Cognitive Architectures for Virtual Humans

Paul S. Rosenbloom | 6/15/2011

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Outline

- **Desiderata**
- **Dichotomies**
- **Techniques**
- **Results**

Desideratum I
Broad Spectrum Architectures

- **Easy to create simple virtual humans**
  - *Data driven*, like NPCEditor (as in SimCoach and other systems)
- **Can create very sophisticated virtual humans**
  - *Model based*, like SASO and MRE
- **Incrementally extend to arbitrary points in between**

Combining Paradigms

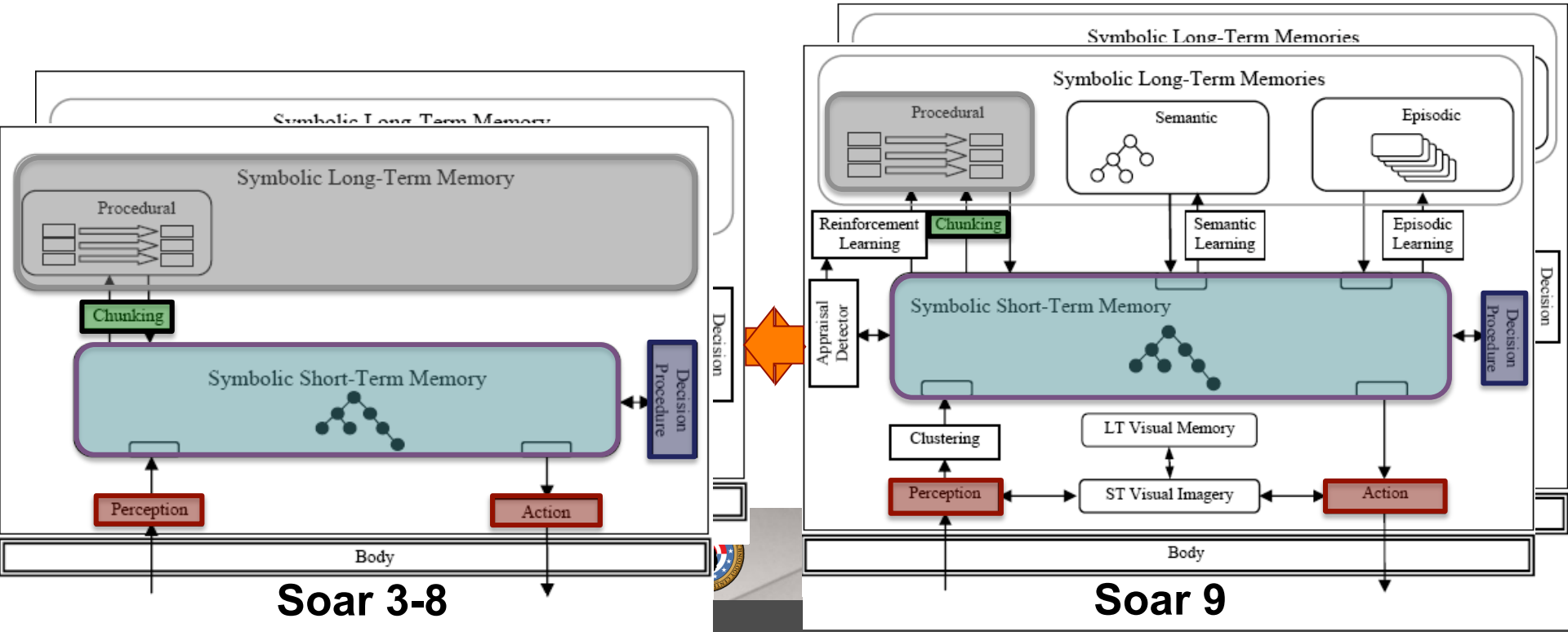
- **Data driven (*shallow*)**
  - *Simple statistical architecture in combination with large amounts of (uncertain) data/knowledge*
  - Achieves robustness through breadth of data/knowledge and focus on statistical regularities
- **Model based (*deep*)**
  - *Sophisticated symbolic reasoning architecture in combination with articulated models of domains of interest*
  - Achieves robustness via combinatoric flexibility of first principles reasoning over comprehensive models
- **The ideal solution is a *mixed* approach**
  - Probabilistic (statistical) + symbolic (relational)
  - Each provides strengths, and can counterbalance other's weaknesses, in authoring, learning, reasoning, perception, etc.
  - Multiplicative effect on robustness

Desideratum II
Tightly Integrated

- **Within the cognitive system**
  - Typical focus within work on cognitive architecture
- **Between cognition and perceptuomotor system**
  - Needed for virtual humans, intelligent robots, etc.
  - Implies *hybrid* systems
    - Combining discrete and continuous representations and processing
  - Also can benefit from mixed systems
    - Supporting general reasoning in presence of uncertainty

Desideratum III
Functionally Elegant

- **Broad scope of capability and applicability**
  - Embodying a superset of existing VH capabilities (cognitive, perceptuomotor, emotive, social, adaptive, …)
- **Theoretically elegant, maintainable, extendible**



Summary of Desiderata

- **Broadly and incrementally functional**
- **Theoretically elegant and simple for simple things**
- **Mixed and hybrid**
- **Supporting truly robust systems**
- **Maintainable and extendible**

Dichotomies Faced by Cognitive Architectures

- Data-driven versus model-based
- Probabilistic versus logical
- Central versus peripheral
- Discrete versus continuous
- Uniform versus diverse
- Explicit versus implicit
- Symbolic versus subsymbolic/neural
- Procedural versus declarative
- Goal-based versus utility-based
- Reactive versus deliberative
- …

Resolving Dichotomies

- **Choose a side**
  - Can work for some, particularly until challenges get too diverse
  - But usually inadequate over the long run
- **Bridge the dichotomy**
  - *Addition*: Add a box for each side
    - Yields two points on broad spectrum, but not full spectrum
    - Neutral on tight integration
    - Supports functional side of functional elegance, but not elegance
  - *Reduction*: Extract commonality that exists across dichotomy
    - Can yield full spectrum
    - Can provide leverage in tight integration based on what is shared
    - Can add elegance to functionality

    + *May uncover deep scientific results*

    - *May require compromise or yield residual*

Reduction Methods

- **Create generalization that subsumes both sides**
  - Markov logic yields a generalization over logic and probability
    - Also generalizes over other dichotomies
  - Traditional shallow rule systems can be thought of as generalizing over data-driven and model-based
    - Compromises both ends of dichotomy for simplicity and efficiency
- **Implement one side via other**
  - Soar implements deliberation via reactivity (plus decision proc.)
  - Data chunking tried to implement declarative via procedural
  - Graphical architecture implements diversity via uniformity
  - *Requires level/time-scale difference and non-peer integration*
- **Generalize implementation level beneath dichotomy**
  - Factor graphs implement both procedural and declarative

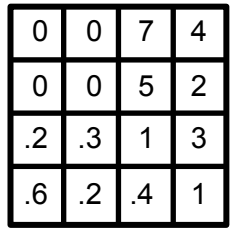
Techniques

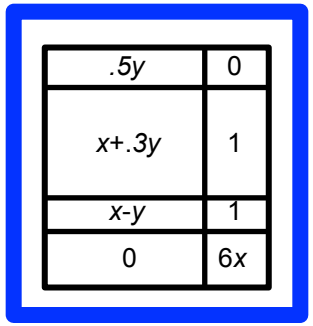
- **Piecewise continuous functions**
  - *Subsumption generalization* for representational primitives
    - N-ary predicates become N-dimensional functions
  - Embodies aspects of both discrete and continuous functions
    - Exact for discrete and symbolic functions
    - Can represent some continuous functions exactly and approximate others as closely as needed
- **Factor graphs w/ summary product algorithm**
  - *Implementation generalization* for complex reps. and processing
  - Generalizes over algorithms underlying many capabilities
    - Implement memories, decisions, etc.

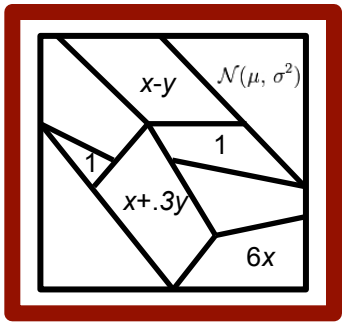
Both are relevant to bridging all listed dichotomies

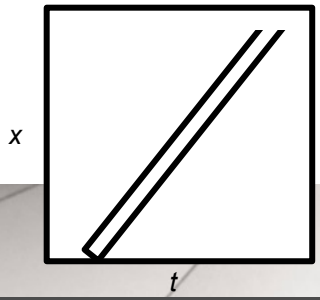
Space of Piecewise Continuous Functions

- **Types of regions**
  - Hypercubes (squares, cubes, etc.)
  - Hyperrectangles/orthotopes (rectangles, etc.)
  - Polytopes (polygons, etc.)
- **Types of functions over regions**
  - Constant, linear, polynomial, exponential, Gaussian, wavelet, ...
- **Additional sources of variation**
  - Axially aligned or not (for hypercubes/orthotopes)
  - Totally explicit or inactive regions implicit
  - Local borders or space-wide slices









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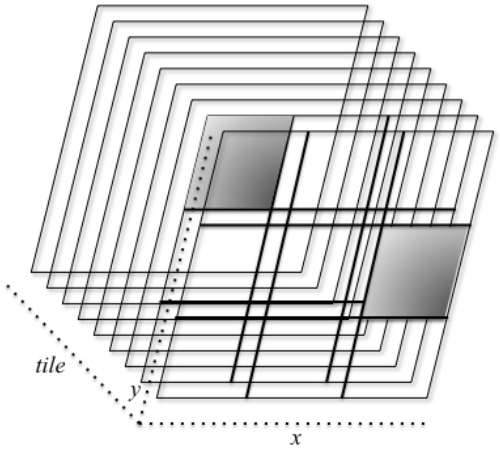
Examples

- **Working memory**
  - `(O1 ^color Green) (O2 ^color Yellow) (O3 ^color Yellow) (O4 ^color Red)`

	Red	Green	Yellow	Blue
O1	0	1	0	0
O2	0	0	1	0
O3				
O4	1	0	0	0

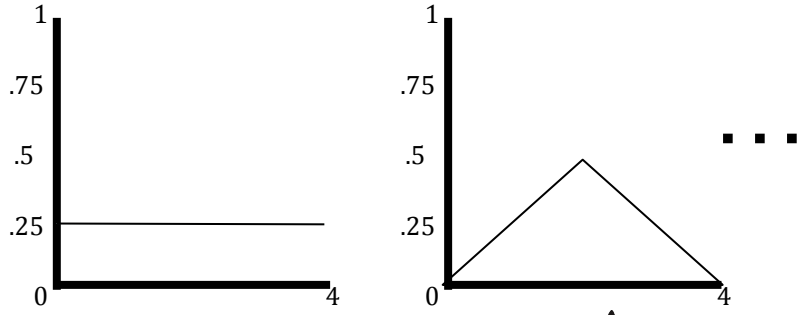
- **Mental imagery**



- **Episodic memory**

operator \ time	1	2	3	4	5
Left	1	0			0
Right	0	0			0
Up					
Down	0	1			0

- **Probability densities**



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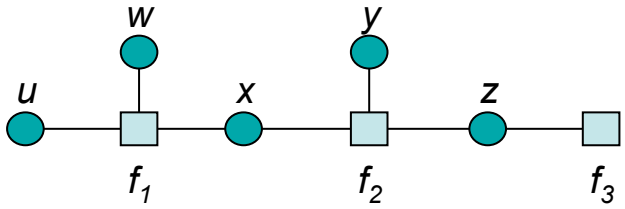
Factor Graphs w/ Summary Product

- **Factor graphs are the most expressive form of GM**
  - More complex rep. + inference

$$f(u,w,x,y,z) = f_1(u,w,x)f_2(x,y,z)f_3(z)$$

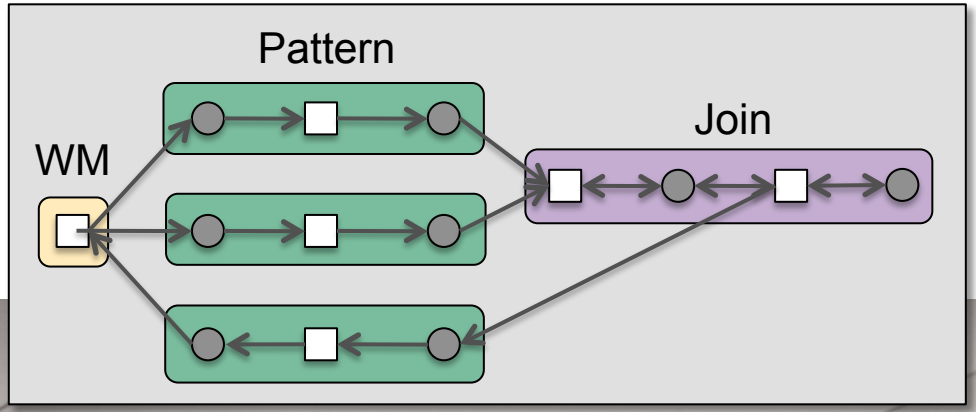


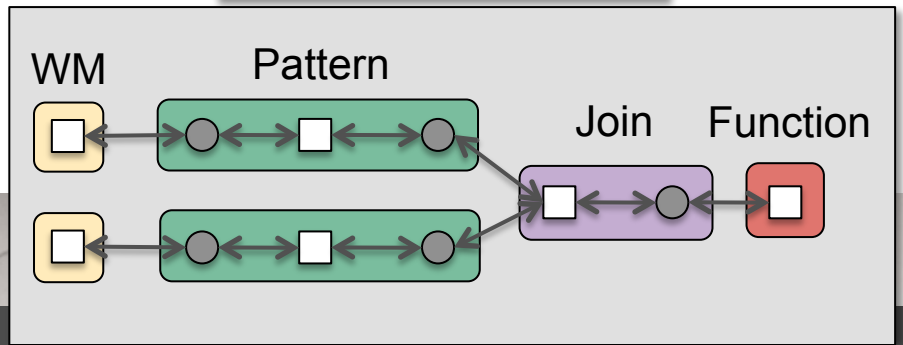
- **Summary product processes messages on links**
- **Implements a generalized conditional language**

```
CONDITIONAL Transitive
    conditions: (Next ob1:a ob2:b)
                (Next ob1:b ob2:c)
    actions:    (Next ob1:a ob2:c)
```

```
CONDITIONAL Concept-Weight
    condacts:  (concept object:O1 class:c)
               (weight object:O1 value:w)
    function:
```

w\c	Walker	Table	…
[1,10>	.01w	.001w	…
[10,20>	.2-.01w	"	…
[20,50>	0	.025-.00025w	…
[50,100>	"	"	…





Some Recent Results

- **Decision making**
- **Mental imagery**
- **Episodic learning**
- **Statistical question answering**
- ***Prediction-based supervised learning***

Decision Making

- **Preferences encoded via actions and functions**

```
CONDITIONAL goal-best ; Prefer operator that moves a tile into its desired location
     :conditions (blank state:s cell:cb)
                 (acceptable state:s operator:ct)
                 (location cell:ct tile:t)
                 (goal cell:cb tile:t)
     :actions (selected states operator:ct)
     :function 10

CONDITIONAL previous-reject ; Reject previously moved operator
     :conditions (acceptable state:s operator:ct)
                 (previous state:s operator:ct)
     :actions (selected - state:s operator:ct)
```

- **Most processing happens in graph via SP algorithm**
- **Complete implementation of Eight Puzzle**
  - 747 nodes (404 variable, 343 factor)
  - Solves a simple problem in 9 decisions
    - 113 messages/decision, 2.5 seconds/decision
- **Also initial implementation of reflection, but slow(er)**

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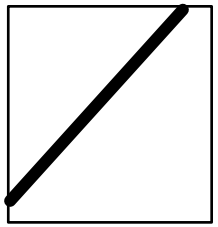
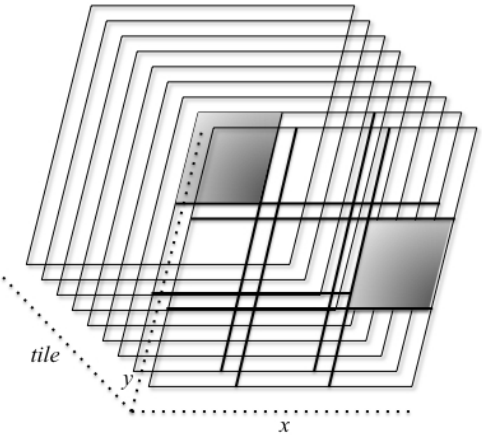
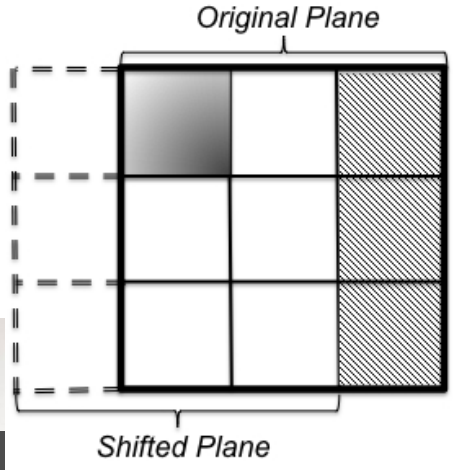
Mental Imagery

- **Beginnings of mental imagery**
  - 2D imagery with translation operation
- **Translation requires an angled, shifted delta function**
  - Need extended functional form for efficiency in uniform rep.
  - Implemented a special purpose optimization: *offset* factors
    - Also currently important in reflection and may be relevant to EM
- **Need 3D, time, scaling, rotation, …**
- **Need more focus on predicate extraction**



```
CONDITIONAL Move-Right
   :conditions (selected state:s operator:o)
               (operator id:o state:s x:x y:y)
               (board state:s x:x y:y tile:t)
               (board state:s x:x+1 y:y tile:0)
   :actions (board state:s x:x+1 y:y tile:t)
            (board – state:s x:x y:y tile:t)
            (board state:s x:x y:y tile:0)
            (board – state:s x:x+1 y:y tile:0)
```





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Episodic Learning

- **Initialize LTM with a temporal prior and an EM conditional for each predicate that includes state**

```
CONDITIONAL Time
 Condacts: (Time value:t)
 Function: [1,2) — .6667t
```

```
CONDITIONAL Time-Selected
 Condacts: (Time value:t)
           (Selected state:0 operator:op)
 Function: [1,∞)×[Left,Right,Up,Down] — 1
```

- **History of top-level state in WM is recorded in temporal slices of functions in EM conditionals**

operator

	1	2	3	4	5
Left	1	0			0
Right	0	0			0
Up					
Down	0	1			0

time

Final region extends to ∞, implicitly extrapolating to future

- **Scope & slope of temporal prior updated each cycle**

```
Function: [1,5) — .0833t
```

- **Retrieve best previous state given cues by SP/max**

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Statistical Question Answering

- **The NPCEditor learns to choose appropriate answers to questions from statistics gathered over pairs of questions and answers**
  - Also has additional dialogue components that can affect choice
- **Implemented Bayesian computation of language model of answers given question**

$$P(a,Q) = \sum_{s} \varphi(a,s) \prod_{i} \phi(s,q_i)$$

  - Compiled sentence-pair statistics into semantic memory
  - Can be used directly to choose best answer
- **Extending to full Kullback-Liebler divergence**

$$D\big(P(Q)||P(A)\big) = \sum_{a} P(a|Q) \log \frac{P(a|Q)}{\pi_A(a)}$$

- **Also looking to further extend capabilities and run scale-up experiments**

Plans

- **Continue with mental imagery**
  - Including extending function representation
- **Pervasive prediction**
  - Decisions choose next operator *and* predict next situation
  - Support perception, understanding, learning, appraisal, …
- **Implement more complete learning capability**
  - Based on predictions, actuals and dependencies
  - Chunking, reinforcement, supervised and unsupervised
- **Pursue further capabilities**
  - Theory of Mind, behavior understanding, speech and natural language, perceptuomotor behavior (SLAM), …
- **Evaluate, optimize and apply architecture**

Gold

- On path to bridge dichotomies
- Decisions, reflection and beginnings of imagery with little additional code
  - Continued promise of *functional elegance*
  - Step towards *tight integration*
- Getting experience with data-driven statistical processing
  - A significant step towards *broad spectrum*
- First bit of learning
- Lots of exciting projects starting

Coal

- Still little learning and no true perception
- Function representation needs significant rethinking
- Speed of code becoming an issue