Lecture 9: Search - 8

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Blackboard Architecture

- Example of More Complex Search Paradigm
- Reference article:

  Erman, L.D., Hayes-Roth, F., Lesser, V.R., and Reddy, D.R. (1980). "The HEARSAY-II Speech Understanding System: Integrating Knowledge to Resolve Uncertainty." *Computing Surveys 12*, (2), pp. 213–253.

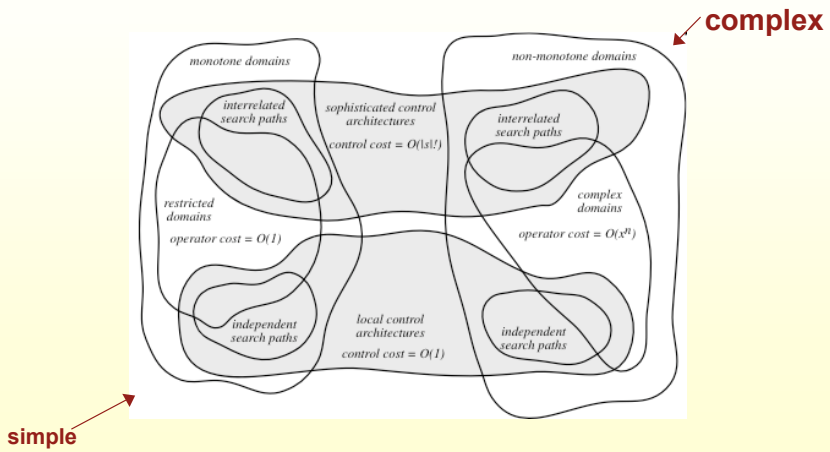
  Additional Reading (Optional):

  Carver, N. and Lesser, V. (1992). "The Evolution of Blackboard Control Architectures." Computer Science Technical Report 92–71, University of Massachusetts, Amherst. (This is a revised and extended version of paper with same title in *Expert Systems with Applications— Special Issue on the Blackboard Paradigm and Its Applications*.)

Blackboard Problem Solving

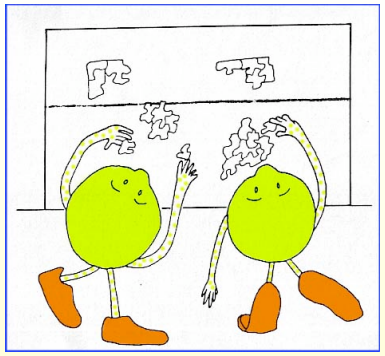
- **Multi-Level Search**
  - Integrated Search across multiple problem representations
- **Interdependence of Search Paths**
  - Information can be mined from the results of other search paths
  - Leads to problem solving associated with control
- **Non-Monotonic Domain**
  - Can't use A* type of heuristic to guarantee completeness
- **Cost of Control Expensive/Non-uniform cost of operator application**
  - Node evaluation cost is dynamic and expensive
  - Ratings need to be re-evaluated when new nodes are created
  - More complex choice process for next node to expand
    - Take into account cost of operator application which can vary depending on node and operator

Defining Sophisticated Search



BB Problem Solving Model

Solving Jigsaw Puzzles



- **Solution finding is viewed as an integrated search process**
  - –On different levels of abstraction
  - –On different perspectives
  - –On different partial solutions

- **No *a priori* order for people contributing**
  - Incremental and opportunistic construction
- **Cooperative behavior mediated by blackboard**
  - Group of experts in a medical staff meeting

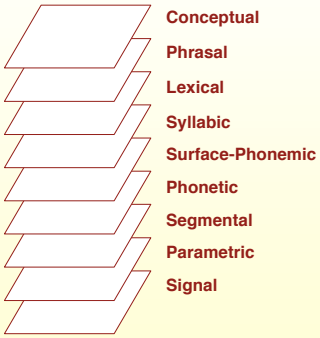
- **Work from:**
  - middle → out
  - left-to-right
  - where the constraints are

BB Search Operators -- Knowledge Sources

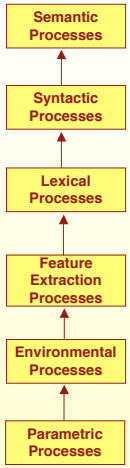
- **Function of a KS:**
  - Know when it has something useful to contribute (data-directed)
  - Generate hypotheses
  - Evaluate hypotheses
- **Structure of a KS: independent and separable**
  - Large Grain Computation
  - Other KSs are not dependent on existence of other KSs
- **Attention focusing of KSs:**
  - Limited context for a KS's execution
  - Control decoupled from data environment
  - Sensitive to current state

A system is composed of many diverse knowledge sources (KSs)

Organizing A Multi-Level Search



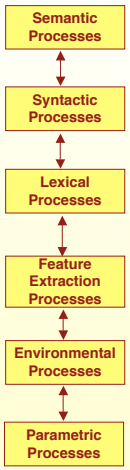
Levels of Representation for Speech Understanding Systems



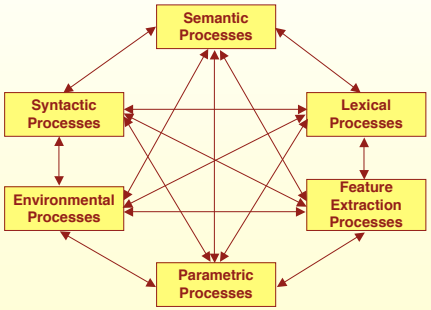
The hierarchical model

Other Models

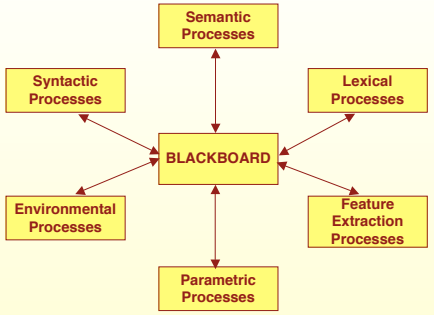
The Goal-directed Model



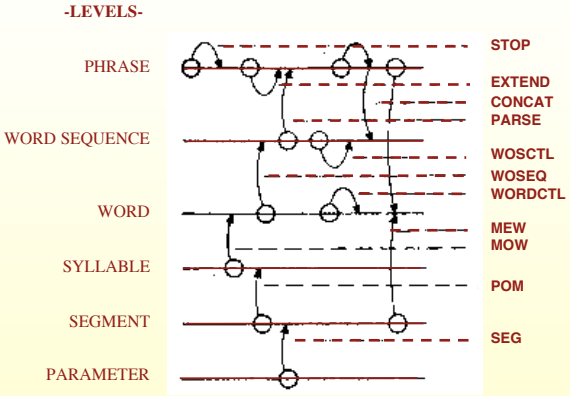
The Heterarchical Model



Blackboard Model



Emphasizing Cooperating Experts



At all levels: RPOL

Appropriate Problem Domains

- **Problem with very large and complex search spaces**
  - Computationally intractable to generate entire search space
    - Generally impossible to guarantee optimality of solution
  - Incremental generation of partial solutions
  - Aggregation of constraints
  - Search space may be viewed in terms of different perspectives and levels of abstraction
  - Constraint optimization

Knowledge-Rich Domain Problem Solving

- **Problem which requires large amounts of knowledge**
  - Applicable knowledge covers wide, diverse set of areas
  - Knowledge may be partitioned in terms of specific areas
  - Knowledge and input data may be errorful, incomplete and approximate

Knowledge-Rich Control Strategies

- **Opportunistic Processing**
  - Problem solving should be driven by current state of problem solving and available knowledge applicable to this state
  - Cooperation among different sources of knowledge which permit resolution of ambiguous situation and correction of incorrect decisions
- **Knowledge Acquired Along Different Search Path can be exploited in making control decisions**
- **Adapting Control Strategies based on state of search**

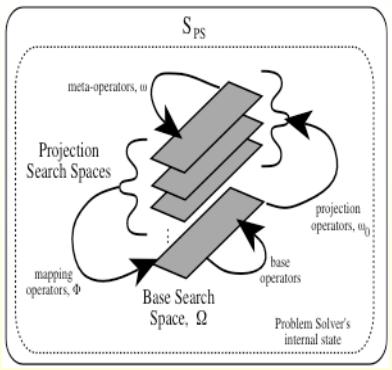
Applications

- **Planning and scheduling**
  (Intelligent Material Handling, Factory Scheduling)
- **Data Interpretation/Situation Assessment**
  (Speech and Vision Understanding, Multi-sensor Fusion)
- **Layout and Arrangement**
  (Protein Molecular Layout, Building Design)

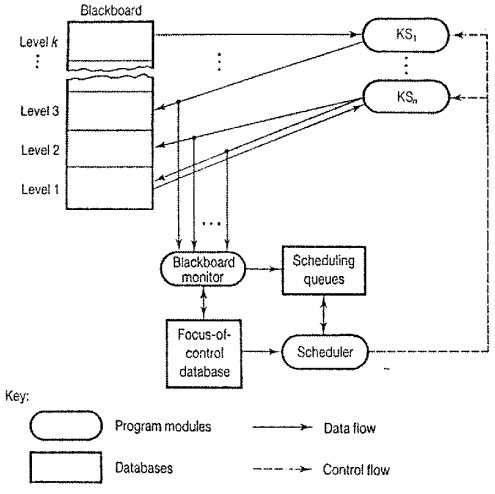
Review of Blackboard Architecture

Sophisticated Problem Solving Search:

- **multi-level**
- **incremental**
- **opportunistic**
- **non-monotonic**
- **expensive and non-uniform operator costs**
- **sophisticated control**



Hearsay-II Architecture



Blackboard Control

- **Application of knowledge is triggered by current state of blackboard (data directed)**
- **Based on blackboard events:**
  - A change to the blackboard (addition, deletion, modification)
  - Non-occurrence of an expected change
- **Trigger evaluation of preconditions of relevant KS**
- **KS whose preconditions are satisfied is instantiated with appropriate context and placed on scheduling queue (agenda)**
- **Focus of attention mechanism evaluates agenda and chooses for execution KS(s) that are most promising for further system progress**
- **KS(s) are executed and alter state of blackboard, trigger new blackboard events**

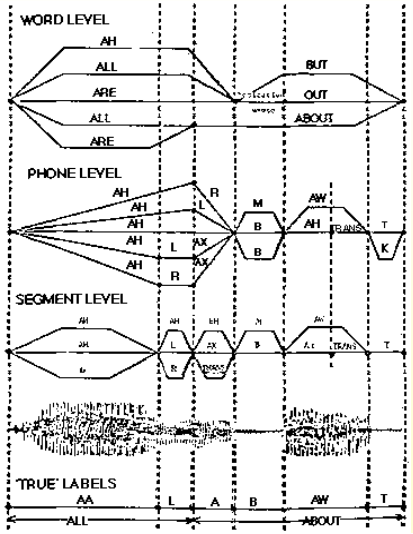
Blackboard Structure

- **Partitioned into distinct information levels**
  - Each level holds a different representation of the problem space, with its own primitive elements
- **KS decomposition relates naturally to one or a few information levels**
  - Localization of KS activity
- **Levels form a loose hierarchical structure**
  - Abstraction of elements of the next lower level
  - An *a priori* framework of a plan for problem solving
  - Analysis/synthesis action between levels

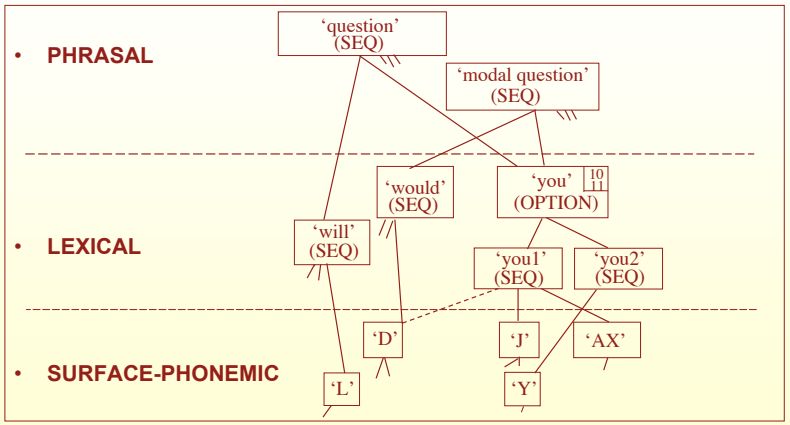
Blackboard Nodes

- **Nodes (partial solutions) exist at particular level and associated with a primitive element**
  - Each level has associated with it a vocabulary that defines the range of primitive elements
  - Each node has a set of attributes that can be level-dependent
- **Nodes can be related to other nodes at the same or different levels**
  - Explicitly through links and Implicitly based on node attributes
- **Nodes may represent alternative competing partial solutions**
  - Permits direct comparison of alternative search paths
  - Integrated representation of alternative search paths

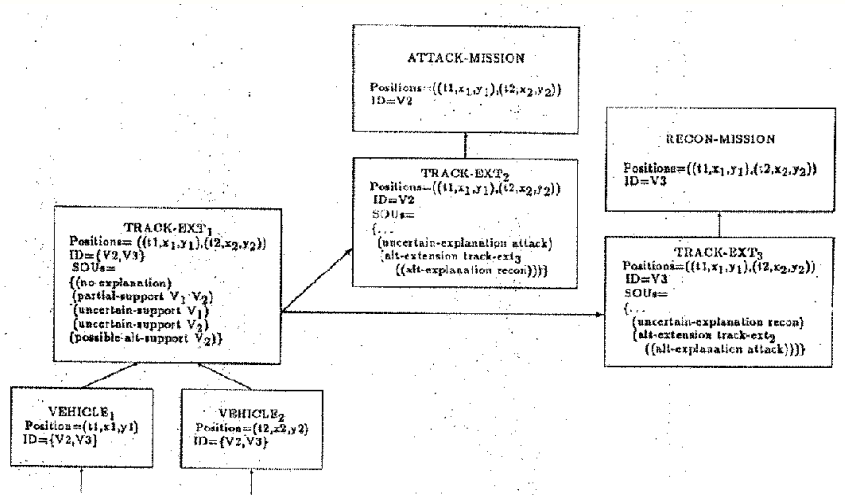
Implicit linking of Nodes through Time



Explicit Linking of Nodes



Evidential Representation for Node Hypotheses



Knowledge Source Structure (KS)

- **Trigger** specifies a set of event predicates that need to be true for KS to be considered for execution
- **Precondition** specifies a set of state predicates that need to be true for KS to execute
- **Context** specifies where KS will be applied (KSAR)
- **Obviation** condition specifies a set of state-based predicates that if all true indicate KS/Context is to be removed from agenda
- **KS action** arbitrarily complex program
- **Declarative Information** used for scheduling

An Example Knowledge Source: Yoke KS *(Hayes-Roth, '86)*

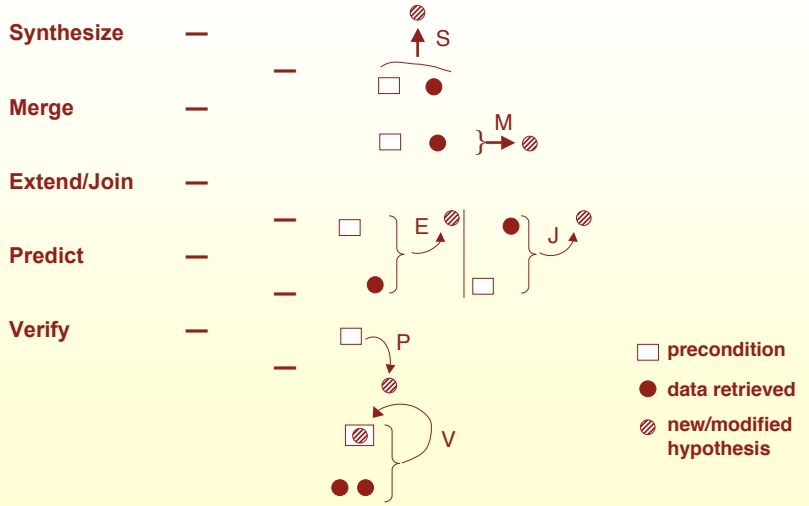
Name: Yoke-Structures
Trigger Conditions:
((**$EVENT-LEVEL-IS STRUCTURAL SOLID**)
(**$EVENT-TYPE-IS Modify**)
(**$CHANGED-ATTRIBUTE-IS APPLIED-CONSTRAINTS**)
(**$SET Possible-Combinations (Get-Possible-Combinations $TRIGGER-OBJECT**)))
Context Variables:
((**PS-Anchor Anchoree1 Anchoree2**) **Possible Combinations**)
Preconditions:
((**$SET Yoking-Info (There-is-Yoking-Info-For Anchoree1 Anchoree2**))
(**$VALUE Anchoree1 'Applied-Constraints**)
(**$VALUE Anchoree2 'Applied-Constraints**))
Obviation Conditions: **NIL**
KS Variables:
((**NewLocLabelForAnchoree1 (Generate-LocTableLabel PS-Anchor Anchoree 1**
(**LENGTH ($VALUE Anchoree 1 'Legal Orientations**))))
(**NewLocLabelForAnchoree2 (Generate-LocTableLabel PS-Anchor Anchoree2**
(**LENGTH ($VALUE Anchoree2 'Legal-Orientations**))))
(**Descriptor 1(Make-Descriptor-For-Yoke PS-Anchor Anchoree1 Anchoree2**))
(**Descriptor2(Make--Descriptor-For-Yoke PS-Anchor Anchoree2 Anchoree1**)))
Actions:
((**1 (T)**
(**EXECUTE ($SET YokeResult (Yoke-Structures PS-Anchor**
Anchoree1 Anchoree2
(CADAR (LAST ($VALUE Anchoree1 'Legal-Orientations)))
(CADAR (LAST ($VALUE Anchoree2 'Legal-Orientations)))
NewLocLabelForAnchoree1 Descriptor1
NewLocLabelForAnchoree2 Descriptor2
(LENGTH Yoking-Info) Yoking-Info VanderWaalsCheck?))))
(**2 (T)....**

Instantiated KS (KSAR) on Scheduling Queue

NAME - KSAR50
TRIGGER-EVENT - ANCHOR-HELIX modifying attributes of HELIX1
ContextVars - ((PS-Anchor Helix1)
(Anchoree1 Helix3)
(Anchoree2 Helix2))
KS - Yoke-Structures
BoundVars - ((NewLocLabelForAnchoree1 Hel1inHel3-5)
(NewLocLabelForAnchoree2 Hel1inHel2-4)
(Descriptor1 Yoke-Helix3-andHelix2-around-Helix1)
(Descriptor2 Yoke-Helix2-and-Helix3-around-Helix1))
ExecutableCycle - 18
ScheduledCycle - NIL
ExecutedCycle - NIL
Status - EXECUTABLE

A Yoke-Structures KSAR. Yoke-Structures has been triggered by a modification of helix1's applied-constraints. This KSAR represents the blackboard context in which helices 2 and 3 have constraints with one another and with helix1. Since both helices have previously identified locations, the KSAR is executable.

Generic Interpretation KSs



Issues in BB Control

- **How to decide which of many potential KS instantiations are the most preferred**
  - How to compare apples and oranges
  - Different levels and parts of seach space
- **How to control the potential for combinatorial explosion of hypotheses on the blackboard**
  - Overhead significantly increases as large number of partial solutions are placed on BB
- **How to decide when the system has an acceptable solution**
  - Non-monotonic character of search

Hearsay-II Speech Understanding System

Information Retrieval Based on Interpreting Connected Speech

Sample sentences:

"Which abstracts refer to theory of computation?"

"List those articles."

"What has McCarthy written since 1974?"

Why Connected Speech Understanding is Difficult

- **Large search space**
  - ≈10^8 legal sentences
- **Uncertainty and Approximate Knowledge**
  - Sensors
  - Acoustic phonetic knowledge
- **Knowledge costly to apply**
- **Difficult to subdivide problem solving**
- **Interacting constraints**
  - Co-articulation phenomenon
- **Wide variety of knowledge needs to be applied**

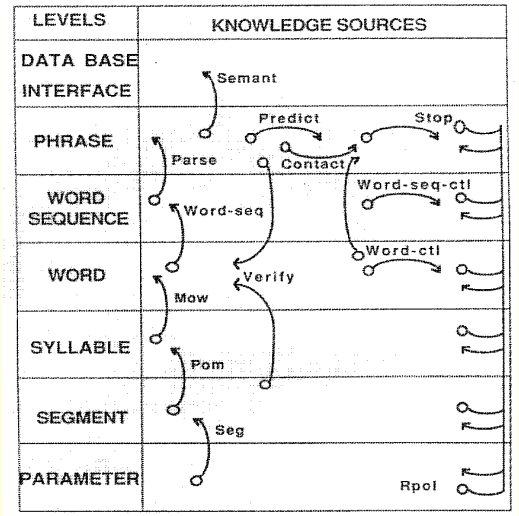
Interpretation is a "Hard" Problem

- **Combinatorial number of possible interpretations**
- **Data-related uncertainty**
  - Noisy,uncertain, and/or missing data
  - Masking phenomena
  - Incomplete domain model
- **Correlation ambiguity**
  - Multiple, indeterminate number of instances of each interpretation and data type
  - "data-association problem"
- **Volume of data too large to be completely processed**
- **Multi-sensor fusion**

Hearsay-II Speech Understanding System

- **BB levels**
- **Knowledge sources**
- **Control Strategy**
- **Trace**

Functional Description of the Speech-Understanding KSs



Hearsay-II Knowledge Sources

- ***Signal acquisition, parameter extraction, segmentation and labeling***
  - SEG: digitizes the signal, measures parameters and produces a labeled segmentation
- ***Word spotting***
  - POM: creates syllable-class hypotheses from segments
  - MOW: creates word hypotheses from syllable classes
  - WORD-CTL: controls the number of word hypotheses that MOW creates
- ***Phrase-island generation***
  - WORD-SEQ: creates word-sequence hypotheses that represent potential phrases from word hypotheses and weak grammatical knowledge
  - WORD-SEQ-CTL: controls the number of hypotheses that WORD-SEQ creates
  - PARSE: attempts to parse a word sequence and, if successful, creates a phrase hypothesis from it

Hearsay-II Knowledge Sources, *cont'd*

- ***Phrase extending***
  - PREDICT: predicts all possible words that might syntactically precede or follow a given phrase
  - VERIFY: rates the consistency between segment hypotheses and a contiguous word-phrase pair
  - CONCAT: creates a phrase hypothesis from a verified contiguous word-phrase pair
- ***Rating, halting, and interpretation***
  - RPOL: rates the credibility of each new or modified hypothesis, using information placed on the hypothesis by other KSs
  - STOP: decides to halt processing (detects a complete sentence with a sufficiently high rating, or notes the system has exhausted its available resources) and selects the best phrase hypothesis or set of complementary phrase hypotheses as the output
  - SEMANT: generates an unambiguous interpretation for the information-retrieval system which the user has queried

Abstract State Space Through Approximate Knowledge

Approximate K_1 by $\tilde{K}_1$

$\rightarrow$ more errors/uncertainty

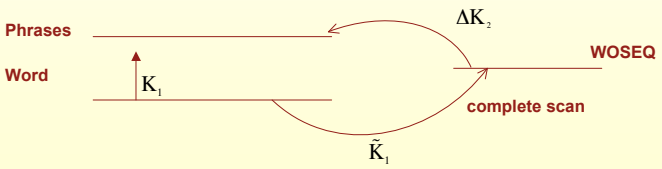
Correct with ΔK_2

Win if $\text{Cost}(\tilde{K}_1 + \Delta K_2) < \text{Cost}(K_1)$

$K_1 = \text{PARSE}$

$\tilde{K}_1 = \text{WORD} - \text{SEQ's matrix}$

$\Delta K_2 = \text{PARSE applied to sequences}$



Basic Control Cycle

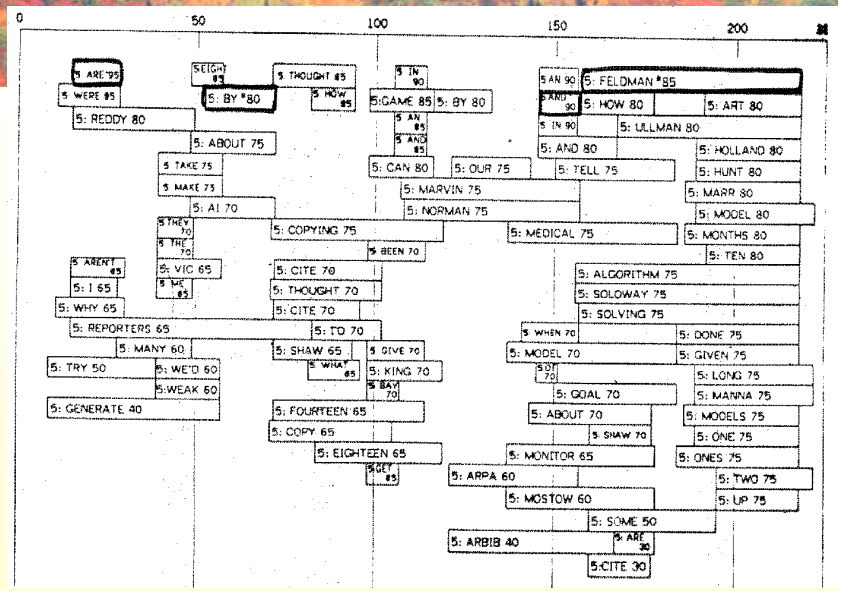
- **Scheduler invokes highest-rated KS with specific context**
  - Check before running whether precondition still valid
- **KS modifies blackboard**
  - Focus-of-control database is updated
  - Relevant precondition procedures are notified
- **Relevant precondition procedures are evaluated**
  - New KS instances are posted on scheduler with context
- **Priority of new KS instances are calculated and those old ones are affected by change in control database**

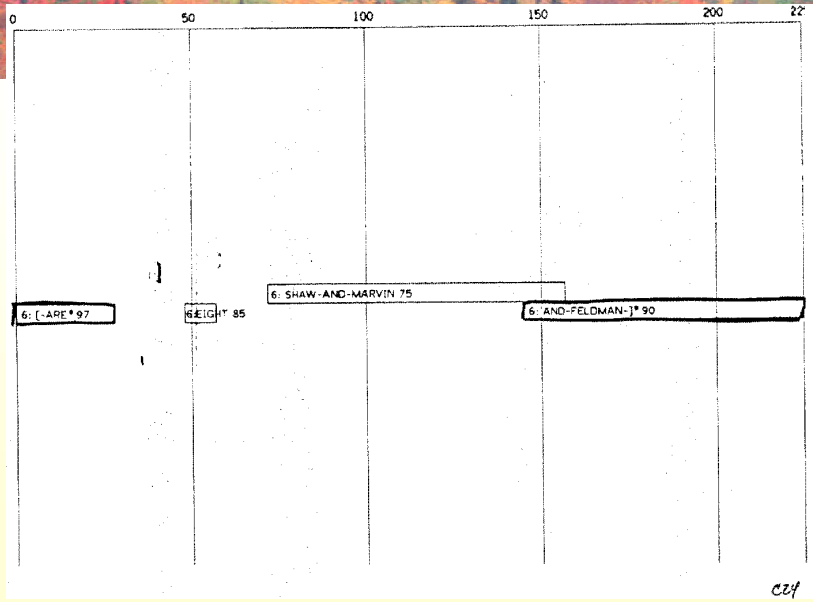
Control Strategy

- **Bottom-up processing to word level**
  - Sufficient reliability for opportunistic processing
- **KS as generator functions**
  - Limited generation of alternatives
  - Retriggered to generate additional hypotheses as search stagnates
- **Select sequence of word hypotheses as candidates for phrase hypotheses**
- **Opportunistic search at Phrase Level**
  - Islands-of-reliability
  - Integrate partial phrases coming from different directions
  - Fill out words not bottom-hypothesized

Control Strategy, cont'd

- **If search not progressing, retrigger KSs for more hypotheses**
  - Implement with control KSs stimulated by agenda
- **Search termination**
  - Special mode when a spanning hypothesis is constructed of sufficient credibility
  - Use hypotheses to constrain further search





Trace of Hearsay-II

1. KS: SEG
   Stimulus: Creation of ZAPDASH parameters for the utterance.
   Action: Create segment hypotheses.
2. KS: WORD-CTL
   Stimulus: Start of processing.
   Action: Create goal hypotheses at the word level. These will control the amount of hypothesization that MOW will do.
3. KS: WORD-SEQ-CTL
   Stimulus: Start of processing.
   Action: Create goal hypotheses at the word-sequence level. These will control the amount of hypothesization that WORD-SEQ will do.
4. KS:POM
   Stimulus: New segment hypotheses.
   Action: Create syllable-class hypotheses

Trace of Hearsay-II, *p.2*

5. KS:MOW
   Stimulus: New syllable hypotheses.
   Action: Create word hypotheses.
6. KS:WORD-SEQ
   Stimulus: New words created bottom-up.
   Action: Create 4-word sequence hypotheses:
   AND-FELDMAN-]* (90, 145:225),
   [-ARE* (97,0:28),
   SHAW-AND-MARVIN(75,72:157),
   EIGHT(85,48:57).
7. KS:PARSE*
   Stimulus: [-ARE* (word sequence)
   Action: Create phrase: [+ARE* (97,0:28)

Trace of Hearsay-II, *p.3*

8. KS:PARSE*
   Stimulus: AND-FELDMAN-]* (word sequence)
   Action: Create phrase: AND + FELDMAN +]* (90, 145:225)
9. KS:PARSE
   Stimulus: EIGHT (word sequence)
   Action: Create phrase: EIGHT (85,48:57)
10. KS:PARSE
    Stimulus: SHAW-AND-MARVIN (word sequence)
    Action: Create phrase: SHAW+AND+MARVIN (75,72:157),

Trace of Hearsay-II, *p.4*

11. KS:PREDICT & VERIFY*
    Stimulus: [+ ARE* (phrase)
    Action: Predict (from the grammar) 292 words following.
    Reject (using the acoustic information) 277 of them. The four highest-rated of the fifteen verified words are
    REDDY (85,26:52),
    ANY* (65,24:49),
    HUGH (55,30:39), and
    YOU (55, 28:39).
12. KS:CONCAT
    Stimulus: [+ ARE* (phrase), REDDY (word)
    Action: Create phrase: [+ ARE + REDDY(91,0:52)
13. KS: CONCAT*
    Stimulus: [+ ARE* (phrase), ANY* (word)
    Action: Create phrase: [+ ARE + ANY* (86,0:49)

Trace of Hearsay-II, *p.5*

14. KS:PREDICT & VERIFY*

Stimulus: AND + FELDMAN +]* (phrase)

Action: Predict 100 words preceding. Reject 76 of them. The best of the verified 24 (in descending rating order) are

FEIGENBAUM* (80,72:150),
WEIZENBAUM (70,72:150),
ULLMAN (70,116:150),
NORMAN (70, 108:150), and
NEWBORN (70, 108:150).

15. KS:PREDICT & VERIFY

Stimulus: EIGHT (phrase)

Action: Predict the word NINE following and verify it (80,52:82).

Predict SEVEN preceding, but reject this because of mismatch with the acoustic segments.

Trace of Hearsay-II, *p.6*

16. KS:CONCAT*

Stimulus: FEIGENBAUM* (word), AND + FELDMAN +]* (phrase)

Action: Create phrase: FEIGENBAUM + AND + FELDMAN +]* (85,72:225)

17. KS: PREDICT & VERIFY*

Stimulus: FEIGENBAUM + AND + FELDMAN +]* (phrase)

Action: Predict eight preceding words. Reject one (DISCUSS).

Find two already on the blackboard:

BY* (80,52:72) and
ABOUT (75,48:72).

Verify five others:

NOT(75,49:82),
ED(75,67:72),
CITE(70,49:82),
QUOTE(70,49:82),
CITES(65,49:82).

Trace of Hearsay-II, *p.7*

18. KS:CONCAT*

Stimulus: BY* (word), FEIGENBAUM + AND + FELDMAN +]* (phrase)

Action: Create phrase: BY + FEIGENBAUM + AND + FELDMAN +]* (84,52:225)

19. KS:CONCAT

Stimulus: ABOUT (word), FEIGENBAUM + AND + FELDMAN +]* (phrase)

Action: Create phrase: ABOUT+FEIGENBAUM+AND+FELDMAN +] (83,48:225)

20. KS:PREDICT & VERIFY

Stimulus: ABOUT+FEIGENBAUM+AND+FELDMAN +] (phrase)

Action: Predict one preceding word: WHAT. Verify it (10,20:49).

Trace of Hearsay-II, *p.8*

21. KS:CONCAT

Stimulus: CITE (word), FEIGENBAUM + AND + FELDMAN +] (phrase)

Action: Create phrase: CITE + FEIGENBAUM + AND + FELDMAN +] (83,49:225)

22. KS:PREDICT & VERIFY

Stimulus: CITE + FEIGENBAUM + AND + FELDMAN +] (phrase)

Action: Predict four preceding words. Reject two of them:

BOOKS, PAPERS. Verify

THESE(25, 28:49),
YEAR(20,30:49).

Trace of Hearsay-II, *p.9*

23. KS: PREDICT & VERIFY*
    Stimulus: BY + FEIGENBAUM + AND + FELDMAN +]* (phrase)
    Action: Predict 10 preceding words. Reject five:
    ABSTRACTS, ARE, BOOKS, PAPERS, REFERENCED. Find two already on the blackboard:
        ANY* (65, 24:49),
        THESE(25,28:49).
    Verify three more:
        ARTICLE(25,9:52),
        WRITTEN(25,24:52),
        ARTICLES(10,9:52).

24. KS: CONCAT
    Stimulus: NOT (word), FEIGENBAUM + AND + FELDMAN +]*
    Action: Create phrase:
    NOT + FEIGENBAUM + AND + FELDMAN +] (83,49:225)

Trace of Hearsay-II, *p.10*

25. KS: CONCAT*
    Stimulus: ANY* (word),
    BY + FEIGENBAUM + AND + FELDMAN +]* (phrase)
    Action: Create phrase:
    ANY + BY + FEIGENBAUM + AND + FELDMAN +]* (82,24:225)
    [+ ARE + ANY + BY + FEIGENBAUM + AND + FELDMAN +]* (85,0:225) is also created, from
    [+ ARE + ANY and BY + FEIGENBAUM + AND + FELDMAN +].

26. KS:STOP
    Stimulus: [+ ARE + ANY + BY + FEIGENBAUM + AND + FELDMAN +]* (complete sentence)
    Action: Deactivation of several dozen competing hypotheses.

Trace of Hearsay-II, *p.11*

27. KS:PREDICT & VERIFY
    Stimulus: [+ ARE + REDDY
    Action: Predict three following words. Verify CITED (60, 52:86), OR(30,52:67), AND(25,52:82).

28. KS:CONCAT
    Stimulus: [+ARE* (phrase), HUGH (word)
    Action: Create phrase: [+ HUGH + YOU (83, 0:39)

29. KS:CONCAT
    Stimulus: [+ ARE (phrase), YOU (word)
    Action: Create phrase: [+ ARE + YOU (83,0:39)

30. KS:CONCAT
    Stimulus: [+ ARE + REDDY (phrase), CITED (word)
    Action: Create phrase: [+ ARE + REDDY + CITED (80,0:86)

Trace of Hearsay-II, *p.12*

31. KS:PREDICT & VERIFY
    Stimulus: [+ ARE + REDDY + CITED (phrase)
    Action: Predict two following words. Verify BY(75,83:98), IN (20,86:114).

32. KS:CONCAT
    Stimulus: [+ ARE + REDDY + CITED (phrase), BY (word)
    Action: Create phrase: [+ ARE + REDDY + CITED + BY (80,0:98).

33. KS:PREDICT & VERIFY
    Action: Predict one following word. Verify ANY(30,105:126).

34. KS:PREDICT & VERIFY
    Stimulus: [+ ARE + HUGH (phrase)
    Action: Predict one following word. Verify NAGEL(40,42:63).

Trace of Hearsay-II, *p.13*

35. KS:PREDICT & VERIFY

Stimulus: [+ ARE + YOU (phrase)

Action: Predict three following words. Reject USUALLY.

Verify

REGULARLY(25,39:116),

ALWAYS(15,39:72).

36. KS:CONCAT

Stimulus: [+ ARE + REDDY (phrase), OR (word)

Action: Create phrase: [+ ARE + REDDY + OR (79,0:67).

37. KS:CONCAT

Stimulus: [+ ARE + REDDY (phrase), AND (word)

Action: Create phrase: [+ ARE + REDDY + AND (78,0:82).

Trace of Hearsay-II, *p.14*

38. KS:STOP

Stimulus: Stagnation

Action: Stop search and accept

[+ ARE + ANY + BY + FEIGENBAUM + AND + FELDMAN +]*

39. KS:SEMANT*

Stimulus: Recognized utterance:

[+ ARE + ANY + BY + FEIGENBAUM + AND + FELDMAN +]*

Action: Generate an interpretation for the database retrieval system.

Advantages of Blackboards

- Many and diverse sources of knowledge can participate in forming and modifying the emerging solution
  - Linking partial solutions at the same level of abstraction and those at different levels
- Each knowledge source can be implemented using
  - The most appropriate representation of it knowledge
  - The most efficient inference engine for its reasoning

Advantages of Blackboards Continued

- No a priori commitment to the order of inferencing steps
  - Bottom-up or Top-down
  - Data-directed or Model/Goal directed
- Each knowledge source can contribute opportunistically since each has continual access to the current state of the search.
  - The right knowledge can be applied at the right time.
  - Permits Differential diagnosis
- Control Knowledge can exploit a global view of the emerging set of potential solutions and their relationships

Next Lecture

- New Section on Reason About Uncertainty on October 10