3.5 Revisiting Jackendoff's Challenges

- **The Binding Problem.** How to combine concepts into a new concept? ⇒ Binding operators

$$\texttt{RED} \circledast \texttt{SQUARE} + \texttt{BLUE} \circledast \texttt{CIRCLE}$$

- **The Problem of Two.** How can the same concept be active in two different contexts? ⇒ Use symbols denoting the role. (Little star besides big star)

$$\begin{aligned} \texttt{OBJ1} \circledast (\texttt{TYPE} \circledast \texttt{STAR} + \texttt{SIZE} \circledast \texttt{LITTLE}) + \\ \texttt{OBJ2} \circledast (\texttt{TYPE} \circledast \texttt{STAR} + \texttt{SIZE} \circledast \texttt{BIG}) + \\ \texttt{REL} \circledast \texttt{BESIDES} \end{aligned}$$

- **The Problem of Variables.** How to express rules containing variables? ⇒ Use inverse and role designators

$$\begin{aligned} \texttt{RULE} &= \texttt{RED} \circledast \texttt{NOUN} \\ \texttt{VAR} &= \texttt{NOUN}^{-1} \circledast \texttt{BALL} \\ \texttt{RULE} \circledast \texttt{VAR} &\approx \texttt{RED} \circledast \texttt{BALL} \end{aligned}$$

- **Working vs. Long-Term Memory.** How to manifest symbols in working and long-term memory? ⇒ NEF: neural activities ⇝ working memory, connection weights ⇝ functions (e.g., associative memory)

THE SEMANTIC POINTER ARCHITECTURE

1. Introduction

- VSAs: solve interesting cognitive tasks (Raven's Progressive Matrices, Jackendoff's Challenges)
- But: not a cognitive architecture → unclear how to build a behaving agent

⇒ Semantic Pointer Architecture (SPA)

  - What is a semantic pointer?
  - Working memory
  - Action selection

2. Semantic Pointers Combination of several concepts

- VSAs (binding operator, circular convolution)
- NEF (computational substrate, neurons)
- Source of vectors: reversible compression/decompression (dereferencing $\rightsquigarrow$ semantic pointer, deep semantics)
- Architecture: basal ganglia/cortex control loop

$\Rightarrow$ can build small and large scale models

$\Rightarrow$ flexible architecture, solve multiple tasks within the same model (SPAUN)

2.1 Deep vs. Shallow semantics

- Related to the "symbol grounding problem"
- Shallow semantics: relational
- Deep semantics: symbols link at "subjective experience"
- Example for shallow semantics: random vectors, word embeddings
- word2vec example:

$$\texttt{WOMAN} + (\texttt{KING} - \texttt{MAN}) \approx \texttt{QUEEN}\,,$$
$$\texttt{SPACE} + (\texttt{SHIPS} - \texttt{WATER}) \approx \texttt{SPACESHIP}\,.$$

2.2 Deep Semantics for Perception

- Example: visual processing in cortex
- Dimensionality reduction/compression from layer to layer
- First layer: high-dimensional visual input
- Final layer: semantic pointer
- Can decompress: clamp semantic pointer and compute most likely intermediate layer representations (i.e., "mental imagery")

2.3 Deep Semantics for Action

- Decompress low-dimensional semantic pointer
- Input: high-level action ("grab bottle")
- Output: body muscle tensions over time
- See HTBAB for an example (Chp. 3)

2.4 Using Semantic Pointers in Nengo

- *See example*

2.5 SPAUN

- *See slides*

3. Serial Working Memory

- Can use high-dimensional integrator for (working) memory
- Bind elements to position semantic pointer

$$\begin{aligned} \texttt{WM} &= \texttt{ITEM\_A} \circledast \texttt{POS\_1} + \texttt{ITEM\_B} \circledast \texttt{POS\_2} \\ &= \texttt{ITEM\_A} \circledast \texttt{POS} + \texttt{ITEM\_B} \circledast \texttt{POS} \circledast \texttt{POS} \end{aligned}$$

- In humans: primacy and recency effects
- Can model using two separate systems