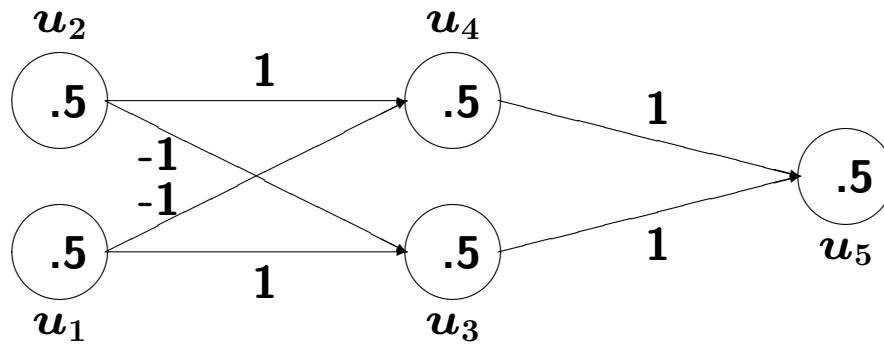


Spreading of Activation

▶ Feed forward networks: no loops.

▶ **Example**



Reflexive Reasoning

- ▶ Humans are capable of performing a wide variety of cognitive tasks with extreme ease and efficiency.
- ▶ For traditional AI systems, the same problems turn out to be intractable.
- ▶ Human consensus knowledge: about 10^8 rules and facts.
- ▶ Wanted: “Reflexive” decisions within sublinear time.

SHRUTI

Shastri, Ajjanagadde: *From Associations to Systematic Reasoning: A Connectionist Representation of Rules, Variables and Dynamic Bindings using Temporal Synchrony.* Behavioural and Brain Sciences 16, 417-494: 1993.

SHRUTI – Knowledge Base

- ▶ Finite sets of constants \mathcal{A}_C , variables \mathcal{A}_V and relation symbols \mathcal{A}_R .
- ▶ Rules:
 - ▷ $(\forall X_1 \dots X_m) (p_1(\dots) \wedge \dots \wedge p_n(\dots)) \rightarrow (\exists Y_1 \dots Y_k) p(\dots)$
 - ▷ $p, p_i, 1 \leq i \leq n$ multi-place predicate symbols
 - ▷ arguments of the p_i : variables from $\{X_1, \dots, X_m\} \subseteq \mathcal{A}_V$
 - ▷ arguments of p are from $\{X_1, \dots, X_m\} \cup \{Y_1, \dots, Y_k\} \cup \mathcal{A}_C$
 - ▷ $\{Y_1, \dots, Y_k\} \subseteq \mathcal{A}_V$
 - ▷ $\{X_1, \dots, X_m\} \cap \{Y_1, \dots, Y_k\} = \emptyset$
- ▶ Facts and queries (goals):
 - ▷ $(\exists Z_1 \dots Z_l) q(\dots)$
 - ▷ multi-place predicate symbol q
 - ▷ arguments of q are from $\{Z_1, \dots, Z_l\} \cup \mathcal{A}_C$
 - ▷ $\{Z_1, \dots, Z_l\} \subseteq \mathcal{A}_V$

Further Restrictions

- ▶ **Restrictions to rules, facts, and goals:**
 - ▶ **No function symbols except constants.**
 - ▶ **Only universally bound variables may occur as arguments in the conditions of a rule.**
 - ▶ **All variables occurring in a fact or goal occur only once and are existentially bound.**
 - ▶ **An existentially quantified variable is only unified with variables.**
 - ▶ **A variable which occurs more than once in the conditions of a rule must occur in the conclusion of the rule and must be bound when the conclusion is unified with a goal.**
 - ▶ **A rule is used only a fixed number of times.**

- ▶ **SHRUTI is incomplete.**

SHRUTI – Example

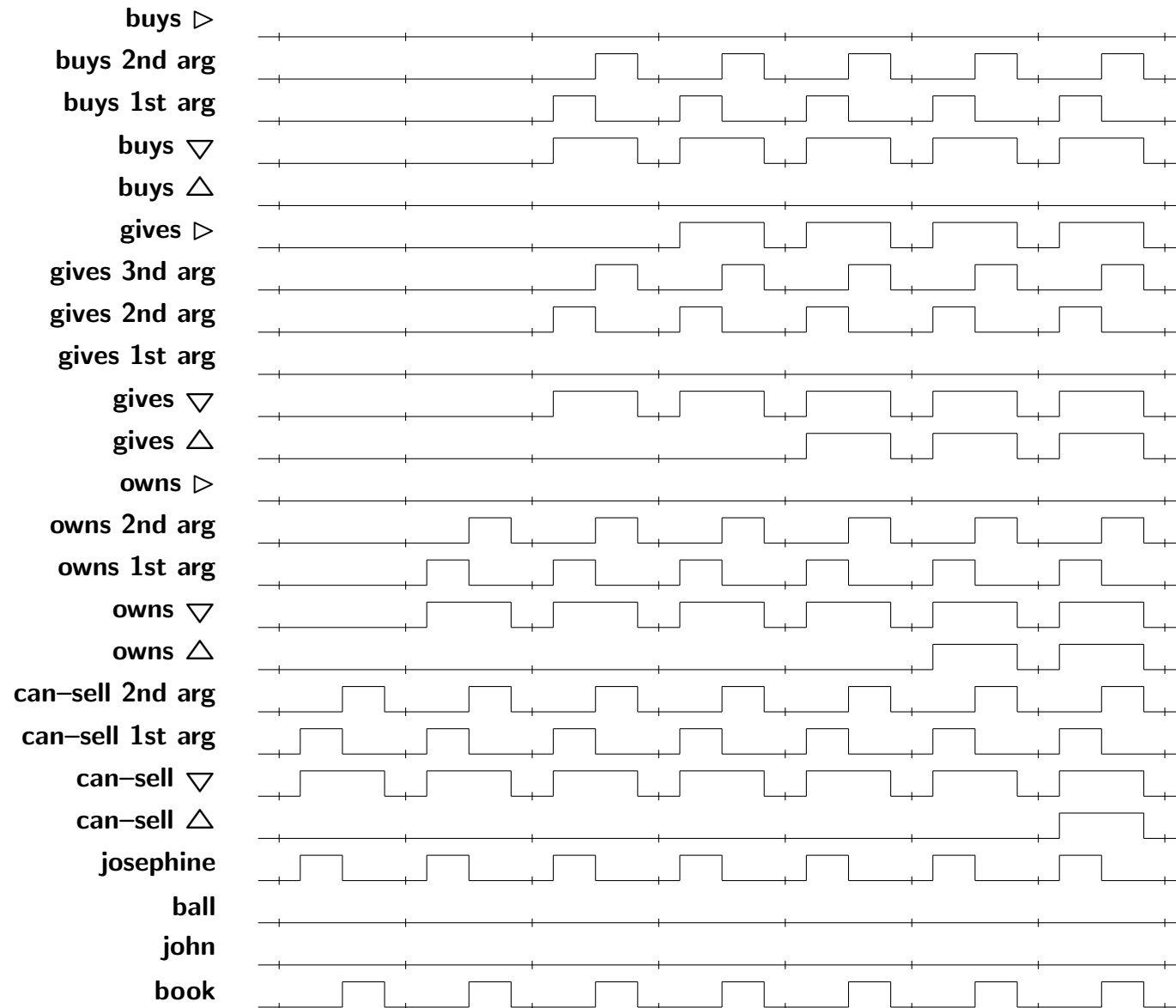
► Knowledge base:

$gives(X, Y, Z) \rightarrow owns(Y, Z),$
 $buys(X, Y) \rightarrow owns(X, Y),$
 $owns(X, Y) \rightarrow can-sell(X, Y),$
 $gives(john, josephine, book),$
 $(\exists X) buys(john, X),$
 $owns(josephine, ball)$

► Queries:

$owns(josephine, book) \rightsquigarrow \text{yes}$
 $(\exists X) owns(josephine, X) \rightsquigarrow \text{yes} \quad \{X \mapsto book\}$
 $\{X \mapsto ball\}$

Solving the Variable Binding Problem



SHRUTI – Remarks

- ▶ Answers are derived in time proportional to depth of search space.
- ▶ Number of units as well as of connections is linear in the size of the knowledge base.
- ▶ Extensions:
 - ▷ compute answer substitutions
 - ▷ allow a fixed number of copies of rules
 - ▷ allow multiple literals in the body of a rule
 - ▷ update the network asynchronously
 - ▷ built in a taxonomy
- ▶ ROBIN (**Lange, Dyer: 1989**): signatures instead of phases.
- ▶ Biological plausibility.
- ▶ Trading expressiveness for time and size.

An Exercise

- ▶ Construct a SHRUTI network for the following rules and facts:

buys (steffen, X) → cheap (X) ∧ beautiful (X).

buys (antje, X) → quality (X).

cheap (swatch)

cheap (ball)

beautiful (ball)

quality (rolex)

How long does it take for the network to find the answer for *buys (X, ball)*?

Another Exercise

- ▶ Consider the following knowledge base:
 - ▷ If X is chasing Y then Y is afraid of X .
 - ▷ Cats are chasing birds.
 - ▷ Cats and birds are animals.
 - ▷ Canaries and parrots are birds.
 - ▷ Tweety is a canary.
 - ▷ Lora is a parrot.
 - ▷ Sylvester is a cat.
- ▶ Represent this knowledge as a set of rules and facts using an *is-a* predicate to represent hierarchical dependencies.
- ▶ Construct an extended SHRUTI network for this knowledge base, where the extensions should be able to handle hierarchical structures. In particular, the network should be able to answer questions like *afraid(birds, cats)*.

A Logical Reconstruction

▶ $F \models G$ iff $(F \wedge \neg G)$ is unsatisfiable.

▶ Skolemization: Let

$$\begin{aligned}\theta_1 &= \{Y_1 \mapsto f_1(X_1, \dots, X_m), \dots, Y_k \mapsto f_k(X_1, \dots, X_m)\}, \\ \theta_2 &= \{Z_1 \mapsto c_1, \dots, Z_l \mapsto c_l\},\end{aligned}$$

where

- ▶ f_i : pairwise different Skolem functions,
- ▶ c_j : pairwise different Skolem constants,
- ▶ $f_i, c_j \notin \mathcal{A}_C$.

▶ Then

$$\begin{aligned}(\forall X_1 \dots X_m) (p_1(\dots) \wedge \dots \wedge p_n(\dots) \rightarrow (\exists Y_1 \dots Y_k) p(\dots)) \\ \rightsquigarrow p_1(\dots) \wedge \dots \wedge p_n(\dots) \rightarrow p(\dots)\theta_1, \\ (\exists Z_1 \dots Z_l) q(\dots) \rightsquigarrow q(\dots)\theta_2.\end{aligned}$$

Parallel SLD-resolution

- ▶ **Problems:**
 - ▶ Variables may be bound differently in different branches of the search space.
 - ▶ If the body of a clause contains two occurrences of the same variable in different subgoals, then the binding generated for this variable by solving the two subgoals must be the same.
- ▶ Restrictions imposed by SHRUTI allow parallel search in the space generated by SLD-resolution

The Connection Method

- ▶ Equivalent to an SLD-resolution for Horn clauses.
- ▶ Allows for a global view on a proof.
- ▶ Usually: affirmative method for proving validity of formulas.
- ▶ Here: dual version for proving unsatisfiability of sets of Horn clauses.

Connections and Spanning Sets

- ▶ A **connection** is an unordered pair of literal occurrences with the same predicate symbol but different signs.
- ▶ A literal L is **connected** in a set S of connections iff S contains L as an element of a connection.
- ▶ A set S of connections is **spanning** wrt $(F \wedge \neg G)$ **iff**
 - ▷ each literal occurring in G is connected in S ,
 - ▷ if the head of (a copy of) a clause in F is connected in S , then each literal occurring in its body is also connected in S .
- ▶ A spanning set is **minimal** iff there is no spanning subset.
- ▶ **Theorem** A spanning set S of connections for $(F \wedge \neg G)$ determines a proof for $\models (F \rightarrow G)$ **iff** there is a substitution θ such that θ simultaneously unifies each connection in S .

Reductions

- ▶ Connections between non-unifiable literals can be removed.
- ▶ A clause is **useless** if its conclusion is not connected or its condition contains an unsolvable subgoal.
 - ▶ Useless clauses can be removed.
- ▶ A connection $\langle L, L' \rangle$ is **isolated** if L and L' are ground or not engaged in any other connection.
 - ▶ Unifiable isolated connections can be evaluated, i.e., the corresponding clauses may be replaced by their resolvent.
 - ▶ Non-unifiable isolated connections can be removed.

More Reductions

- ▶ A connection $\langle p(s_1, \dots, s_n), \neg p(t_1, \dots, t_n) \rangle$ is isolated in its i -th argument iff either
 - the connected literals are not engaged in any other connection or
 - s_i and t_i are ground or
 - s_i is ground and $\neg p(t_1, \dots, t_n)$ is not engaged in any other connection or
 - t_i is ground and $p(s_1, \dots, s_n)$ is not engaged in any other connection.
- ▶ If s_i and t_i are unifiable with substitution θ then the corresponding clauses can be instantiated by θ .
- ▶ If s_i and t_i are not unifiable, then the connection can be removed.

Influence of Restrictions in SHRUTI

- ▶ **Only constants and variables.**
 - ▷ **No complex data structures by unification.**
- ▶ **Only universally quantified variables in conditions of rules.**
 - ▷ **Skolemization does not change these conditions.**
- ▶ **All variables in a fact are existentially bound and removed by skolemization.**
 - ▷ **All facts are ground.**
- ▶ **Existentially bound variables in the head of a rule are replaced by Skolem functions.**
 - ▷ **They can only be unified with variables. Such bindings are not propagated.**
- ▶ **Variables which occur more than once in the conditions of a rule must also occur in the head of a rule and must be bound to a constant when the head is unified.**
 - ▷ **Subgoals in conditions can be solved independently and in parallel.**
- ▶ **Rules are used only a fixed number of times.**
 - ▷ **Logic becomes decidable.**
- ▶ **Alltogether, the underlying logic is decidable in linear time and linear space.**

Final Remarks

- ▶ SHRUTI is not the most efficient parallel system for reflexive reasoning.
- ▶ Reflexive reasoning is reasoning by reductions.
- ▶ Theorem provers applying reduction techniques in parallel are more adequate.
- ▶ Are common sense reasoning problems expressible in the logic underlying SHRUTI?
- ▶ Beringer, H.: *On the Adequateness of the Connection Method*. In: *Proceedings of the AAAI National Conference on Artificial Intelligence*, 9-14: 1993.