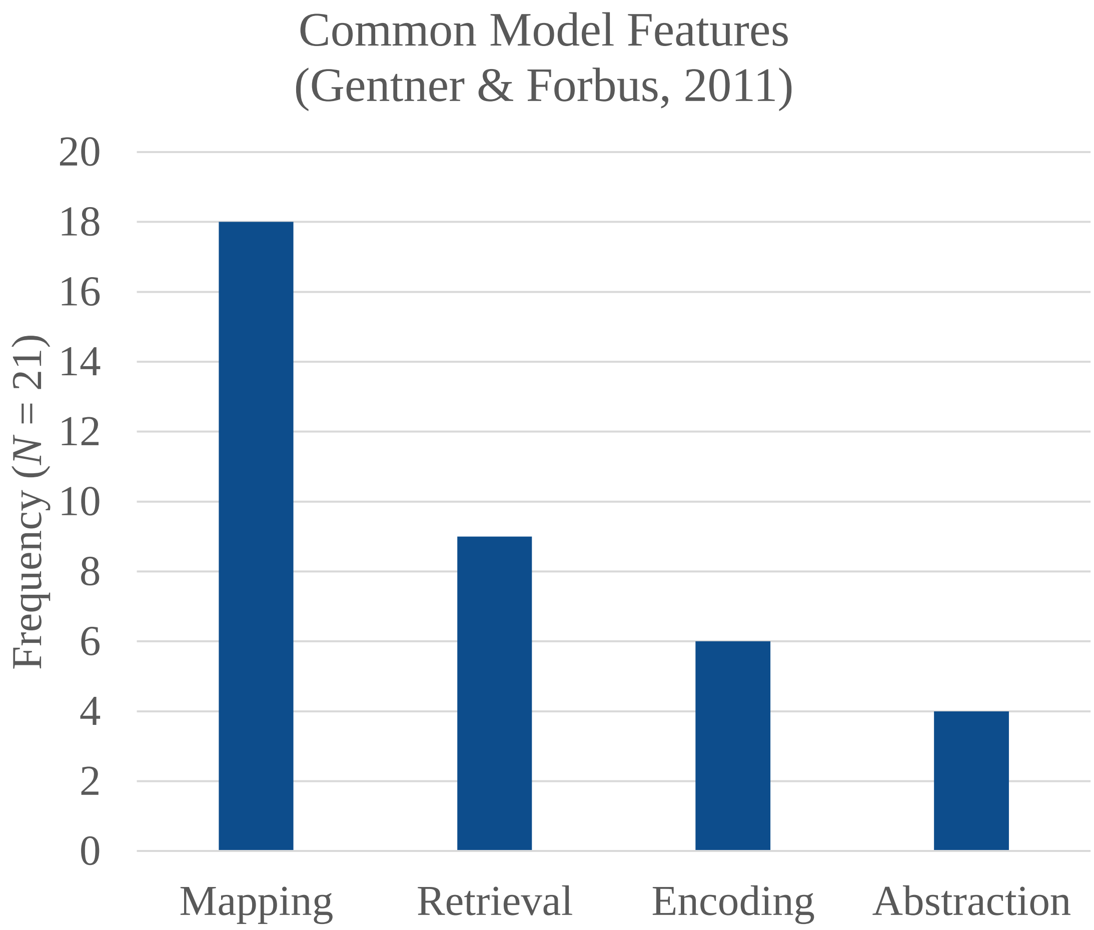


MODELING ANALOGICAL REASONING

Modeling Analogical Reasoning

Core Features (Gentner & Forbus, 2011)

- Mapping
  - Types (Forbus et al., 2017)
  - Constraints
- Retrieval
  - Separate from mapping?
- Encoding/representation
  - Hard coding and other processes
  - Mapping and representation
- Abstraction/generalization
  - Schemas and anti-unification



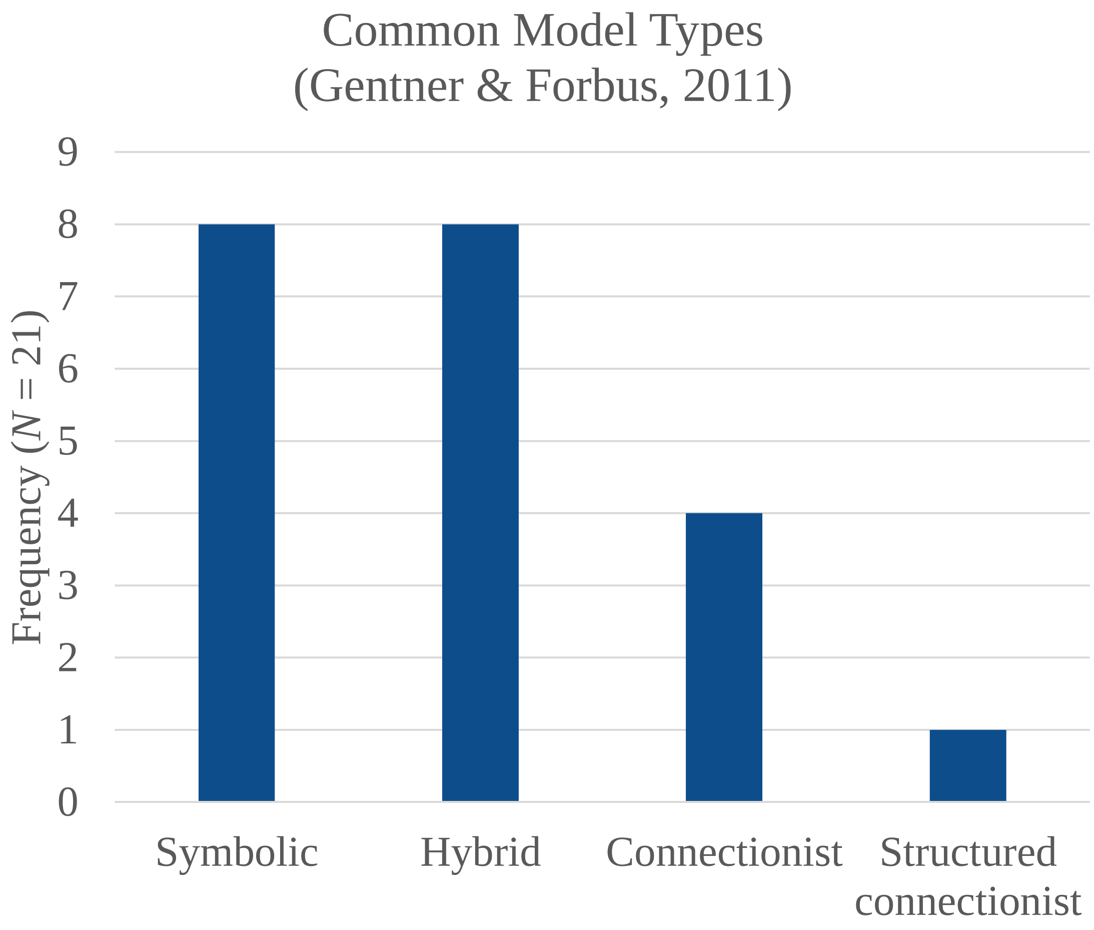
Modeling Analogical Reasoning

Model Types (Gentner & Forbus, 2011)

- Connectionist (ACME, ARCS, CAB, DORA)
- Structured Connectionist (LISA)
- **Symbolic** (CARL, HDTP, IAM, NLAG, **SME**, **MAC/FAC**, **SEQL**, SOAR, Winston)
- **Hybrid** (**ACT-R**, AMBR, **Companions CA**, CopyCat**,** DUAL, EMMA, TableTop)

Challenges (Genter & Forbus, 2011; Forbus et al., 2017)

- Appropriate representations
- Hard/hand coding and databases
- Interleaving cognitive processes
- Applying to cognitive phenomena
- Cognitive plausibility

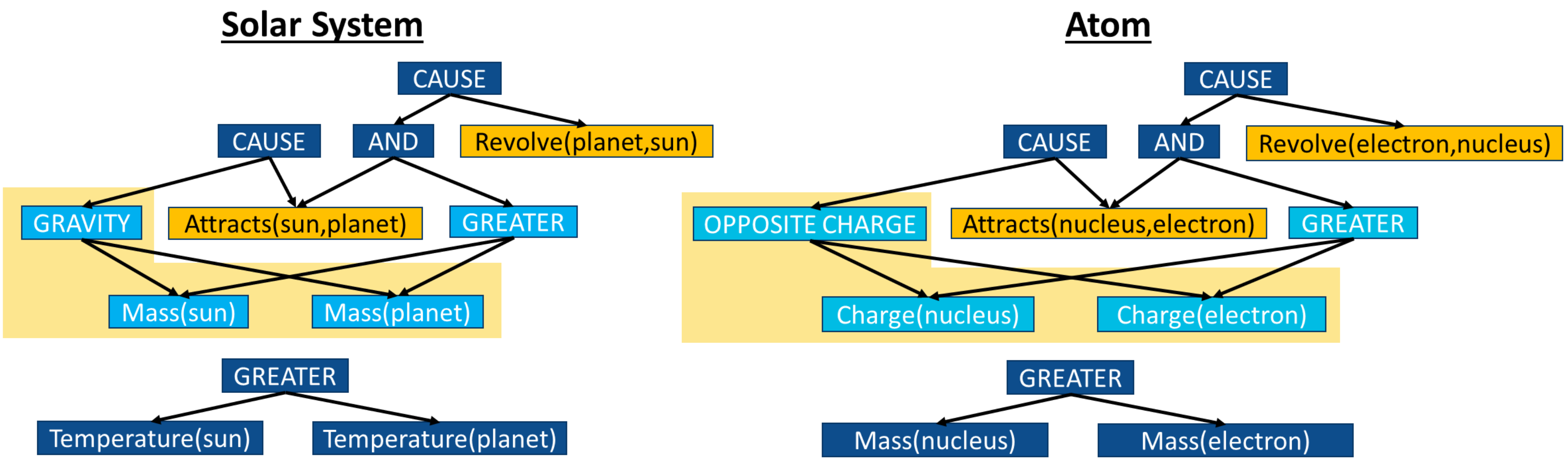


EXAMPLE MODELS

Example Models – Structure Mapping Engine

SME - Structure Mapping Engine (Falkenhainer et al., 1989; Forbus et al., 2017)

- Component used in larger systems
- Similarity and extrapolation (candidate inferences)
- Finds deep structure to compare systems (analogs)
  - **Greater force(gravity/charge)** → attraction → revolve
- Used in:
  - MAC/FAC (Forbus et al., 1995)
  - SEQL (Kuehne et al., 2000)
  - Companions architecture (Blass & Forbus, 2017; Forbus et al., 2009; Ribeiro & Forbus, 2021)

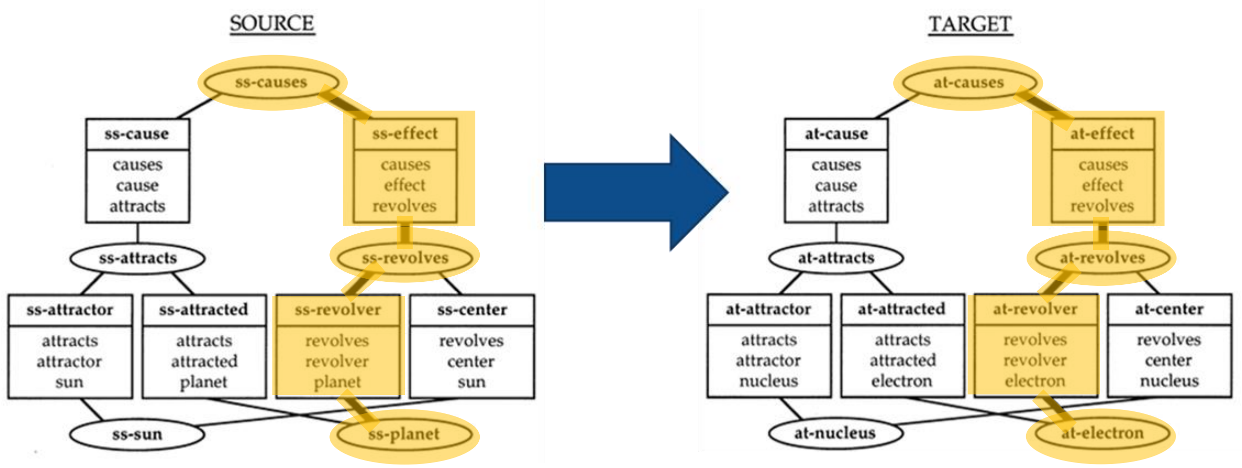


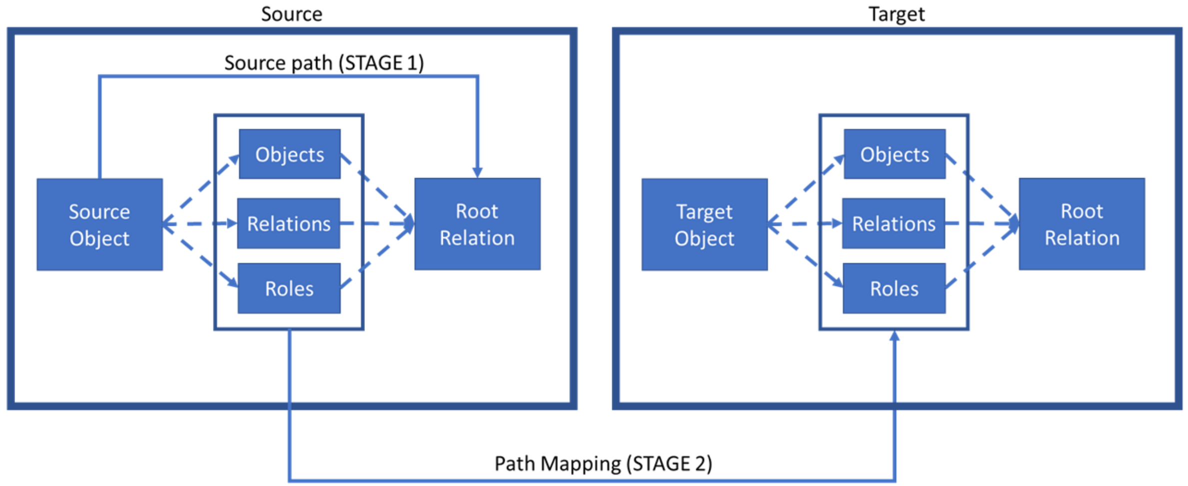
Example Models – Path Mapping Model

ACT-R – path mapping theory

(Salvucci & Anderson, 2001)

- Representation
  - Decomposed into chunks with objects, relations, and roles
- Path Mapping
  - Domain general set of rules to map object in source to one in target
- Organization (encoding)
  - When/how to use path mapping for specific tasks





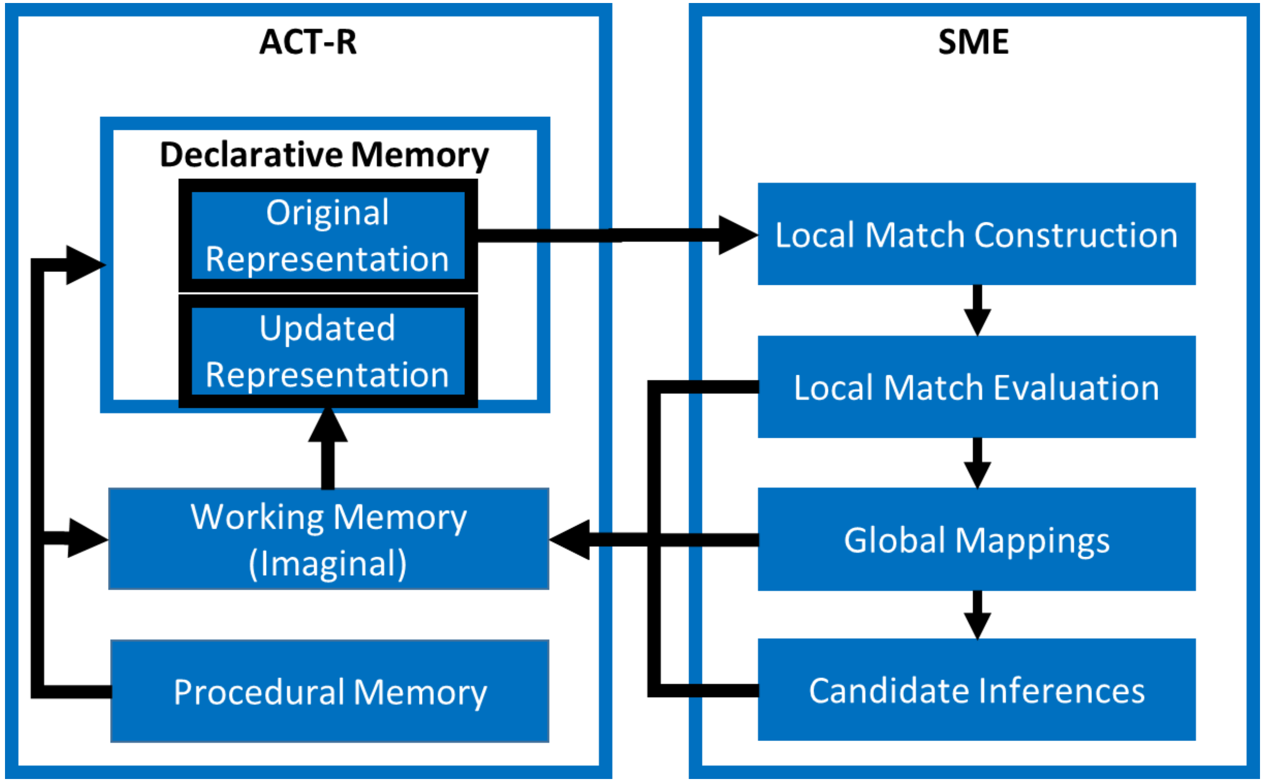
CAN WE OVERCOME CHALLENGES?

Can We Overcome Challenges

- Desired Capabilities
  - Take input and appropriately represent
  - Determine word and relation similarity/meaning
  - Structure alignment/mapping
  - Cognitive plausibility
    - Interleave cognitive processes
    - Apply to different high-level cognitive phenomena
- An exploration…
  - Leveraging ACT-R and SME
    - Get cognitive plausibility for free with ACT-R
    - Remaining 3 require some hard coding

Overcoming Challenges – Proof of Concept Model

- Refine knowledge with analogical processes
- SME as external ACT-R module
- Given base → find best matching target
    - Retrieve chunks for system
    - Compile into file (abstract representation)
    - Use SME to compare two systems
    - Leverage SME output to update
- Desired capabilities from SME
    - Relation/structural similarity and extrapolation



Overcoming Challenges – Proof of Concept Model

- Knowledge of systems or analogs
  - Define system – **solar-system** contains **sun** and **planet** (objects)
  - Define attribute(s) – **solar-system** object **sun** has property **hot**
  - Define relation(s) – **solar-system** has relation **gravity** where **sun** is **greater-than planet**
  - Causality chains? – **mass** causes **gravity**, **gravity** causes **attraction**, **attraction** causes **revolving**
    - New or existing chunk?

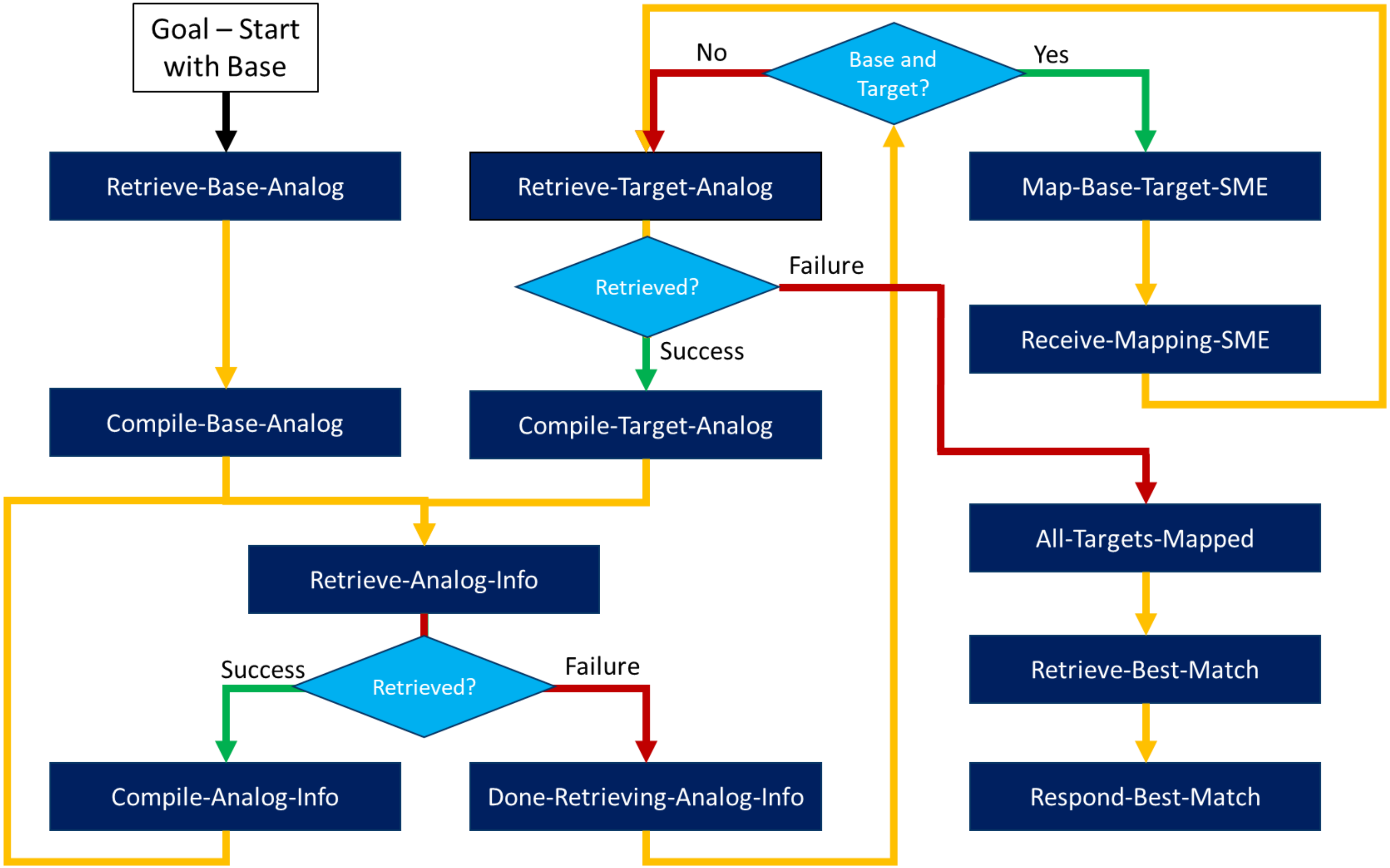
Ss-system	isa	**system**
System-name		ss
Entity1		sun
Entity2		planet

Ss-sun1	isa	**attribute**
System		ss
Entity		sun
Property		hot

Ss-force	isa	**relation**
System		ss
Type		gravity
Role-E1		greater
Entity1		sun
Entity2		planet
Cause?		*Mass?*

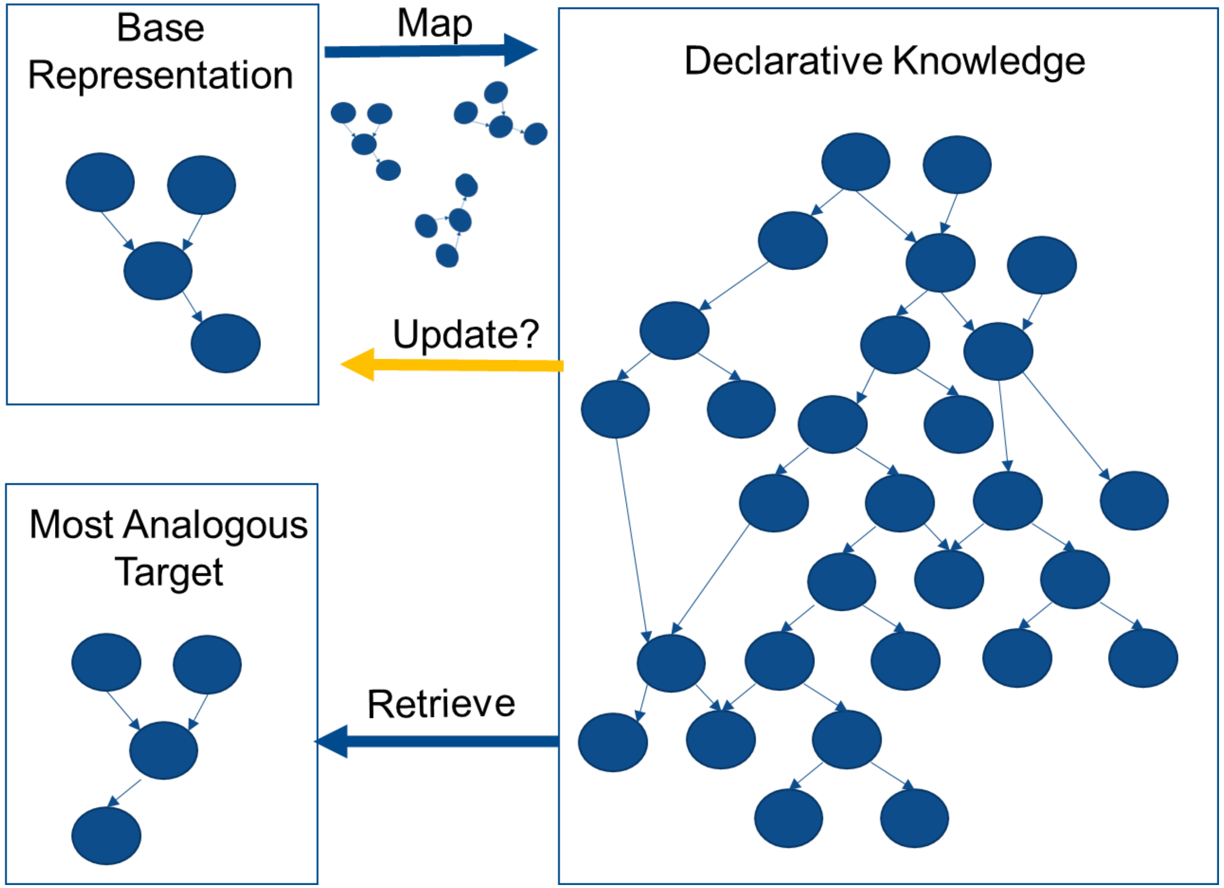
Ss-mass-gravity	isa	**relation**
System		ss
Type		effect
Role-E1		**causes**
Entity1		**mass**
Entity2		**gravity**

Overcoming Challenges – Proof of Concept Model



Overcoming Challenges – What We Still Need

- Proof of Concept Model
  - Cognitive plausibility challenges
  - Knowledge of what and how
  - Cognitive flexibility
- Challenges not addressed
  - Knowledge Representation
  - Method to leverage complete SME output
  - Efficient search with constraints
- Questions remain



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QUESTIONS?

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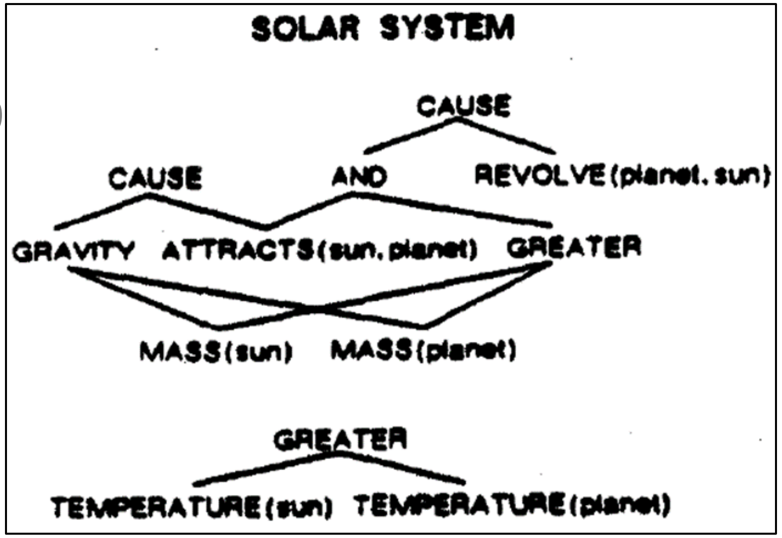
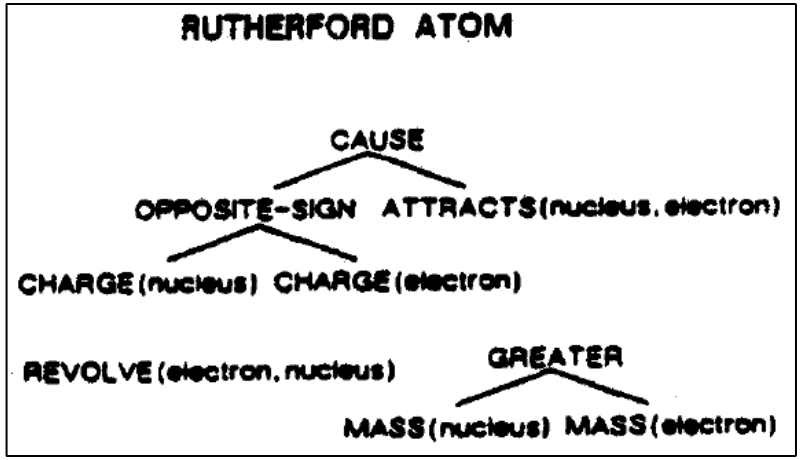
EXTRA SLIDES

Example Models – Structure Mapping Engine

SME - Structure Mapping Engine (Falkenhainer et al., 19

- Component used in larger systems
- Similarity and extrapolation (candidate inferences)
- Finds deep structure to compare systems (analogs)
- Five SME features
  - Greedy merging, structural evaluation, incremental matching, ubiquitous predicates, and match filters
- Used in:
  - MAC/FAC (Forbus et al., 1995)
  - SEQL (Kuehne et al., 2000)
  - Companions cognitive architecture (Blass & Forbus, 2017; Forbus et al., 2009; Ribeiro & Forbus, 2021)



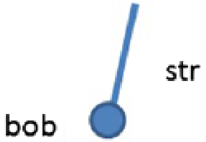


Structure Mapping Engine – Updated

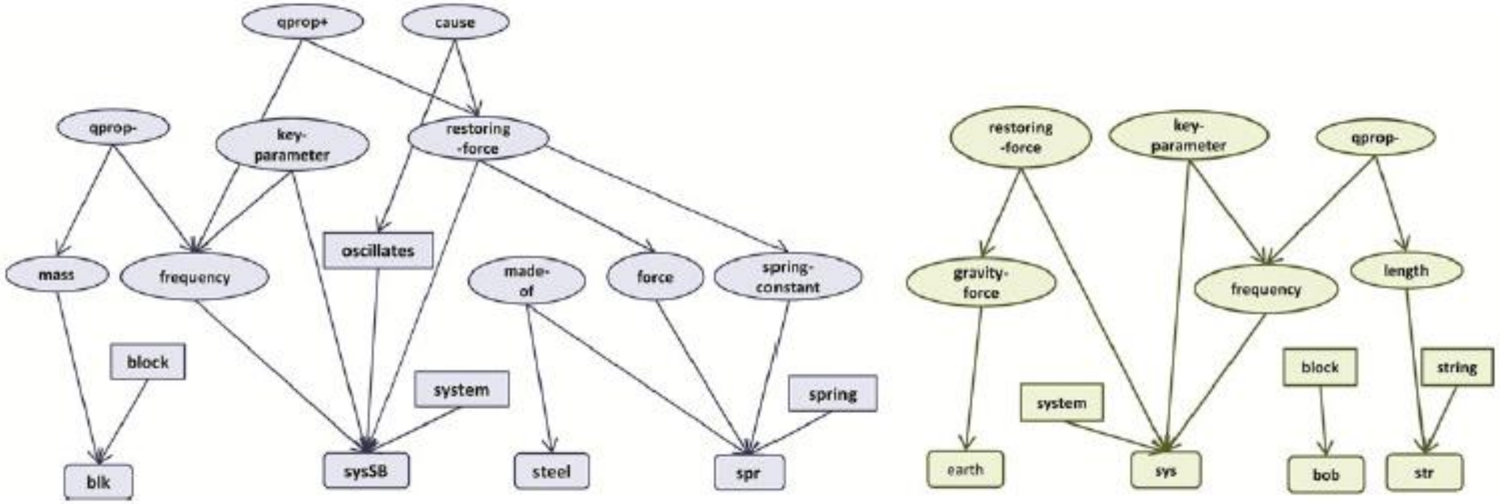
A spring-block oscillator

(spring spr)
(block blk)
(system sysSB)
(made-of spr steel)
(key-parameter sysSB (frequency sysSB))
(qprop+ (frequency sysSB) (spring-constant spr))
(qprop- (frequency sysSB) (mass blk))
(restoring-force sysSB (force spr))
(cause (restoring-force sysSB (force spr))
(oscillates sysSB))

A pendulum



(string str)
(block bob)
(system sys)
(key-parameter sys (frequency sys))
(qprop- (frequency sys) (length str))
(restoring-force sys
(gravity-force earth))))



Forbus et al., 2017

Structure Mapping Engine – Updated

Mapping 15 SME #1

Score: 0.1791

Base: spring-block-oscillator

Target: pendulum

Support	Base Item	Target Item	MH Score
(5)	sys	sys	0.0560
(2)	blk	bob	0.0080
(2)	spr	earth	0.0992

Expression Correspondences SME #1 Mapping 15

[9 items]

Base Item	Target Item	Score
(force spr)	(gravity-force earth)	0.0082
(frequency sys)	(frequency sys)	0.0045
(spring-constant spr)	(gravitational-constant earth)	0.0042
(block blk)	(block bob)	0.0005
(key-parameter sys (frequency sys))	(key-parameter sys (frequency sys))	0.0005
(qprop+ (force spr) (spring-constant spr))	(qprop+ (gravity-force earth) (gravitational-constant earth))	0.0005
(restoring-force sys (force spr))	(restoring-force sys (gravity-force earth))	0.0005
(part-of sys blk)	(part-of sys bob)	0.0005
(system sys)	(system sys)	0.0005

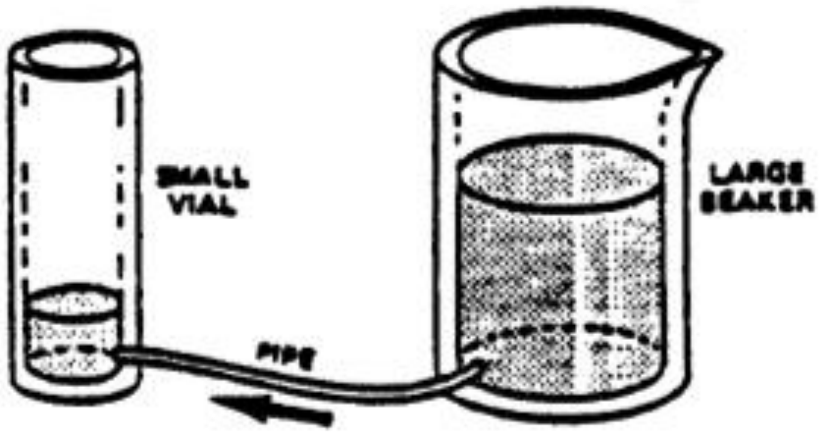
Candidate Inferences SME #1 Mapping 15

[5 items]

	Inference	Support	Extrapolation
?	(spring earth)	0.0005	0.9000
?	(part-of sys earth)	0.0015	0.8500
?	(qprop+ (frequency sys) (gravitational-constant earth))	0.0068	0.5556
?	(qprop- (frequency sys) (mass bob))	0.0050	0.6296
?	(cause (restoring-force sys (gravity-force earth)) (oscillates sys))	0.0090	0.4857

Forbus et al., 2017

Structure Mapping Engine - Input




```
(defDescription simple-water-flow
  entities (water beaker vial pipe)
  expressions (((flow beaker vial water pipe) :name wflow)
              ((pressure beaker) :name pressure-beaker)
              ((pressure vial) :name pressure-vial)
              ((greater pressure-beaker pressure-vial) :name >pressure)
              ((greater (diameter beaker) (diameter vial))
               :name >diameter)
              ((cause >pressure wflow) :name cause-flow)
              (flat-top water)
              (liquid water)))
```

```
(defDescription simple-heat-flow
  entities (coffee ice-cube bar heat)
  expressions (((flow coffee ice-cube heat bar) :name hflow)
              ((temperature coffee) :name temp-coffee)
              ((temperature ice-cube) :name temp-ice-cube)
              ((greater temp-coffee temp-ice-cube) :name >temperature)
              (flat-top coffee)
              (liquid coffee)))
```

Falkenhainer et al., 1989

Structure Mapping Engine – Output

```
Rule File: literal-similarity.rules     Number of Match Hypotheses: 14

Match Hypotheses:

  (0.6500  0.0000)  (>PRESSURE >TEMP)
  (0.7120  0.0000)  (PRESS-BEAKER TEMP-COFFEE)
  (0.7120  0.0000)  (PRESS-VIAL TEMP-ICE-CUBE)
  (0.9318  0.0000)  (BEAKER-6 COFFEE-1)
  (0.6320  0.0000)  (PIPE-8 BAR-3)
      o        o              o
      o        o              o
```

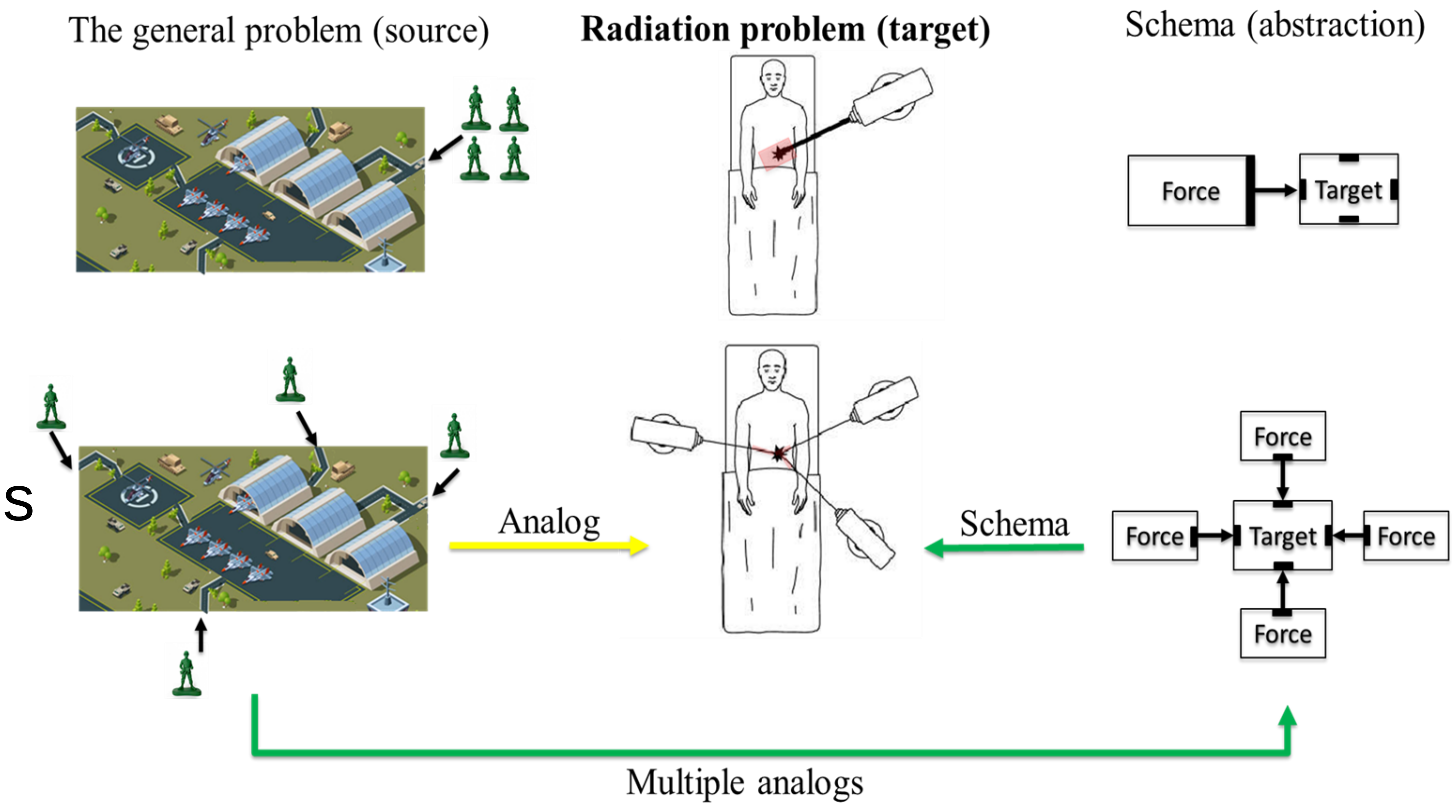
```
Global Mappings:

  Gmap #1:  (>PRESSURE  >TEMPERATURE)  (PRESSURE-BEAKER  TEMP-COFFEE)
            (PRESSURE-VIAL  TEMP-ICE-CUBE)  (WFLOW  HFLOW)
    Emaps:   (beaker coffee)  (vial ice-cube)  (water heat)  (pipe bar)
    Weight:  5.99
    Candidate Inferences: (CAUSE >TEMPERATURE HFLOW)

  Gmap #2:  (>DIAMETER  >TEMPERATURE)  (DIAMETER-1  TEMP-COFFEE)
            (DIAMETER-2  TEMP-ICE-CUBE)
    Emaps:   (beaker coffee)  (vial ice-cube)
    Weight:  3.94
    Candidate Inferences:

  Gmap #3:  (LIQUID-3  LIQUID-5)  (FLAT-TOP-4  FLAT-TOP-6)
    Emaps:   (water coffee)
    Weight:  2.44
    Candidate Inferences:
```

Falkenhainer et al., 1989

Analogical Reasoning – What is it?

Schemas and transfer in problem solving (Gick & Holyoak, 1983)

- Analogy - partial mapping and extension of attributes/relations
  - Not always noticed, include surface and deep structure
- Schema – deep structure/relations
  - Effort and experience, can transfer



Analogical Reasoning Models - Comparison

Qualities		SME	ACT-R PM
Input		Structured information - parsed text or processed visual information	Structured knowledge - abstract analogs with defined objects and relations, and chunk similaries
New information and incremental input		Yes, can re-map/structure by starting over	Yes, but not as is. New structured knowledge must be given or added
Mapping types		Surface, analogy, literal, and anomoly	Analogy. Could potentially do more with added structure/information and rules
Mapping ability		Degree of similarity and structure	Exact match
Inferences or extrapolation?		Yes	No
Mapping/similarity/inference scores		Yes	No
Interleaving of cog process		No, separate cognitive operations (map, retrieval)	Yes, mapping can be interleaved with cog processes

Analogical Reasoning Models - Comparison

Qualities	SME	ACT-R PM
Model tracing	Some	Yes, process, memory, attention, utility…
External guidance	Rules	Rules, goals, and “skills”
Natural constraints	No, but match filters extract them from task?	Yes
Scalabilty?	Yes	Not by itself, could with ML or additional model
Gaps types?	Possible capability for: Homonym, cue, explanatory, memory (omission), metonymy	Possible capability for: Homonym, cue, explanatory, memory (omission), metonymy, rationality
Knowledge base needed	Needs more, but less structured	Needs less, but needs processed information with more structure
Computation speed	Relatively fast - parallel and serial	Likey very slow at symbolic level
Complete model?	No, it is a component	No, it is an analog mapper