Title
A representation of space

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A Representation of Space

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ABSTRACT. The spatial concepts: location, direction, orientation, space, distance, shape, and surface are discussed from a natural language processing perspective. Representations are proposed for all concepts except shape. A sample set of inferences that can be drawn from the representations are presented. Lastly, the interaction between the spatial domain and other knowledge domains is discussed.

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0. Introduction

If our task is to create a program that exhibits intelligent human behavior, then it behooves us to examine some of the basic knowledge humans have. Since we live in a three-dimensional world, we are very familiar with the concepts of space. In fact, our spatial knowledge is pervasive in almost all other areas of knowledge. For example, in the realm of numbers, we say that a number is larger than another; in programming, one travels down the list.

Previous researchers have modeled space in several ways. Fahlman's BUILD program [3] modeled space as a standard three-coordinate Euclidean space. For the simple blocks-world problem domain that representation was sufficient. However in more complex spatial domains the mathematical Euclidean space has several drawbacks. First, more complex shapes are difficult to represent. Secondly, instead of absolute coordinates of E-3, humans think in terms of relative relationships.

Kuiper's TOUR machine [5] uses a hybrid of three spatial models: "cognitive map", "patchwork map", and "street map." All three models deal with large-scale spatial concepts. His model was design to simulate traveling through city streets. The model was not designed to operate in a three-dimensional environment. His model did not represent the vertical component of space. Additionally, it does not deal with the notion of distance.

This paper will address the basic concepts of space and discuss the problems involved in representing them. The discussion will center around a set of representative sentences that involve spatial concepts. In the analysis of the sentences, I will point out the important concepts that are necessary in the representation of the meaning but are not stated in the sentence. Sample sentences will be represented to help illustrate the concepts involved. The representation will be in a form as close as possible to Roger Schank's [7] Conceptual Dependency (CD).

Most spatial concepts will be presented in four parts. The first part is a discussion of key concepts related with each main concept. The second part is the proposed representation. The third part is some examples. And the last part is some inferences that can be made from the representation.

A great amount of spatial knowledge is non-verbal and difficult to represent. For example, the notion of round has tactile sensations associated with it. (We have a sense of what round feels like.) Because this paper will take a natural language processing perspective, the non-verbal concepts will be not represented in great detail. More attention will be paid to concepts that help make inferencing possible.

1. Aspects of Space

1.1 Location

1.1.1 Key concepts: (relative location, space relations)

(1a) The notebook was on the table.

One of the basic properties of physical objects is that they have a location. Sentence 1a can be rewritten as, "The location of the notebook was the top of the table." Notice that in 1a, the location of the notebook is *relative* to the location of the table. In the blocks-world, the representation consists of x-y-z coordinates for each object and the relation ON between the objects. This representation is not close to the representation a human would use. The notebook's location, to us, is relative to the table. We do not convert relative location to absolute measure without reason. In relating two objects, there are the standard space relationships between the two locations: (left, right) (above, below) (in-front, behind). However to discuss relationships between two locations, one must also discuss the concept of direction.

Ideally, we think of a location as a single point in space. However, operationally we use a location to signify a locus of points. The meaning of "the location of X" will be discussed in more detail in section 1.4.

1.1.2 Representation of location

```
State: <loc> ::= (*LOC* PART <object>) |
                 (*CENTER* PART <object>)
```

LOC represents location, and *CENTER* represents the idealized center point of the object.

1.2 Direction

1.2.1 Key concepts: (frame of reference, relative direction, absolute direction)

(2a) John is right of Mary.

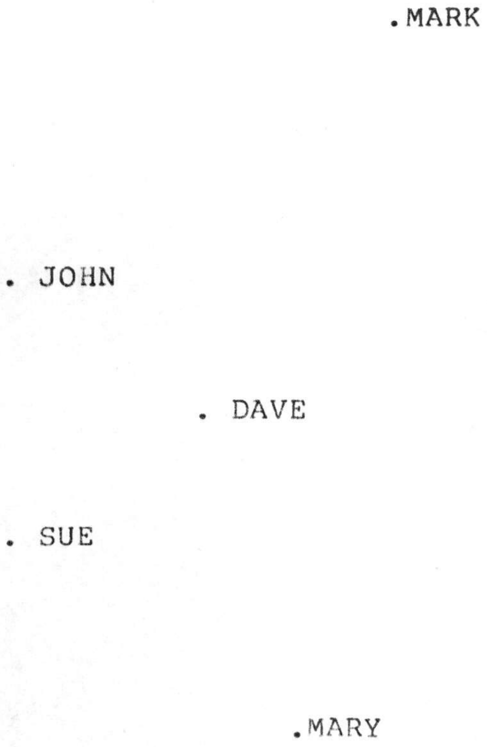
There are really two interpretations of the sentence 2a: John is right of Mary with respect to an observer's right, or John is on Mary's right. Because of this ambiguity, "frame of reference" is an important part of specifying a space relation. A "frame of reference" is composed of a location and an orientation. Orientation, to be discussed in more depth later, is the direction the object or person is "facing." In the latter interpretation of 2a, Mary turns right from where she was facing to see John. In this sense, direction can be described by the movements that the observer must perform in order to look at the object directly.

(2b) The balloon was above the building.

Sentence 2b uses the preposition "above," and its use implies gravity as a frame of reference. That is to say, "above" uses the earth (gravity) to specify the direction of an object; namely, the distance between the earth and the balloon is greater than the distance between the earth and the building's top.

(2c) John is between Dave and Sue.

Consider the following diagram.



From the point of view of Mary, John will appear between Dave and Sue; but for Mark, John will appear to be right of both of them. Now suppose Mary is looking directly at Sue. Then Dave is to the front and to the right. But suppose Mary is looking directly at Mark. Then Dave is to Mary's left.

(2d) San Francisco is north of Los Angeles.

The previous examples have been using relative directions, that is, relative to objects in current environment. Sentence 2d might be considered an example of absolute direction. However there is no advantage in representing 2d differently than the previous examples, because the basic concepts still apply. It is advantageous to represent absolute directions as relative to the "frame of reference" of earth. There are some subtle differences (e.g., if you go in one direction for 25,000 miles you arrive at the same place), but they will be ignored in this paper. It might be noted, however, that humans usually ignore the differences also. E.g., it is faster to go to Japan via Alaska than it is to go "west," contrary to most people's belief.

The following representation, in some sense, is equivalent to E-3. However the important difference is that the proposed representation is closely tied to how humans view space. That is, humans view space in terms of their bodies. That means that their view is affected by the shape and function of the body. If the human had eyes in the back of his head, then direction would be represented differently.

1.2.1 Representation of direction

State: <dir> ::= (*DIRECTION* VEC <vec> FROM <loc>)

Direction can be specified by two methods: either by two locations or a vector in a frame of reference. The sentence, "The smoke was towards the mountain" is an example of direction specified by the locations of the observer and the mountain. The sentence, "John is to Mary's right" is an example of a direction specified by Mary's frame of reference.

Rolename: VEC
Concept: specification of direction
Filler: <vec>::= <loc> |
(*REL* X <ang> Y <ang> Z <way>
ORIENT <object>)

Rolename: FROM
Concept: the endpoint from which the direction originates
Filler: <loc>

Rolename: X
Concept: the horizontal direction
Filler: <ang> ::= any number between -90 to 90,
or a concept which specifies a range.
Examples: dead center=0, directly left=-90,
center=*C* {45 to -45}, right=*P* {45 to 90},
left=*N* {-90 to -45}

Rolename: Y
Concept: the vertical direction
Filler: <ang>
Examples: level=0, directly above=90, below=*N* {-90 to -45}

Rolename: Z
Concept: the direction in depth
Filler: either *FRONT* or *BACK*

Rolename: ORIENT
Concept: the orientation of the frame of reference
Filler: <object> | EARTH | WIND

Although the roles X and Y are very similiar to spherical coordinates, the representation is not intended to do mathematical calculations. The inferences are rule-based, and there is no associated "calculus" with the representation.

Every object in the ORIENT role must have an orientation type (to be discussed in section 1.3). EARTH and WIND have special inference rules, and they do not behave as normal reference frames.

The three CD primitives PTRANS, ATTEND, and PROPEL have been extended to make them conform with the spatial concepts.

PTRANS has a new role ROUTE.

Rolename: ROUTE
Concept: the path taken between the TO and FROM slots
Filler: <path> | <dir>

A path is a sequence of locations and directions, and it will be discussed in detail in section 1.4.

Both ATTEND and PROPEL have the new role VEC. For ATTEND the FROM role is not needed because the ACTOR's location serves as the endpoint of the direction. For the PROPEL, the endpoint of the direction is the location of the OBJECT.

1.2.3 Examples

1. John is to Mary's right.

```
((ACTOR (JOHN) IS (*DIRECTION*
                  VEC (*REL* X (*P*) ORIENT (MARY))
                  FROM (*LOC* PART (MARY))))
```

2. John is to the right of Mary. (via observer)

```
((ACTOR (JOHN) IS (*DIRECTION*
                   VEC (*REL* X (*P*) ORIENT (OBSERVER))
                   FROM (*LOC* PART (MARY))))
```

3. Mary is to the left of John. (via observer)

```
((ACTOR (MARY) IS (*DIRECTION*
                   VEC (*REL* X (*N*) ORIENT (OBSERVER))
                   FROM (*LOC* PART (JOHN))))
```

--NOTE 2 and 3 can be inferred from each other.

4. San Francisco is north of Los Angeles.

```
((ACTOR (SF) IS
  (*DIRECTION* VEC (*REL* X (*C*) Z (*FRONT*) ORIENT (EARTH))
               FROM (*LOC* PART (LA))))
```

--Absolute direction is treated as though earth has an orientation of north. The Y direction refers to gravity.

5. The balloon is above the building.

```
((ACTOR (BALLOON) IS
  (*DIRECTION* VEC (*REL* Y (*P*) ORIENT (EARTH))
               FROM (*LOC* PART (BUILDING)))))
```

6. The building is below the balloon.

```
((ACTOR (BUILDING) IS (*DIRECTION*
                       VEC (*REL* Y (*N*) ORIENT (EARTH))
                       FROM (*LOC* PART (BALLOON))))
```

--Both 5 and 6 can be inferred from each other.

7. The smoke was towards the mountain.

```
((ACTOR (SMOKE) IS (*DIRECTION* VEC (*LOC* PART (MOUNTAIN))
                                FROM (*LOC* PART (OBSERVER))))
```

8. John walked toward Mary.

```
((ACTOR (JOHN) <=> (*PTRANS*) OBJECT (JOHN)
   ROUTE (*DIRECTION* VEC (*LOC* PART (MARY)) FROM (*SPEC*))))
```

9. John walked in front of Bill. (and continued on)

```
((ACTOR (JOHN) <=> (*PTRANS*) OBJECT (JOHN) ROUTE (LOC1)))
((ACTOR (LOC1) IS (*DIRECTION* VEC (*REL* X (*C*) Z (*FRONT*)
   ORIENT (BILL)) FROM (*LOC* PART (BILL)))))
```

10. John walked to the front of Bill.

```
((ACTOR (JOHN) <=> (*PTRANS*) OBJECT (JOHN) TO (LOC1)))
((ACTOR (LOC1) IS (*DIRECTION* VEC (*REL* X (*C*) Z (*FRONT*)
   ORIENT (BILL)) FROM (*LOC* PART (BILL)))))
```

11. John looked to the right of Mary.

```
((ACTOR (JOHN) <=> (*ATTEND*) OBJECT (*EYES*) VEC (LOC1)))
((ACTOR (LOC1) IS (*DIRECTION* VEC (*REL* X (*P*)
    ORIENT (JOHN)) FROM (*LOC* PART (MARY))))
```

12. John looked starboard.

```
((ACTOR (JOHN) <=> (*ATTEND*) OBJECT (*EYES*)
    VEC (*REL* X (*P*) ORIENT (BOAT))))
```

13. The cut was above the knee.

```
((ACTOR (CUT) IS (*DIRECTION*
                  VEC (*REL* Y (*P*) ORIENT (LEG))
                  FROM (*LOC* PART (KNEE)))))
```

1.2.4 Inference of Direction

```
((ACTOR (A) IS (*DIRECTION*
  VEC (*REL* X (D1) Y (D2) Z (D3) ORIENT (B))
  FROM (*LOC* PART (C))))
```

I. If B=C then

- a. if A and B have the same orientation
  and A is right of B, then B is left of A [reference A].
  E.g. John and Mary are facing the blackboard.
  John is to Mary's right. => Mary is to John's left.
  Analogous inferences apply to: left, below, above, back, and front.

- b. if B is facing C
  and if B rotates D1,D2,D3 and ATTEND with eyes
  then B will ATTEND to A.

- c. if A is behind B
  then B cannot ATTEND with eyes to A without changing orientation.

- d. if object A is PROPELed in the direction D then
  then the caused PTRANS will have a direction D.

II. if B is not equal to C

- a. The inference Ia holds with respect to reference B.
  (A's orientation doesn't matter)
  Examples 4 and 5 can be inferred from each other.

III. Let A, B, and C be three locations.

- a. If A's and B's direction are the same from reference point C, then with the distance of A to C and B to C, the distance between A and B can be computed by $|(A,C)-(B,C)|$.

- b. If the direction of A and B are opposite in one direction with the reference of C, then the distance of A to B is $|(A,C)+(B,C)|$.

1.3 Orientation

1.3.1 Key concepts: (orientation types, frame of reference)

(3a) Beth was facing the mirror.

(3b) The mirror was facing Beth.

Kuiper's notion of orientation is closely tied to "sense of direction," whereas this paper applies orientation to all objects which have some kind of shape or functional characteristic that is important in space. Some objects have a natural orientation that is inherent from the shape and function.

Sentence 2a was shown to be ambiguous. The reason it is ambiguous was because there are two possible objects with orientations that could serve as frames of reference: Mary and an observer. If the objects were a pen and pencil, neither of which have inherent orientations, then the sentence would not be ambiguous. When one refers to the right side of the pen, one is using an "outside frame of reference" to specify which side is meant. The two most common outside frames of reference are the earth and the observer.

The sentences 3a and 3b have different meanings because both the mirror and Beth have their own orientation. It is interesting to note however that most people assume 3a also includes the mirror facing the person.

There are six orientation types.

Type 1

Examples: human,boat,car,telephone

Type-1 objects have a complete frame of reference inherent in them. Therefore the six relations can refer to a part of the object without an outside frame of reference. In sailing, for example, the right-hand side, the left-hand side, the front, and the back of the boat are called starboard, port, bow, and stern respectively. Naming the parts of the boat are important in sailing, because the sailboat constantly serves as a frame of reference. This way "left" cannot be confused as the boat's left.

Type 2

Examples: plate,lamp,table

Type-2 objects have only one direction, the vertical, inherent in them. The top of a lamp is well specified, whereas the left side of a lamp depends on an outside frame of reference.

Type 3

Examples: mirror

The mirror has a front and back.

Type 4

Examples: book

The book has a top, a bottom, a front, and a back.

Type 5 - special objects

Examples: earth, wind

The earth is a special frame of reference. We use it for gravity and the absolute directions such as north. The wind is also a special frame of reference (especially in sailing). It does not have a location as part its frame of reference, because it is not an object.

Type 6

Examples: orange,pen,ball

Type-6 objects have no inherent orientation.

1.3.2 Representation of Orientation

Each physical object has the property ORIENTATION with a value of either Type-1, Type-2, Type-3, Type-4, Type-5, or Type-6.

Associated with the state of orientation is a new primitive act ROTATE. The inferences of the primitive involve situations that matter if an object changes its orientation. For example, turning a cup containing liquid upside down would generate an inference that the liquid would fall out.

Primitive Act: ROTATE

```
(ACTOR <actor> <=>(*ROTATE*) OBJECT <object>
 X <ang> Y <ang> Z <ang> ORIENT <object> TO <loc> FROM <loc>)
```

There two main forms of ROTATE. One is for movements relative to an outside object and the other for movements relative to a frame of reference, e.g., "John turned towards Mary," and "John turned left." The sentence "John turned left towards Mary" is an example of a combination of the forms.

The orientations of objects are related by equating directions. For example, the sentence "John is upside down" is relating John's orientation to the earth's orientation. Another way of stating the sentence is: John's up-direction is the same as the Earth's down-direction. The CD form for equating two directions is: (CON <dir> IS <dir>).

```
Predicate: *OBJPRT*

<object> ::= <pp> | (*OBJPRT* PART <object> DESC <part>
                              QUA <dir>)

*OBJPRT* is used to specify a part of the object.
<pp> is any physical object
```

Rolename: DESC
Concept: the description of a body part.
Fillers: *LEG*,*TIRE*,*HALF*,*PIECE*, etc.

Rolename: QUA
Concept: the direction in which the body part is located
Filler: <dir>

1.3.3 Examples

1. Beth was facing the mirror.

```
((ACTOR (MIRROR) IS
  (*DIRECTION* VEC (*REL* X (0) Z (*FRONT*) ORIENT (BETH))
               FROM (*LOC* PART (BETH)))))
```

2. The mirror was facing Beth.

```
((ACTOR (BETH) IS
  (*DIRECTION* VEC (*REL* X (0) Z (*FRONT*) ORIENT (MIRROR))
               FROM (*LOC* PART (MIRROR)))))
```

3. John turned right.

```
((ACTOR (JOHN) <=> (ROTATE) OBJECT (JOHN) X (*P*)
               ORIENT (JOHN)))
```

4. John turned to Bill.

```
((ACTOR (JOHN) <=> (ROTATE) OBJECT (JOHN)
               TO (*LOC* PART (BILL))))
```

5. John turned from Bill to Mary.

```
((ACTOR (JOHN) <=> (ROTATE) OBJECT (JOHN)
     FROM (*LOC* PART (BILL)) TO (*LOC* PART (MARY))))
```

6. The stern of a boat.

```
(*OBJPRT* PART (BOAT) DESC (*HALF*)
    QUA (*DIRECTION*
            VEC (*REL* Z (*BACK*) ORIENT (BOAT))
            FROM (*CENTER* PART (BOAT))))
```

7. The spider was on the right side of the orange.

```
((ACTOR (SPIDER) IS (*PHYSCONT* PART
  (*OBJPRT* PART (ORANGE) DESC (*HALF*)
     QUA (*DIRECTION* VEC (*REL* X (*P*) ORIENT (OBSERVER))
                      FROM (*CENTER* PART (ORANGE)))))))
```

8. John could not see with his right eye.

```
((ACTOR (JOHN) <=> (ATTEND)
    OBJECT (*OBJPRT* PART (*EYE*) DESC (*HALF*)
```

```
    QUA (*DIRECTION* VEC (*REL* X (*P*) ORIENT (JOHN)))))
  MODE (*NEG*))
```

9. John is upside down.

```
((CON (*DIRECTION* VEC (*REL* Y (90) ORIENT (JOHN)))
  IS (*DIRECTION* VEC (*REL* Y (*N*) ORIENT (EARTH)))
```

10. Mary is lying down.

```
((CON (*DIRECTION* VEC (*REL* Y (90) ORIENT (MARY))
 IS (*DIRECTION* VEC (*REL* Y (0) ORIENT (EARTH)))
```

1.3.4 Inferences for Orientation

I. If the orientation of X is not "normal" then the function of X is inhibited. "Normal" is defined by each object individually. Usually, normal is defined as the object's above direction being in the same direction as earth's above. For example,

> The picture was upside down.
>
> The cup was on its side.
>
> The boat was capsized.

Specfic Inferences for the object Sailboat.

1. If SAILBOAT is upside down

```
    then ((ACTOR (*SPEC*) <=> (*SDO*) OBJECT ($SAILSCRIPT))
          MODE (*NEG*))
```

2. IF SAILBOAT is facing the wind then

```
   ((ACTOR (*) <=> (PTRANS) OBJECT (SAILBOAT)
    ROUTE (*DIRECTION* VEC (*REL* X (0) Z (*FRONT*)
         ORIENT (SAILBOAT))) MODE (*CANNOT*))
```

3. If the sailboat is pointing downwind and the mainsail is perpendicular to the wind then the sailboat will go forward.

```
((CON (*DIRECTION*
```

```
          VEC (*REL* X (0) Z (*FRONT*) ORIENT (SAILBOAT))
   IS (*DIRECTION*
          VEC (*REL* X (0) Z (*FRONT*) ORIENT (WIND))))
((CON (*DIRECTION* VEC (*REL* X (0) ORIENT (MAINSAIL))
   IS (*DIRECTION* VEC (*REL* X (90) ORIENT (WIND))))
implies
((ACTOR (*) <=> (PTRANS) OBJECT (SAILBOAT)
   ROUTE (*DIRECTION* VEC (*REL* X (0) ORIENT (SAILBOAT)))
```

4. If the sailboat is not heading directly downwind or upwind,
   and the sail is up, and the centerboard is up,
   then the boat will capsize.

```
((CON (*DIRECTION* VEC (*REL* X (0) ORIENT (SAILBOAT))
   IS (*DIRECTION* VEC (*REL* X (0) ORIENT (WIND))
  MODE (*NEG*)))
((CON (*DIRECTION* VEC (*REL* Y (0) ORIENT (SAIL))
   IS (*DIRECTION* VEC (*REL* Y (0) ORIENT (EARTH))))
((CON (*DIRECTION* VEC (*REL* Y (-90) ORIENT (CENTERBOARD))
   IS (*DIRECTION* VEC (*REL* Y (0) ORIENT (EARTH))))
enables
((ACTOR (*) <=> (ROTATE) OBJECT (SAILBOAT) Y (*C*)
  ORIENT (EARTH)))
```

1.4 Spaces

1.4.1 Key Concepts: (contain, enclosed, open, object)

(4a) The book was in the house.

(4b) The house was in Paris.

Given the sentences 4a and 4b together, it can be concluded that the book is in Paris. This demonstrates one can have a set of "spaces" where one space contains another. In a description of an object's location, it is always relative to a particular space. Spaces are the same as "maps" [6] and similiar to "regions" [5].

(4c) The chairs are around the table.

(4d) The chairs are around the room.

The sentences 4c and 4d have two very different meanings, and this is because a room is really serving as an enclosed space.

(4e) The chairs are around the house.

(4f) The lawn chairs are around the house.

Notice the change in meaning with the slight modification of sentence 4e to 4f. This is because "house" can be used for either an object or enclosed space. Normally chairs are inside, so the default interpretation is the house as an enclosing space. However lawn chairs are typically outside, so the other interpretation is taken.

(4g) The heart is in the chest.

An object can be considered a space also. The inferences about the "space" of an object are different. A bullet going through an object has a set of inferences on what happens to that object. E.g., if it is a human, then blood spurts out and the person probably dies.

1.4.2 Representation of Spaces

The representation of space is an extension of maps. A space is one of three types: (1) enclosed, (2) object, (3) open. Each space can have a size. The size can be expressed as either just a size, or having a height, width, and depth. If a size is specified then the three dimensions are assumed to be the same, unless the space (object) has some typical description. Spaces have locations relative to other objects, and there can exist spatial relations (direction and distance) between them. Location has two more types, and it includes spaces.

```
<loc> ::= (<locpred> PART <space>)
<locpred> ::= *LOC* | *CENTER* | *OUTSIDE* | *INSIDE*
```

1.4.3 Examples

The following is an incomplete description the Computer Science Building at UCI. It is assumed that the building is contained in a larger space. The format for the map is: (space number, space name, subspaces, connecting spaces).

```
(1 ICS-building (2 3 4 5 6 7) NIL)
(2 1st-Floor)
(3 2nd-Floor)
(4 3rd-Floor)
(5 4th-Floor (8 9 10) NIL)
(6 Stairs1 NIL (3 4 13))
(7 Stairs2 NIL (2 3 4 11))
(8 Hall (11 12 13) NIL)
(9 ICS-lounge NIL (13 10))
(10 ICS-library NIL (13 9))
(11 Hall1 NIL (12 7))
(12 Hall2 NIL (11 13))
(13 Hall3 NIL (12 9 10 6))
```

The following conceptualizations are some relationships between the spaces.

```
((ACTOR (4TH-FLOOR) IS
 (*DIRECTION* VEC (*REL* Y (*P*) ORIENT (EARTH))
              FROM (3RD-FLOOR))))
((ACTOR (STAIRS1) IS
 (*DIRECTION* VEC (*REL* X (*C*) Z (*FRONT*) ORIENT (EARTH))
              FROM (*CENTER* PART (ICS-BUILDING))))
((ACTOR (STAIRS2) IS
 (*DIRECTION* VEC (*REL* X (*C*) Z (*BACK*) ORIENT (EARTH))
              FROM (*CENTER* PART (ICS-BUILDING))))
((ACTOR (HALL1) IS
 (*DIRECTION* VEC (*REL* X (*C*) Z (*FRONT*) ORIENT (EARTH))
              FROM (*CENTER* PART (ICS-BUILDING))))
((ACTOR (HALL3) IS
 (*DIRECTION* VEC (*REL* X (*C*) Z (*BACK*) ORIENT (EARTH))
              FROM (*CENTER* PART (ICS-BUILDING))))
((ACTOR (ICS-LOUNGE) IS
 (*DIRECTION* VEC (*REL* X (*C*) Z (*BACK*) ORIENT (EARTH))
              FROM (*CENTER PART (HALL3)))
((ACTOR (ICS-LIBRARY) IS
  (*DIRECTION* VEC (*REL* X (*P*) ORIENT (EARTH))
               FROM (*CENTER* PART (ICS-LOUNGE))))
```

--NOTE: these are not the only way to represent the relationships.

1.4.4 Inferences for Space

1. If object A is in the space B, then the size of A is smaller than B.

2. If object A is in space B and space B is enclosed or an object, then if C is outside of B then C cannot see A.

3. If A is in space B, then for spaces that contain B, the location of A is the location of B. E.g., Los Angeles is in California and California is in the US, therefore Los Angeles is in the US.

1.5 Distance

1.5.1 Key concepts: (absolute, relative, comparative, functional)

(5a) The ball was closer to John than to Bill.

(5b) They had five yards to go for a touchdown.

One rarely uses absolute distance measure when referring to the distance of an object. Usually the measure is relative to distances between other objects in the space. The sentence 5a uses a comparative measure. The actual distance to the ball is not relevant. The important part of the measure is the fact that John can probably get to the ball faster than Bill because John has a shorter distance to travel. It doesn't matter whether the distance is 10 or 20 feet.

(5c) He hit a long fly ball.

The same principle holds for sentence 5c; the important feature is the relative distance to the outfielder. Distance can be expressed in absolute distance but seemingly humans only use the absolute when they have the tools to measure. It is interesting to note that in football games, even though the field is marked (absolute measure), a comparsion measure (yardsticks) is used to determine the 1st down.

(5d) It's 10 minutes away.

Sentence 5d shows that functional features of distance are very important. That is to say, perception of distance depends on the mode of movement through the space. For example, people from Los Angeles always talk in terms of minutes away (by car, of course) as opposed to miles, because the time it takes to go 5 miles can drastically change depending on the route (freeway or non-freeway).

(5e) John is taller than Bill.

In sentence 5e, the importance is in the comparsion. John could be an elephant and Bill an ant, but the height comparsion is still valid. If John and Bill are humans then one can assume that there is some default range (e.g. 5-7 feet) in which the comparsion is being made.

(5f) John is tall.

Sentence 5f is completely different from 5e. John is not compared to a specific height, e.g., Bill's, but rather his height is compared to some range of heights. Tall means that the height is somewhere in the upper range of human heights.

All this evidence implies that for a representation of distance, any particular distance may be used as a yardstick for other measurements in its space. The important part of distance is the partial ordering and the mode of travel across the distance.

1.5.2 Representation of Distance

State: (*DISTANCE* VAL -)

New role in PTRANS

(ACTOR <actor> <=> (*PTRANS*) DISTANCE <dis>)

The conceptualization in the distance slot is an instance of a distance and has a scales property. Those scales are a partial ordering on a set of distances. Typical scales are: *inches*, *feet*, *miles*, *largedist*. The smaller scales (in distance) do not represent all distances. That is, each scale represents only distances within its limited range (though the range is fuzzy). The primary use of the scales is to draw inferences.

The ratio scale operates differently from the previous scales. It is used to represent a sentence like "It's half the distance." The only difference in this scale is that the number between two distances represents a factor. The scale still represents a partial order; but, instead of distances being added, they are multiplied.

The concepts of large and small are relative to a particular interval defined on a scale. For example, the "tall" in "the tall person" is defined as some point on the interval of the height of a person. The interval might be defined as 58 to 88 on the *inches* scale. The point, let us say X1, will be declared between this interval and also have the property *large*. Large might be considered the top third on this interval. ("Large" is dependent on the object.)

Predicates: *SIZE*, *AREA*, *HEIGHT*, *WIDTH*, *DEPTH*

The predicates are for specifying the dimensions of the objects. *SIZE* is used for objects that do not have an orientation, or when the values of each dimension are not specified. *AREA* is for surfaces.

1.5.3 Examples

```
1. John's place is five miles away.
((ACTOR (*PLACE*0) IS (*DISTANCE* VAL (X1)) TO (*HERE*0)))
The property of DISTANCE, X1 has the value (*MILES*).
The value of X1 on the scale is 5.
```

```
2. The penalty was half the distance to the goal.
((ACTOR (BALL) IS (*DISTANCE* VAL (X1)) TO (*GOAL*1))
    TIME (T1))
((ACTOR (BALL) IS (*DISTANCE* VAL (X2)) TO (*GOAL*1))
    TIME (T2))
X2 is 2 before X1 on the ratio scale.
X1 and X2 are on the *FEET* scale.
```

```
3. John is tall.
((CON (*HEIGHT* PART (JOHN)) IS (*DISTANCE* VAL (X1))))
On the property of DISTANCE, X1 has the value (*INCHES*).
X1 is between 44 and 88 on that scale.
The value of X1 is *LARGE*.
```

```
4. John is taller than Bill.
((CON (*HEIGHT* PART (JOHN)) IS (*DISTANCE* VAL (X1)))
((CON (*HEIGHT* PART (BILL)) IS (*DISTANCE* VAL (X2)))
X2 is before X1.
```

```
5. The batter hit a long fly ball into right-center field.
((ACTOR (BATTER) <=> ROTATE OBJECT (BAT)
     X (*SPEC*) ORIENT (BATTER)))
caused
((ACTOR (BAT) IS (*PHYSCONT* PART (BALL)))
enabled
((ACTOR (*) <=> (*PROPEL*) OBJECT (BALL)
```

```
  VEC (*REL* X (20) ORIENT (*HOMEPLATE*))
caused
((ACTOR (*) <=> (*PTRANS*) OBJECT (BALL)
  ROUTE (*DIRECTION* VEC (*REL* X (20) ORIENT (*HOMEPLATE*))
  DISTANCE (X1) FROM (*HOMEPLATE*)))
```

X1 has the property DISTANCE with the value *FEET* and X1 is between 300 and 400. The value of X1 on that scale is *LARGE*.

1.5.4 Inferences of Distance

(*DISTANCE* VAL (X1))

1. (Probabilistic inferences)

   a. If X1 is on the scale of *largedist* then the mode of transportation is probably: airplane, ship, or train.

   b. If X1 is on the scale of *miles* then the mode of transportation is probably: car or bus.

   c. If X1 is on the scale of *feet* then the mode of transportation is probably: walking.

   d. If X1 is on the scale of *inches* then the GRASP or MOVE primitives may be used.

   e. If X1 is on the scales: (*largedist*, *miles*) then the ATTEND with eyes or ears to the object cannot be done.

   f. If X1 is on the scales: (*largedist*, *miles*, *feet*) then a GRASP, INGEST or PROPEL cannot be done to an object.

   g. If X1 is greater than X2 then the amount of resources needed to travel the distance of X1 maybe greater than the resources needed for X2.

   h. If X1 is a size or dimension (height, width, depth) is *large* or *small* then a function of the object might be inhibited or enhanced.

2.

   a. If A is near B, then B is near A.

1.6 Shape

(6a) The ball was placed on the table.

(6b) The ball was placed on the pyramid.

Shape is the most difficult spatial concept to represent, because it relies heavily on visual and kinesthetic perception. The blocks-world programs only represented simple shapes, but no curved surfaces. The TOUR model deals with large-scale space which has no need for concept of shape. Recent work in scene analysis [1,2,8] demonstrates that representation of shape is extremely important in perception.

Representation of knowledge depends on what it is used for. In scene analysis, the primary use is for recognition; however, spatial knowledge includes other aspects. Another part of one's spatial knowledge about shape is functional. For example, the shape "sharp" has the functional use of cutting. Some other examples: a horizontal concave surface can hold liquid; a stick and pen have similiar functional shapes.

The notion of orientation has large part to do with shape. We have the concept of right and left that is derived from the shape of our bodies. But suppose we as humans had three arms radiating 120 degrees apart, our notion of orientation would change. The previously mentioned six orientation types come mostly from the different symmetry of objects.

Because the concept of shape is very difficult to represent satisfactorily, this paper will not try to represent it.

7. Surface

1.7.1 Key Concepts: (orientation, shape, boundary)

(7a) The card is face up.

Although shapes are difficult to represent, one can get a better handle on the concept of surface. In sentence 7a, the surface of the card has a particular orientation. Orientation for a surface is meant to be the direction pointing outward and perpendicular to the surface (normal).

Unfortunately, the same problem of shape pops up in the description of surfaces. Surfaces can be flat, convex, or concave. But also a surface can be arbitrarily complex, such as the outside of an Christmas ornament. The representation of flat surfaces is relativity simple, but the concave and convex surfaces have no simple representation. Complex surfaces will not be represented.

(7b) The book teetered at the edge of the table.

Shapes and surfaces have boundaries. The table's edge is a boundary of the table's surface. An edge is where two surfaces meet. The perimeter, the complete boundary of a surface, is composed of all the edges of the surface. A point is formed by the meeting of three or more surfaces. Similiar to a surface, a boundary can be straight, convex, or concave.

1.7.2 Representation of Surface

Surface will be repesented as having a shape, edges, orientation, and size.

Rolename: SURSHAPE
Concept: the shape of the surface
Fillers: -10 to +10
-10=very convex, 7=convex, 0=flat, 7=concave,
10=very concave

Rolename: FEELSHAPE
Concept: the kinesthetic perception of the surface.
Fillers: -10 to +10
-10=very smooth, 7=smooth, 7=rough, 10=very rough

1.7.3 Inferences for Surface

1. A horizontal concave surface will hold liquid.
2. A non-horizontal surface will not hold liquid.
3. A convex surface will not hold liquid.
4. A smooth surface will reflect light well.
5. A rough surface will not reflect light well.

2. Other Problem Domains and the interaction with the Spatial domain

Previous sections have used concepts outside the spatial domain. In dealing in the real world, there is more knowledge than spatial knowledge, and the interactions between problem domains are tightly intermingled. In this section, the relationship between the spatial domain and other related domains will be discussed briefly.

2.1 Gravity

(1) The book was pushed until it fell off the table.

We have already seen that gravity plays an important role in frame of reference. There are two gravitational properties of objects: center of gravity and weight. Notice that center of gravity is a location, which is a spatial concept. In sentence 1, there are two things going on: first, the location of the book is being changed in the horizontal direction; second, eventually the center of gravity of the book is no longer above the table's surface and causes the book to move vertically to the ground. (Actually there is also rotation involved.) The basic inference for gravity is the following. If object A is not in physical contact with anything then it will move down until it comes in physical contact with something below it.

2.2 Vision

(2a) I looked out the window to see my friend.

(2b) I looked out the wall to see my friend.

The second sentence is strange because walls are typically opaque. THe visibility of an object depends on its spatial relationships and visual properties of objects between the observer and the object. The visual domain includes knowledge about opacity and tranparency; other visual properties are color and brightness. Any object that is totally behind another is not visible, unless the intervening object has some degree of transparency. However, visual perception is extremely complex, and there is no simple distinction between seeing and not seeing.

An inference in this domain is the following. If A is ATTENDing with EYES in direction D, and object B is in front of object C, and if B is transparent; then A can see C, otherwise A cannot see C. Distance inference le and surface inference 4 are other examples of the interaction between the two domains.

2.3 Materials

(3a) The shot put was placed on the paper cup.

(3b) The pencil broke.

(3c) The shot put was placed on the water.

When the shot put is placed on the paper cup, the shape of the cup will change; i.e., it will be crushed. This knowledge of strength of materials explains the effect on the cup, which manifests itself in the spatial domain; that is, the shape of the cup changed. Similiarly, when the pencil breaks, there are new surfaces formed and the pencil is now in two pieces. And each piece has its own center of gravity, location, and surfaces. In sentence 3c, the knowledge of material's states (solid, liquid, gas) helps predict the consequences in the spatial domain; i.e., the shot will sink.

The material domain includes the properties: density, strength, hardness, physical state, and composition (what it is made of).

Typical inferences are the following.

If solid object A is on top of liquid B and A is more dense than B, then A will sink.

If an object is burned, then its shape is changed.

A gas will have the shape of its container.

3. Conclusion

Spatial knowledge is a very basic to human thinking. Some spatial concepts are representable with standard AI notations. Other concepts (namely, shape and surface) are difficult to represent because of the associated perceptual and motor activities needed to understand them. Tightly intermingled with the spatial domain are other knowledge domains such as vision which add to the complexity of representing space adequately.

4. Summary

I. Space
   1. Location
   2. Directions (left, right) (above, below) (in-front, behind)
   3. Frame of Reference (location, orientation)
   4. Spaces (enclosed, object, open)
   5. Distance (relative, absolute, comparative)
   6. Shape
   7. Surface (concave, convex, flat)
   8. Boundary (perimeter, edge, point)
   9. Other problem domains
      a. Gravity (weight, center of gravity)
      b. Vision (opacity-transparency, color, brightness)
      c. Material (density, strength, hardness, state)
      d. Motion (velocity, spin)

II. The Primitive Acts

1. PTRANS
The primitive PTRANS has two new slots: ROUTE and DISTANCE.

2. PROPEL
The primitive PROPEL has one new slot: VEC.

3. ROTATE
The new primitive act has the slots X, Y, Z, TO, FROM, ORIENT. An act of rotating an object will change the object's orientation.

4. ATTEND
The primitive ATTEND has one new slot: VEC.

III. Primitive States and Relations

1. *LOC* - in section 1 and 4
2. *DIRECTION* - in Section 2
3. *OUTSIDE*, *INSIDE* - in section 4
4. *DISTANCE* - in Section 5

IV. Predicates

1. *OBJPRT* - to specify a part of an object
2. *HEIGHT* - the height of an object
3. *WIDTH*

4. *DEPTH*
5. *SIZE* - all dimensions
6. *AREA* - for surface

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