Graphical Models for Cognitive Architecture
Resolving the Diversity Dilemma

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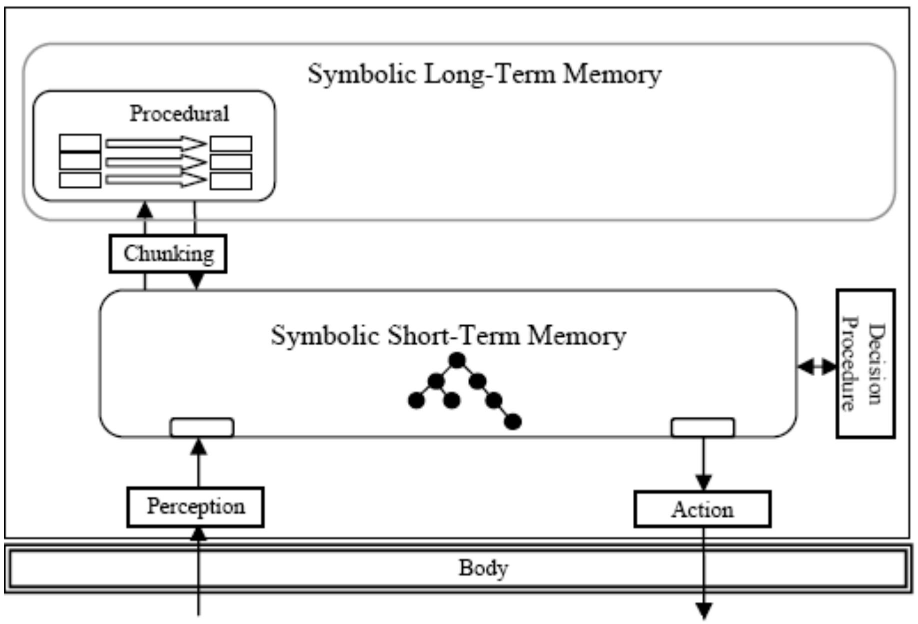
The Diversity Dilemma

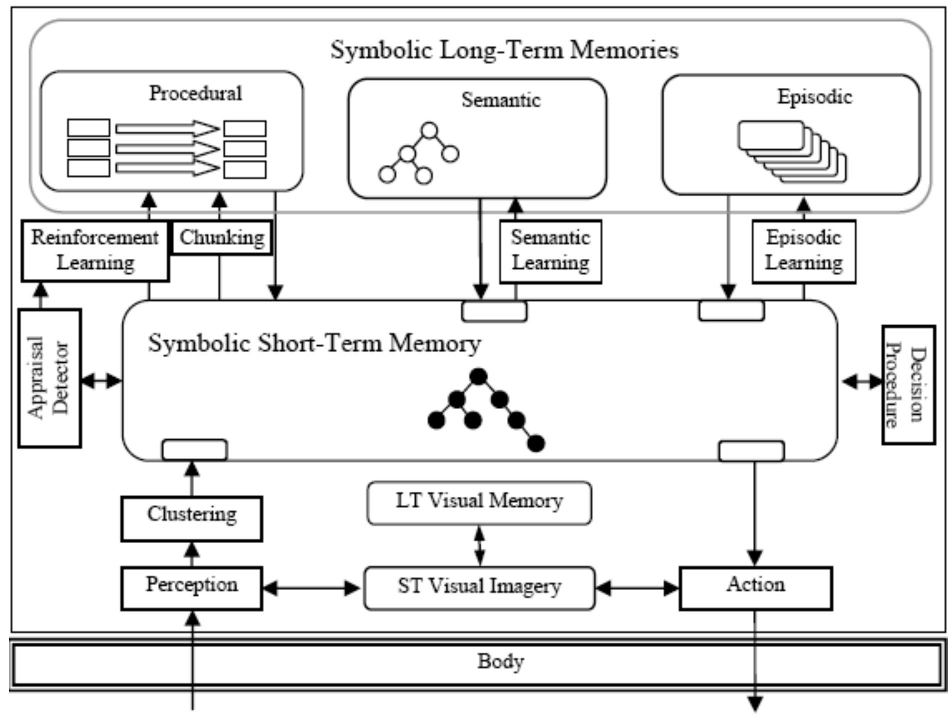
- Should an architecture's mechanisms be uniform or diverse?
- *Uniformity*: Minimal mechanisms combining in general ways
  - Appeals to simplicity and elegance
  - The "physicist's approach"
  - *The Challenge*: Achieving full range of required functionality/coverage
- *Diversity*: Large variety of specialized mechanisms
  - Appeals to functionality and optimization
  - The "biologist's approach"
  - The Challenge: Achieving integrability, extensibility and maintainability
- Want best of both worlds, but a choice seems inevitable
  - Functionality tends to win, leading to the predominance of diversity
  - But is there another way out?

Example: Soar

- Through version 8 was a uniform architecture
- Version 9 has become highly diverse



Soar 3-8



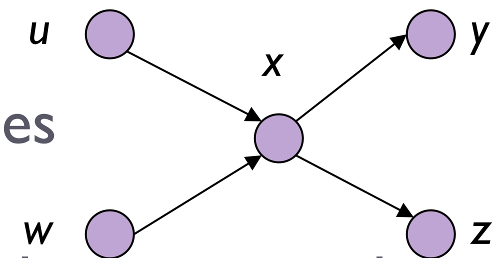
Soar 9

Proposal for Resolving the Dilemma

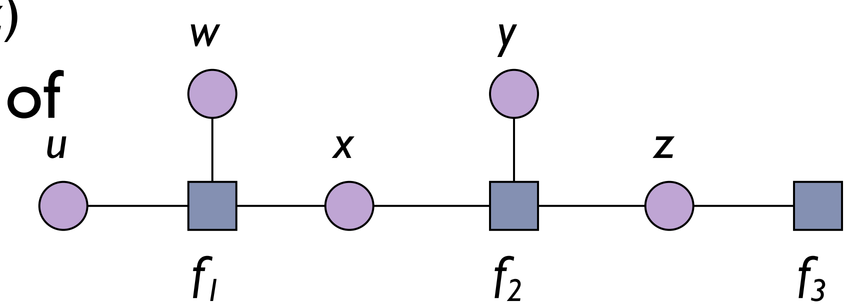
- Dig beneath architecture for uniformity at *implementation level* that supports diversity/functionality in architecture (and above)
  - Implementation level is normally just Lisp, C, Java, etc.
    - Impacts efficiency and robustness but usually not part of theory unless based on neural networks
- Base implementation level on *graphical models* for a uniform approach to symbol, probability and signal processing
  - Related to neural networks but broader
- Reconceive architectures via new implementation level
  - Reimplement, enhance and hybridize existing architectures
  - Develop new architectures
  - *Improve elegance, functionality, extensibility, integrability and maintainability*

Graphical Models

- Efficient computation with multivariate functions
  - By decomposition over partial independencies
  - For constraints, probabilities, speech, etc.
- Come in a variety of related flavors
  - **Bayesian networks**: Directed, variable nodes
    - E.g, $p(u,w,x,y,z) = p(u)p(w)p(x|u,w)p(y|x)p(z|x)$



  - **Markov networks**: Und., variable nodes & clique potentials
    - Basis for *Markov logic* and *Alchemy*
  - **Factor graphs**: Und., variable & factor nodes
    - E.g., $f(u,w,x,y,z) = f_1(u,w,x)f_2(x,y,z)f_3(z)$
- Compute marginals via variants of
  - Sum-product (message passing)
  - Monte Carlo (sampling)



Potential for the Implementation Level

- State-of-the-art algorithms for *symbol*, *probability* and *signal* processing all derivable from the *sum-product algorithm*
  - Belief propagation in Bayesian networks
  - Forward-backward in hidden Markov models
  - Kalman filters, Viterbi algorithm, FFT, turbo decoding
  - Arc-consistency in constraint diagrams
- Potential to go beyond existing architectures to yield an effective and uniform basis for:
  - Fusing symbolic and probabilistic reasoning (mixed)
  - Unifying cognition with perception and motor control (hybrid)
  - Bridging from symbolic to neural processing
- Raises hope of a uniform implementation level that integrates broad functionality at the architecture level

Scope of Sum-Product Algorithm

Message/Variable Range \ *Message/Variable Domain*	Discrete	Continuous
Boolean	Symbols	
Numeric	Probability (Distribution)	Signal & Probability (Density)

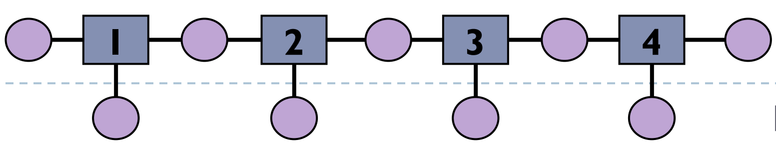
- *Mixed* models combine Boolean and numeric ranges
- *Hybrid* models combine discrete and continuous domains
- *Hybrid mixed* models combine all possibilities
- *Dynamic hybrid mixed* models add a temporal dimension

Research Strategy

- Goals
  - Evaluate extent to which graphical models can provide a uniform implementation layer for existing architectures
  - Develop novel, more functional architectures
    - Enhancing and/or hybridizing existing architectures
    - Starting from scratch leveraging strengths of graphical models
- Initial approach
  - Reimplement and enhance the Soar architecture
    - One of the longest standing and most broadly applied architectures
    - Exists in both uniform (Soar ≤8) and diverse (Soar 9) forms
  - Start from the bottom up, implementing uniform version while looking for opportunities to more uniformly incorporate Soar 9's diversity plus critical capabilities beyond all versions of Soar

Progress to Date

- *Elaboration cycle* implementation via factor graphs
  - **Production match**
  - Production firing
- *Decision cycle* implementation via Alchemy (Markov logic)
  - **Elaboration phase**
  - Decision procedure
- With both also went beyond existing capability
  - *Lower complexity bound* for production match
    - Most recently, also began extension of WM beyond symbols
  - *Mixed* elaboration phase with simple *semantic memory* and *trellises*
- Still preliminary, partial implementations
  - Sufficient to demonstrate initial feasibility
  - Insufficient for full evaluation of impact on uniformity and functionality



Simple Mapping of Production Match onto Factor Graphs

P1: Inherit Color

C1: (<v0> ^type <v1>)

C2: (<v1> ^color <v2>)

-->

A1: (<v0> ^color <v2>)

Model as a Boolean function:

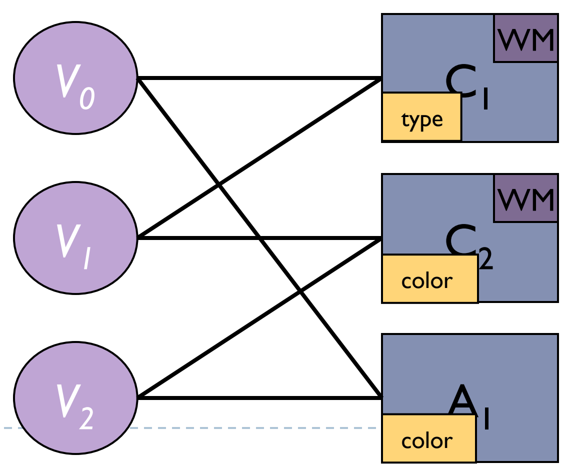
$P_1(v_0,v_1,v_2) = C_1(v_0,v_1)C_2(v_1,v_2)A_1(v_0,v_2)$

WM is 3D Boolean array (*obj* x *att* x *val*)

- 1 when triple in WM
- 0 otherwise

Messages are Boolean vectors

- 1 when variable value possible
- 0 when variable value ruled out



Constant tests hidden in factors

WM is embedded in factors

Confuses binding combinations

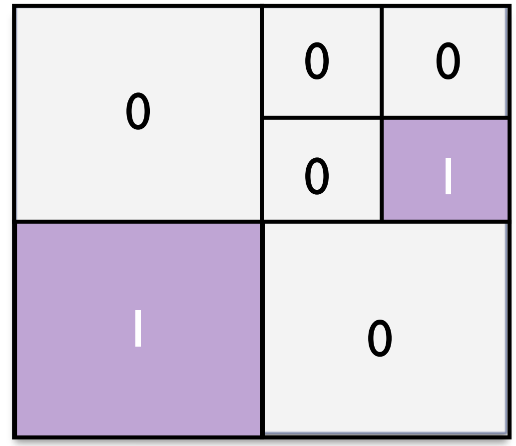
May not check if rule completely matches

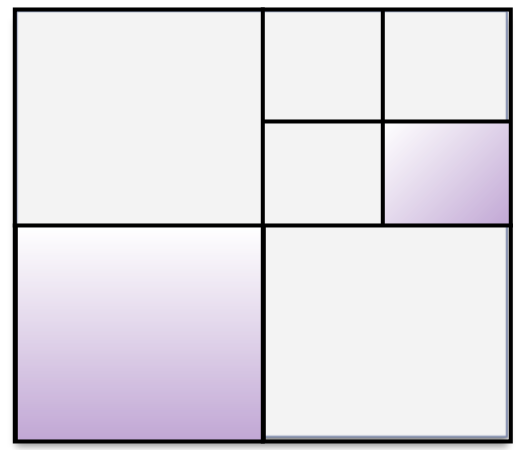
Factor Graph Results

- Four issues have been resolved, yielding a new match algorithm
  - Tracks variable binding combinations only as needed
  - Complexity bound is exponential in *treewidth* rather than conditions
  - Avoids some duplicate instantiations on a cycle
  - Combines discrimination (α) and join (β) activities in uniform graph
- Solutions to binding confusion and rule matching increase number of rule variables processed at variable nodes
  - Yields exponential growth in message size and processing cost
  - Need to leverage tendency towards uniform values in WM and messages to reduce space and time costs
    - WM is nearly all 0 while messages are nearly all 1 or 0

Hierarchical Memories and Messages

- N dimensional variant of *quad/octrees (exptrees)*
  - If entire space has one value, assign it to region
  - Otherwise, partition space into 2^N regions at next level, and recur
- WM & messages are *piecewise constant* functions
- Recently extended to *piecewise linear* functions
  - E.g., in 3D: $f(\langle x,y,z\rangle, r) = A_r + B_{r,1}x + B_{r,2}y + B_{r,3}z$
  - Natural compact representation for probabilities, signals, images, etc.
    - Also handles symbols by setting the Bs to 0
  - *Implemented mem. but not yet all of sum-product*
    - *Product implemented with reapproximation*
- Could also consider more adaptive partitioning that clusters/reorders symbolic data points into regions based on patterns in the data





Support of spatial reasoning with time dimension?

Example Match Times

P1: Inherit Color

C1: (<v0> ^type <v1>)

C2: (<v1> ^color <v2>)

-->

A1: (<v0> ^color <v2>)

With solutions to all four problems, rule graph comprises 8 factor nodes and 8 variable nodes.

WM is 16^3 in size, with 4 wmes

	Sum of Products	**Redistribute P over S**
Arrays	*Exceeded heap space*	1.7 sec.
Hierarchies	132 sec.	.25 sec.

~7

~500

Unoptimized Lisp

Implementing Soar's Elaboration Phase via Alchemy (Markov logic)

- Markov logic = First order logic + Markov networks
  - Compiles weighted FOL into a ground Markov logic network
    - Node for each ground predicate
    - Weight for each ground clause (clique potentials)
      - Along with links among all nodes in ground clause
- Goals for implementation
  - Explore a *mixed* elaboration phase (rules & probabilities)
  - Explore semantic (fact) memory and *trellises*
  - Enable bidirectional message flow across rules
    - Normal elaboration cycle only propagates information forward
    - But need bidirectional settling for correct probabilities and trellises

Analogous to compilation of RL rules?

Encoding

- Convert productions into logical implications
  - Define types for objects and values of triples
    - colors={Red, Blue, Green} and objects = {A, B, C, D, E, F}
  - Define predicates for attributes
    - Color(objects, colors) and Type(objects, objects)
  - Specify implications/clauses for rules
    - (Type(v0, v1) ^ Color(v1, v2)) => Color(v0, v2).
  - Add weights to clauses as appropriate

P1: Inherit Color

C1: (<v0> ^type <v1>)

C2: (<v1> ^color <v2>)

-->

A1: (<v0> ^color <v2>)

- Initialize evidence (db file) with WM
  - Color(C, Red), Color(D, Blue), Type(A, C), Type(B, D)
- Semantic memory: weighted ground predicates: 10 Color(F, Green)
- Trellis: define via a pair of implications (*accept* & *reject* prefs.)
  - Size(step, size) => Size(step+1, size*2).
  - (Size(step, size1) ^ size1!=size2) => !Size(step, size2).

Alchemy Results

- Mapping basically works (modulo trellis strangeness)
  - Mixed representation with simple semantic memory and trellises
- Match occurs via graph compilation not message propagation
  - As Alchemy compiles first-order clauses to ground network
    - All symbolic reasoning in compilation and probabilistic in propagation?
  - Falls short of uniform processing in the graph itself
- Implies a three phase decision cycle
  1. Compile/match to generate a ground/instantiated network
  2. Perform probabilistic inference in the ground network
  3. Decide
- Exptrees yield variants of Alchemy's *laziness* and *lifting*
  - Deal with *default values* and *groups of elements* processed in same way

Locality Implications

- Alchemy, and systems like it, get stuck in local minima
  - Generally considered a problem, but is it really?
- If Alchemy maps onto Soar's decision cycle then it only needs to perform K-Search
  - Conceptualize K-Search functionally as yielding local minima?
  - If so, then finding global minima, in general, requires PS-Search
- Implication would be that Alchemy should just yield local minima, but it also needs PS-Search on top of it
  - The same might then be said for all one-level, logical and/or probabilistic inference systems

Locality Implications (cont.)

- Taking this a step further, we can hypothesize functionally that:
  - Elaboration Cycle (10 ms): Local propagation of information
  - Decision Cycle (100 ms): Global propagation but only local minima
  - Problem Space Search (≥ 1 sec): Global minima (via sequence of local minima)
- But this implies that the elaboration cycle can't do global propagation of information
  - Explicit global: Creating unique identifiers
  - Implicit global: Non-monotonic (negated conditions, operator applications)
  - Accessing all of working memory?
- Could Soar function if global propagation were limited to the decision cycle?
  - I may need to answer this for a graphical implementation of Soar

Minerals

Gold

- New approach to cognitive architecture
  - Via a uniform graphical implementation level
    - Uncertain symbolic processing
    - Signal processing in inner loop
    - Potential bridge to neural
  - May resolve diversity dilemma
    - Improving elegance, scope, integrability and maintainability
- Early results on elaboration cycle/phase are encouraging
  - New match algorithm with improved complexity bound
  - Mixed elaboration phase with semantic memory and trellises

Coal

- Far from complete architecture
  - Combine two experiments
  - Add decisions, impasses, chunking
  - Incorporate Soar 9 extensions
- Locality may be Achilles heel
  - Or mapping from mechanism to implementation may be so complex as to lose benefits of uniformity in implementation
- May be too slow for actual use
- A common implementation level need not guarantee clean integrability
- Need to show not just more elegance, but increased utility