Lecture 11: Search 10

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CMPSCI 683

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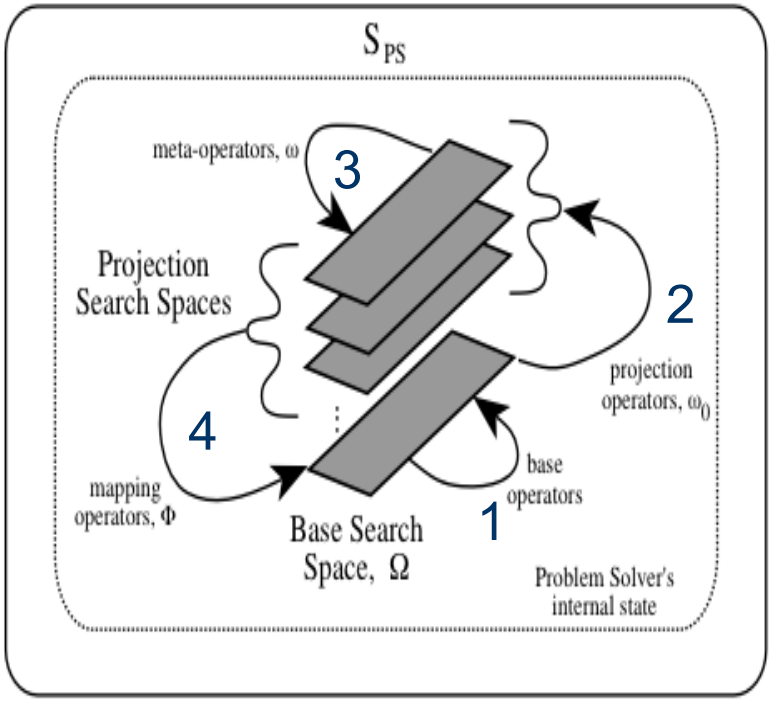
This Lecture

- Multi-Level Search
  - BlackBoard Based Problem Solving
  - Hearsay-II Speech Understanding System

Multi-Level vs Hierarchical Search



Strict Hierarchical Search

- Movement patterns among levels from lower to higher and back are not fixed

- Each level is a complete search space

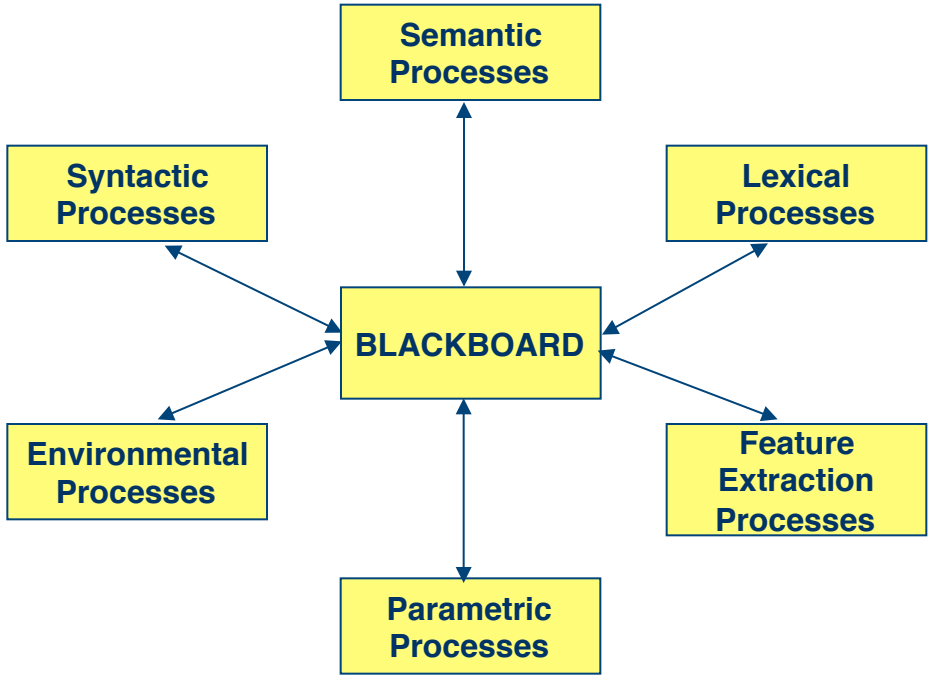
- State (search nodes) held at each of the level do not go away when moving from one level to another

- Operators that modify the search space at one level may use information from multi-levels

Even More Complex Search

- Multi-Level & Bi-Directional
- Non-Monotonic Domain
- Cost of Control
  - Non-uniform and costly with respect to node generation
- Non-uniform cost of operator application

Blackboard Problem Solving Model: Cooperating Experts

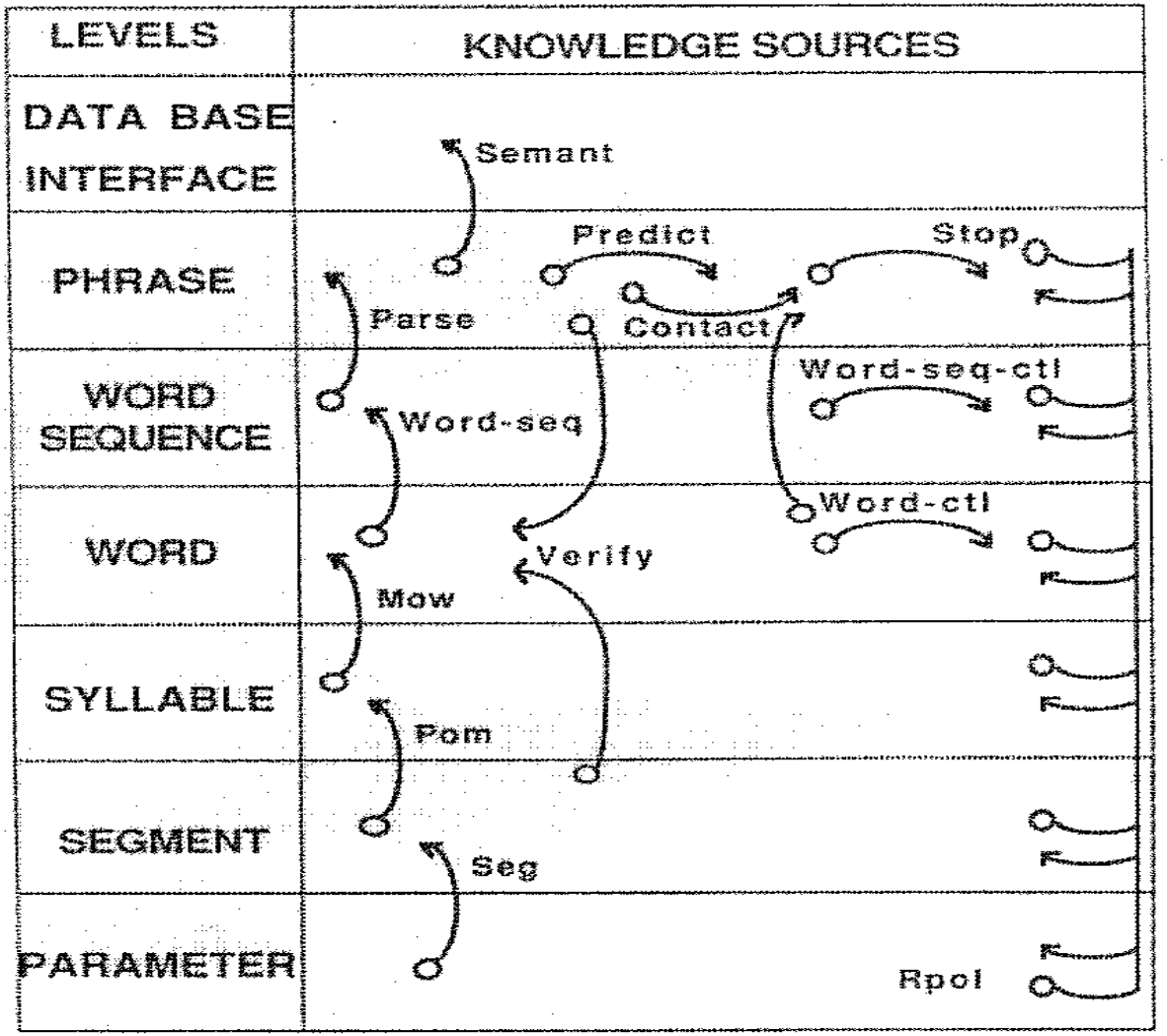


A Set of Knowledge Sources(KSs) Incrementally adding knowledge/ hypotheses/partial solutions through a shared multi-level structure called the blackboard –think of a group problem-solving process

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

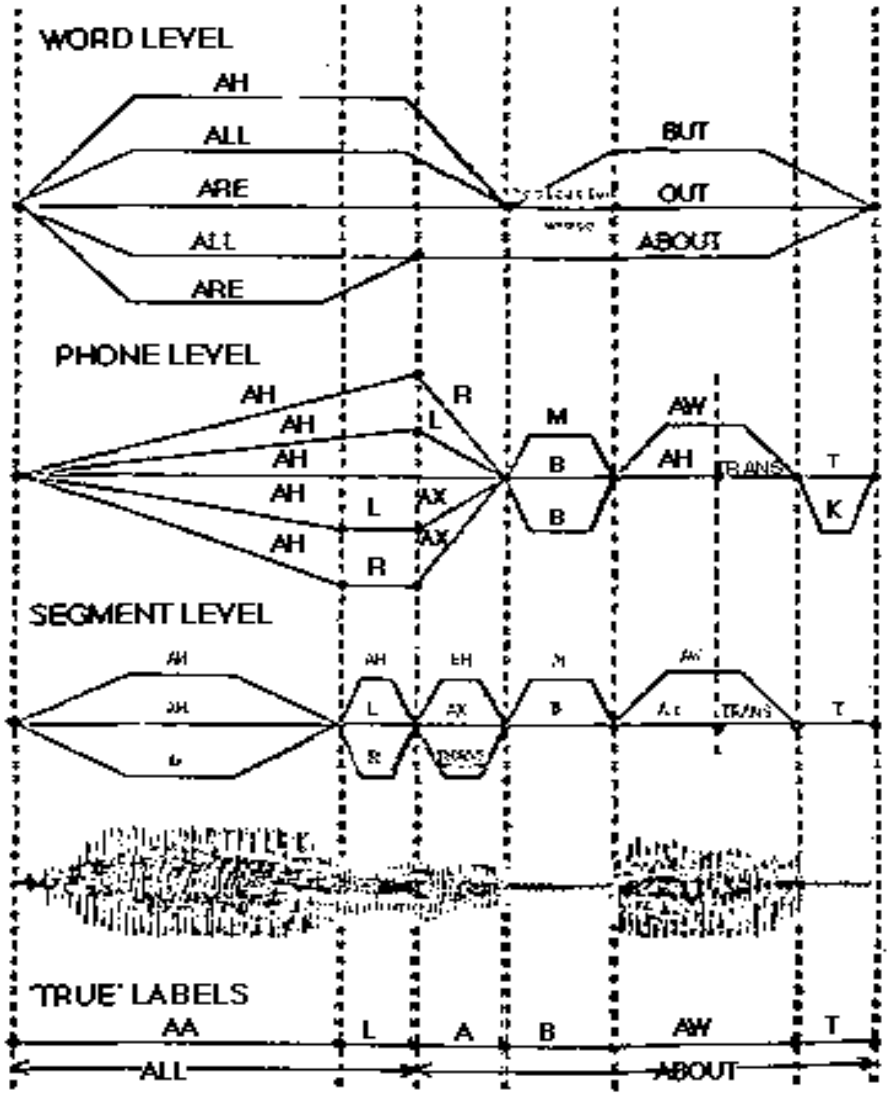
Example BlackBoard System



Blackboard Nodes

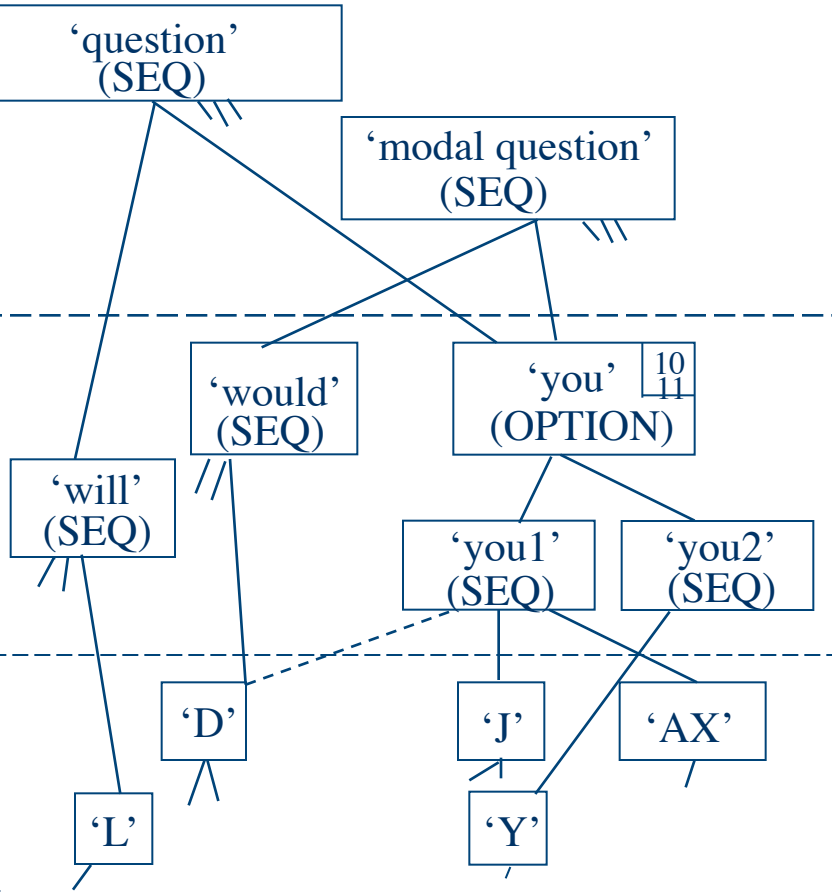
- Nodes (partial solutions) exist at particular level and associated with a primitive element
  - Each level has associated with it a vocabulary that defines the range of primitive elements
  - Each node has a set of attributes that can be level-dependent
- Nodes can be related to other nodes at the 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

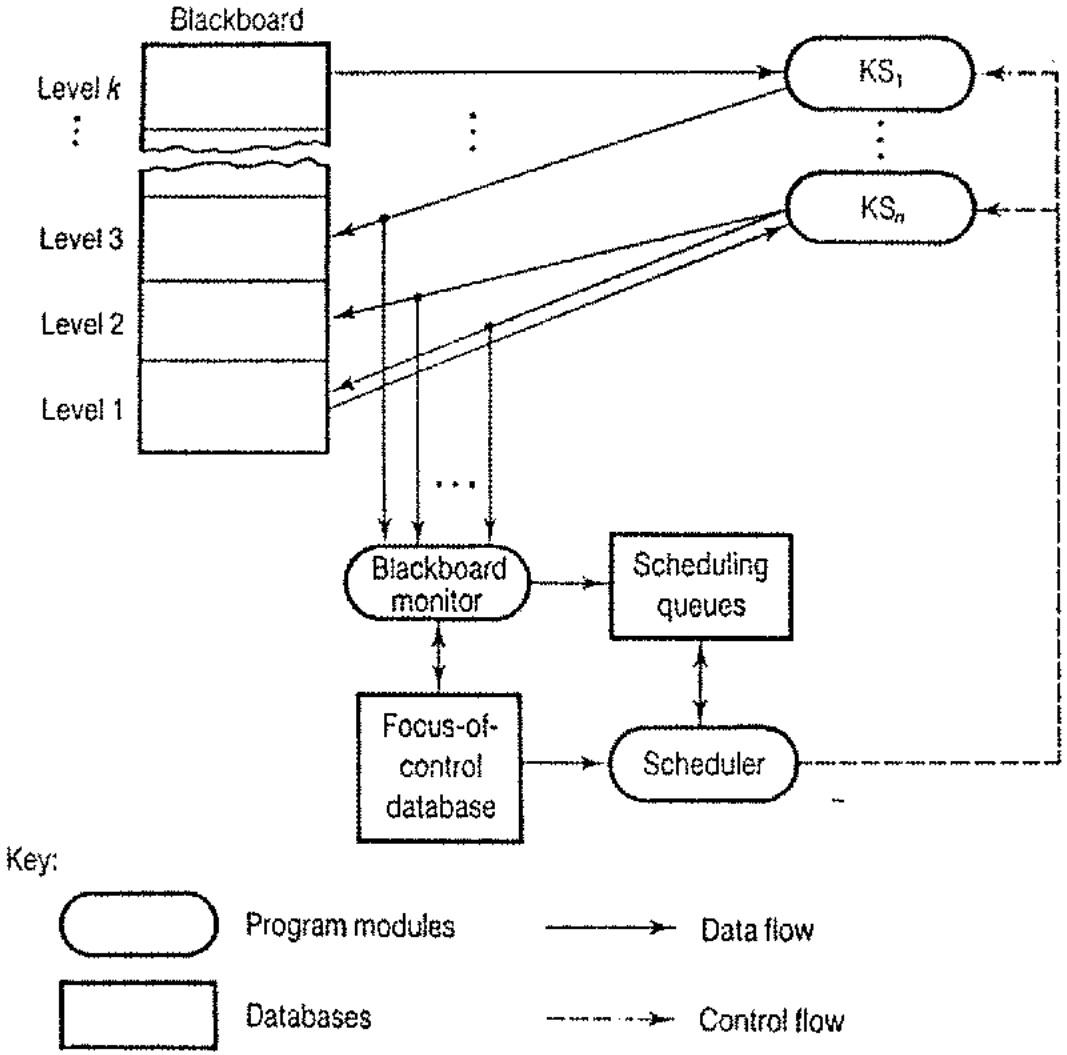
- PHRASAL
- LEXICAL
- SURFACE-PHONEMIC



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, open list)
- 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

Hearsay-II Architecture



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:

```
((SEVENT-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:

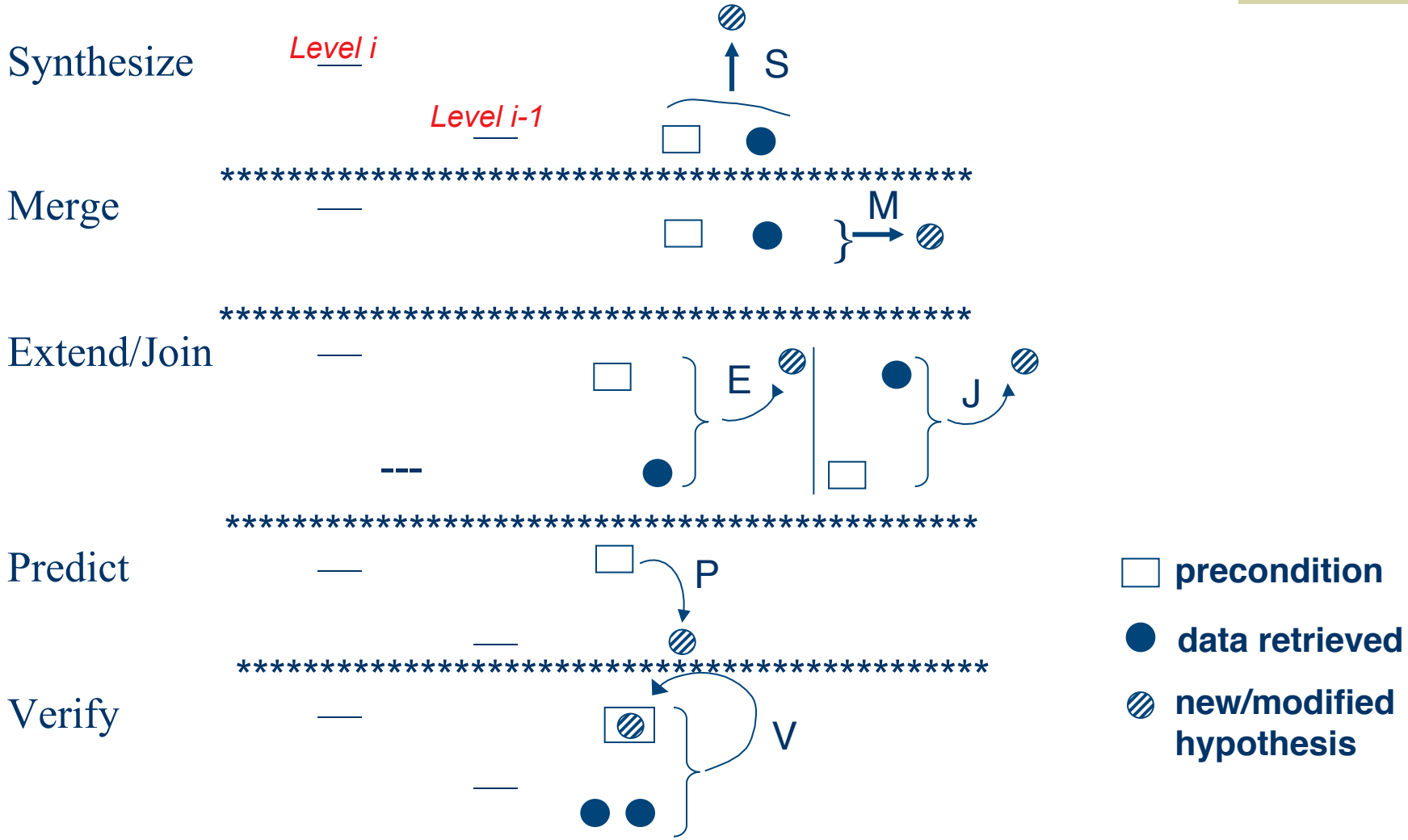
```
((1 (T)
   (EXECUTE ($SET YokeResult (Yoke-Structures PS-Anchor
        Anchoree1 Anchoree2
        (CADAR (LAST ($VALUE Anchoree1 'Legal-Orientations)))
        (CADAR (LAST ($VALUE Anchoree2 'Legal-Orientations)))
        NewLocLabelForAnchoree1 Descriptor1
        NewLocLabelForAnchoree2 Descriptor2
        (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 Data 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 -- search termination criteria
  - 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."

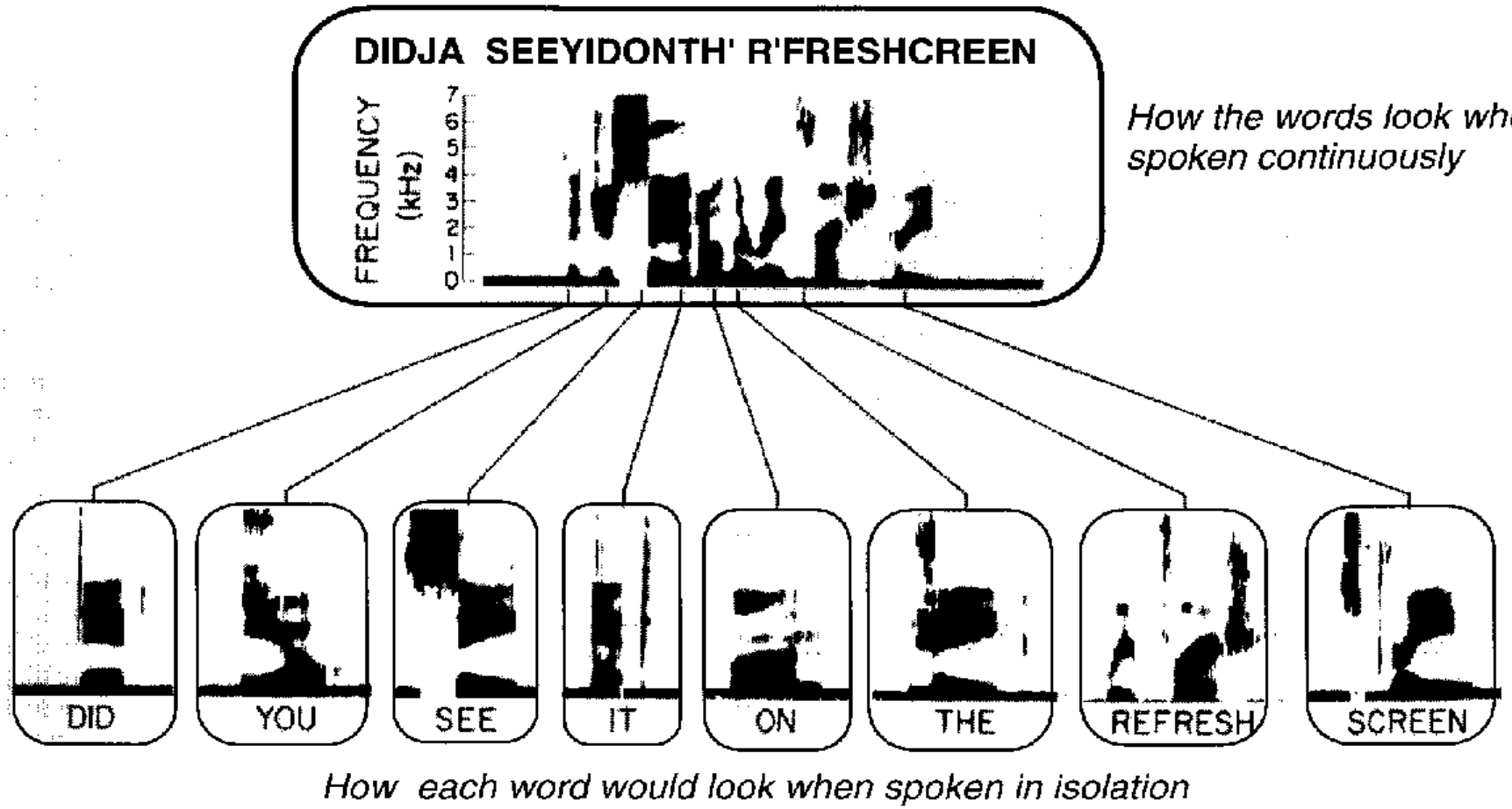
"What has McCarthy written since 1974?"

Why Connected Speech Understanding is Difficult

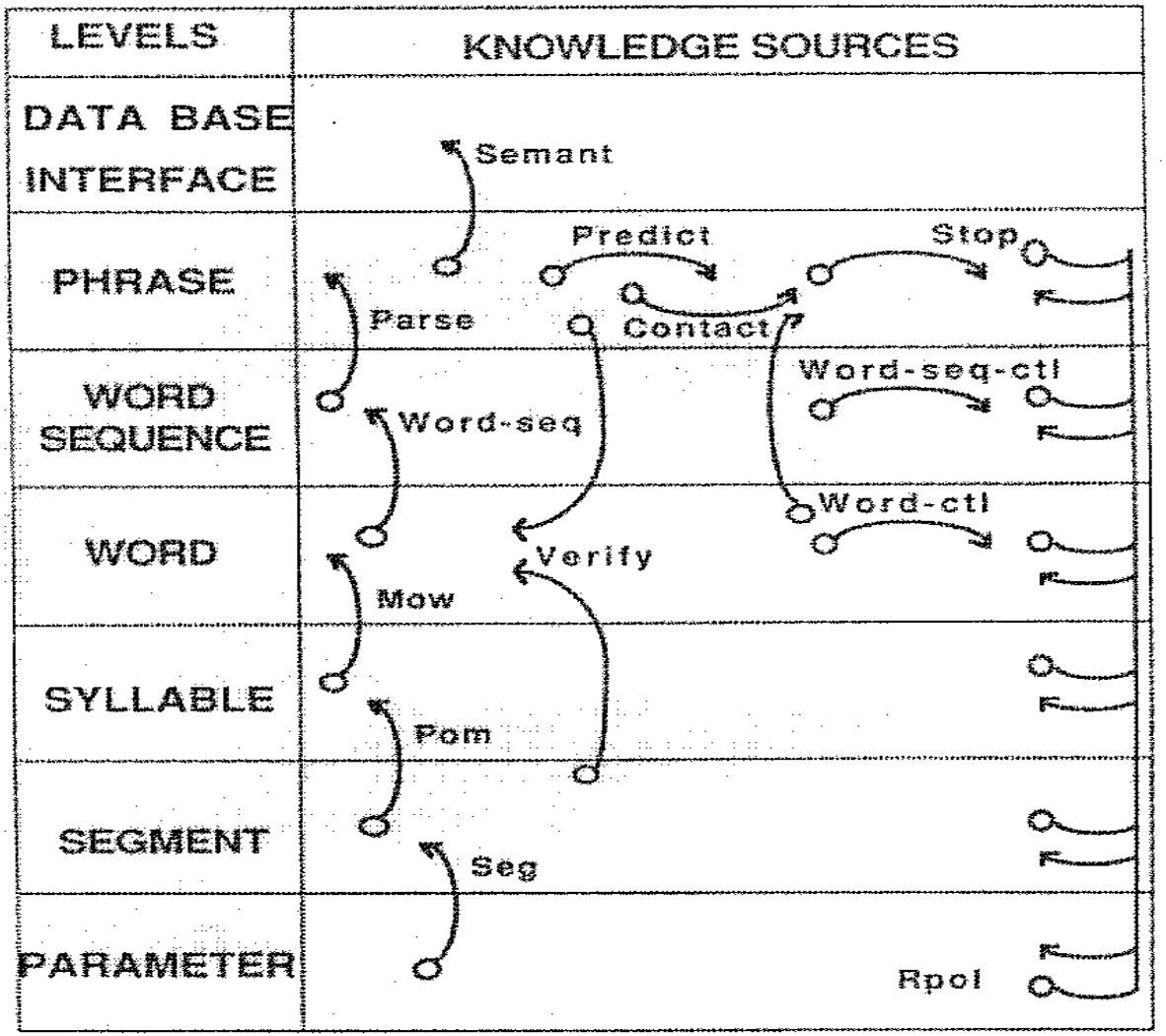
- Large search space
  - $\approx 10^8$ legal sentences
- Uncertainty and Approximate Knowledge
  - Sensors
  - Acoustic phonetic knowledge
- Knowledge costly to apply
- Difficult to subdivide problem solving
- Interacting constraints
    - Co-articulation phenomenon
- Wide variety of knowledge needs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

Masking in Time-Domain: Co-Articulation

- Continuous speech blurs word boundaries and changes pronunciations...



Functional Description of the Speech-Understanding KSs



Hearsay-II Knowledge Sources Domain and Control

- *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

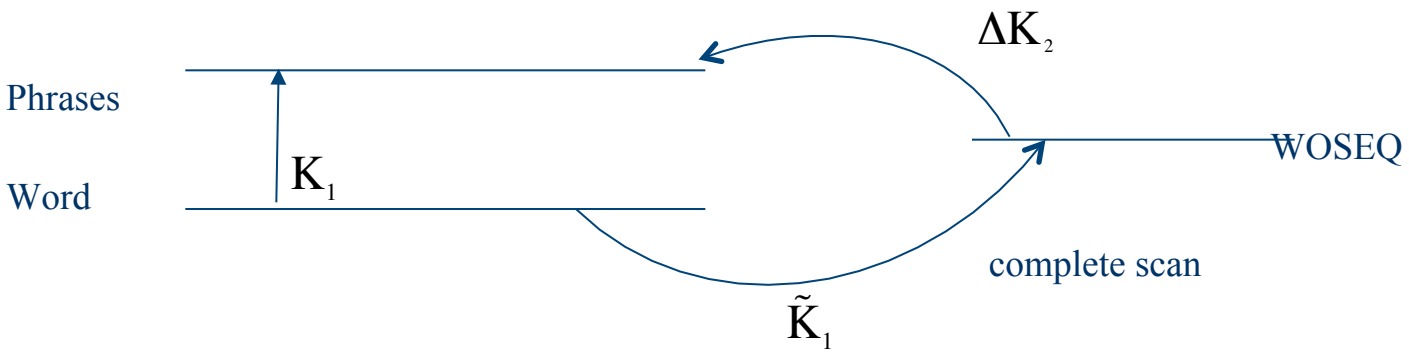
Correct with ΔK_2

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

$K_1 = PARSE$

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

$\Delta K_2 = PARSE$ applied to sequences



Basic Control Cycle

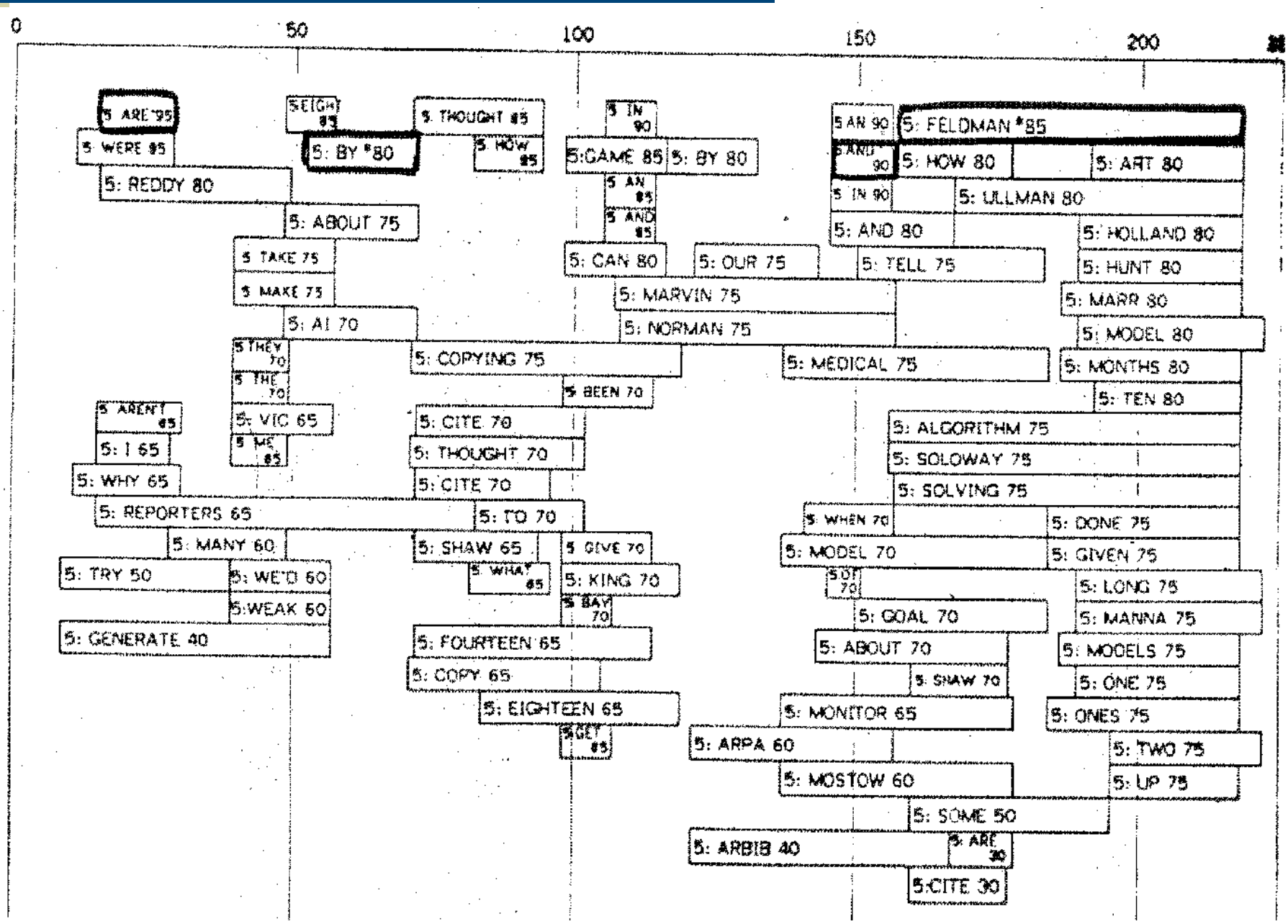
- Scheduler invokes highest-rated KS with specific context
  - Check before running whether precondition still valid
- KS modifies blackboard
  - Focus-of-control database is updated
  - Relevant precondition procedures are notified
- Relevant precondition procedures are evaluated
  - New KS instances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

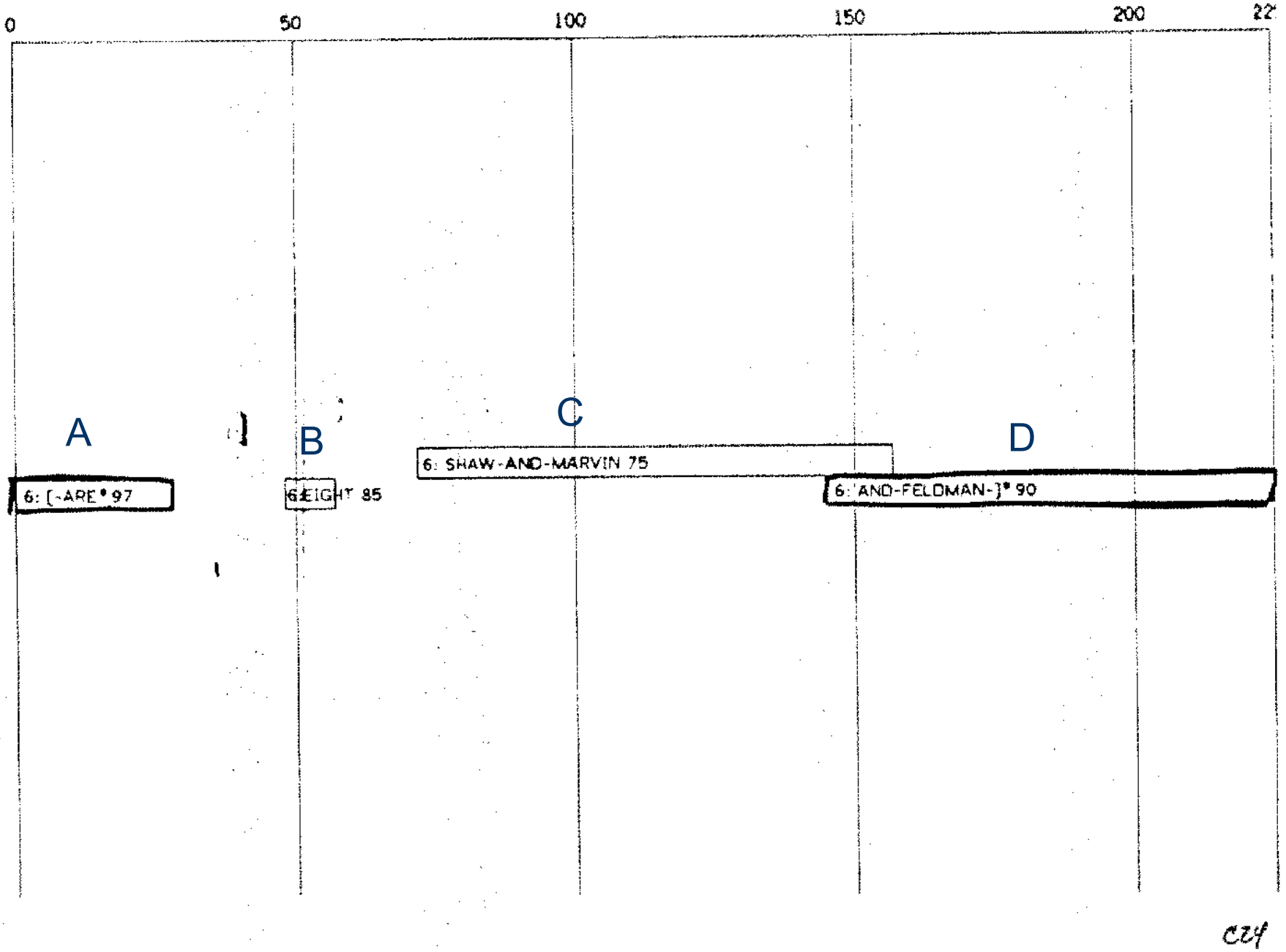
Control Strategy

- 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

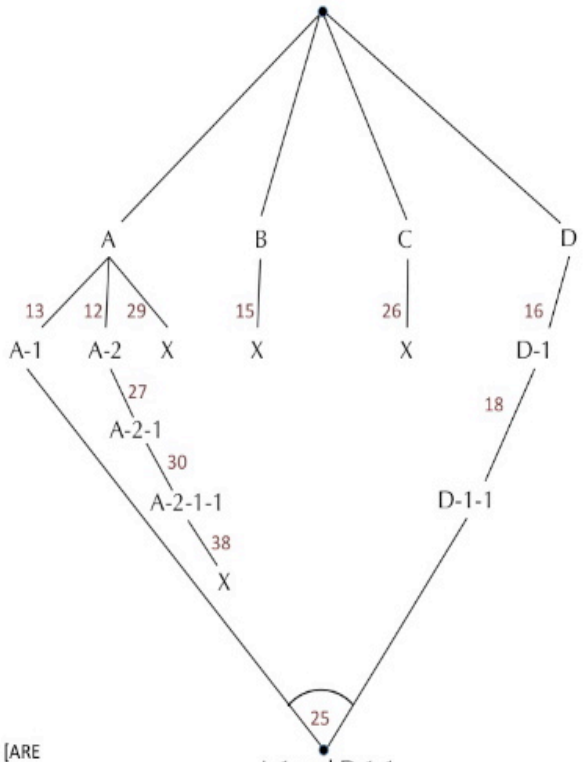
Control Strategy, cont'd

- 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


0
50
100
150
200
5: ARE *95
5: WERE 85
5: REDDY 80
5: EIGHT 85
5: BY *80
5: ABOUT 75
5: THOUGHT 85
5: HOW 85
5: TAKE 75
5: MAKE 75
5: AI 70
5: IN 90
5: GAME 85
5: BY 80
5: AN 85
5: AND 85
5: CAN 80
5: OUR 75
5: AN 90
5: FELDMAN *85
5: AND 90
5: HOW 80
5: ART 80
5: IN 90
5: ULLMAN 80
5: AND 80
5: HOLLAND 80
5: YELL 75
5: HUNT 80
5: MARVIN 75
5: MARR 80
5: NORMAN 75
5: MODEL 80
5: THEY 70
5: THE 70
5: VIC 65
5: COPYING 75
5: MEDICAL 75
5: MONTHS 80
5: BEEN 70
5: TEN 80
5: AREN'T 85
5: I 65
5: WHY 65
5: ME 85
5: CITE 70
5: THOUGHT 70
5: CITE 70
5: ALGORITHM 75
5: SOLOWAY 75
5: SOLVING 75
5: REPORTERS 65
5: TO 70
5: WHEN 70
5: DONE 75
5: MODEL 70
5: GIVEN 75
5: MANY 60
5: SHAW 65
5: GIVE 70
5: WHAT 85
5: KING 70
5: TRY 50
5: WE'D 60
5: WEAK 50
5: GENERATE 40
5: BAY 70
5: FOURTEEN 65
5: COPY 65
5: EIGHTEEN 65
5: GET 85
5: OUT 70
5: LONG 75
5: GOAL 70
5: MANNA 75
5: ABOUT 70
5: MODELS 75
5: SHAW 70
5: ONE 75
5: MONITOR 65
5: ONES 75
5: ARPA 60
5: TWO 75
5: MOSTOW 60
5: UP 75
5: SOME 50
5: ARBIB 40
5: ARE 30
5: CITE 30


0
50
100
150
200
A
B
C
D
6: [-ARE * 97
6: SHAW-AND-MARVIN 75
6: AND-FELDMAN-]* 90

Hearsay-II Trace as a Search Graph



A: [ARE
B: EIGHT
C: SHAW+AND+MARVIN
D: AND+FELDMAN]
A-2: [ARE+REDDY
A-1: [ARE+ANY
D-1: FEIGENBAUM+AND+FELDMAN]
D-1-1: BY+FEIGENBAUM+AND+FELDMAN]
A-1 and D-1-1:
[ARE+ANY+BY+FEIGENBAUM+AND+FELDMAN]

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.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.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 (Wed Oct 20)

- Sequential Decision Problems
  - Markov Decision Processes (MDP)
  - Partial Orderded MDP (POMDP)

Good Luck on Exam on Monday