

CogSketch

Spatial Reasoning

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1 INTRODUCTION

This is a very preliminary draft of documentation describing the spatial reasoning facilities built into CogSketch. We are making this draft documentation available to support those who wish to experiment with these facilities as they evolve.

1.1 ACCESSING SPATIAL REASONING FACILITIES

If you just want to try things out, a good way to get started is to use the Query window available through the knowledge inspector or by selecting the “View/Query Window” menu option. You’ll find the concordance of objects to names in the left-hand frame useful for formulating queries.

These facilities are also available through the KQML server, via the ASK operation.

1.2 BRIEF OVERVIEW OF REPRESENTATION AND REASONING IN COGSKETCH

Mostly yet to be written. Here are the absolutely key points.

1.2.1 STRUCTURE OF SKETCHES

Internally, each subsketch corresponds to a reasoning context (i.e. a microtheory). In our knowledge-representations we use:

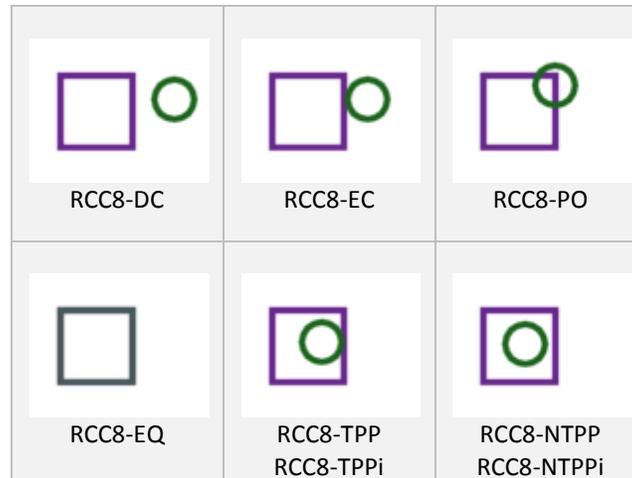
```
(ist-Information <subsketch-context> <fact>)
```

1.2.2 TRUTH-MAINTENANCE CONSIDERATIONS

All results are cached in the LTRE that serves as FIRE’s working memory, so that they can be used in explanations (cf the drill-down in the knowledge inspector). This also enables results to be appropriately retracted when the sketch is changed. This is why spatial conclusions tend to include statements about the time the ink of the glyphs involved were last updated. Whenever a glyph is moved, the now obsolete last-ink assumption is retracted and a new assumption made. This updating is part of what is happening when ink processor (displayed as the left eye in the interface) is operating.

2 RCC-8 RELATIONS

The RCC-8 relations are a set of eight mutually exclusive relations that describe all possible topological relations between two 2D closed shapes.¹



(rcc8-DC glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

disconnected

(rcc8-EC glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

edge-connected

(rcc8-PO glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

partial overlap

(rcc8-EQ glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

equal

(rcc8-TPP glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

tangential proper-part

¹ Cohn A. Calculi for qualitative spatial reasoning. In Artificial Intelligence and Symbolic Mathematical Computation, LNCS 1138, eds: J Calmet, J A Campbell, J Pfalzgraph, Springer Verlag, (1996) 124-143.

(rcc8-TPPi glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

inverse tangential proper part

(rcc8-NTPP glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

non-tangential proper-part

(rcc8-NTPPi glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

inverse non-tangential proper-part

(hasRCC8Relation glyph1 glyph2 rel)

Automatically computed between pairs of glyphs on same layer.

Can be generated on demand by fire:ask.

Says that the given RCC8 relation holds for the two glyphs.

3 HIGHER-LEVEL TOPOLOGICAL RELATIONS

CogSketch can compute several higher-level topological relations, based on the RCC-8 relations described above. The first three are computed automatically and are used during comparison (e.g., in worksheets and other applications). The final two can be computed on demand. Unlike RCC-8, these relations are not mutually exclusive. For example, if one glyph contains another, they may also intersect. If two glyphs are overlapping, they will necessarily intersect.

(containsObject glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Says that glyph1 contains glyph2. This is based on the RCC-8 relations rcc8-TPP and rcc8-NTPP. Note that transitive containment is avoided. That is, if (containsObject glyph1 glyph2) and (containsObject glyph2 glyph3) hold, then (containsObject glyph1 glyph3) will *not* hold.

(objectsIntersect glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Says that the glyph1 and glyph2's ink intersect. This is based on the RCC-8 relations rcc8-EC, rcc8-PO, and rcc8-TPP. Thus, if the relation rcc8-TPP holds, then both containsObject and objectsIntersect will hold.

(objectsOverlap glyph1 glyph2)

Automatically computed between pairs of glyphs on same layer.

Says that the interiors of glyph1 and glyph2 overlap. This is based on the RCC-8 relation rcc8-PO.

(symmetricBisection glyph1 glyph2)

Can be generated on demand by fire:ask.

Says that the two glyphs overlap one another to the extent that each bisects the other.

(objectContains-Transitive glyph1 glyph2)

Can be generated on demand by fire:ask.

Says the same thing as objectContains, except that transitive containment is preserved. I.e., if glyph1 contains glyph2, and glyph2 contains glyph3, then (objectContains-Transitive glyph1 glyph3) will hold, whereas (objectContains glyph1 glyph3) will not.

4 VORONOI DIAGRAM RELATIONS

The following facts are derived from the voronoi diagrams computed for a subsketch. Note that more than one voronoi may be computed for a given subsketch — rules in our knowledge-base which voronoi diagrams get computed. For example, in nuSketch Battlespace voronoi diagrams are made for the terrain information, pathways (avenues of approach, etc.), and the enemy and friendly military units. In CogSketch, we currently just compute one voronoi diagram for each subsketch, using all the glyphs on the subsketch as input.

(vAdjacent *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that the two glyphs are adjacent to each other on at least one of the voronoi diagrams containing both glyphs. The two glyphs are considered adjacent if at least one voronoi site (cell) of *glyph1* is touching a site of *glyph2*.

(vNear *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that the two glyphs are near each other on at least one of the voronoi diagrams containing both glyphs. The notion of 'near' is a bit looser than that of 'adjacent'. To compute a region of nearness around a glyph, we include all the immediately adjacent sites and expand outwards into sites whose area is mostly encompassed by the adjacent sites.

(vBetween *glyph1 glyph2 glyph3*)

Can be generated on demand by fire:ask.

Says that *glyph2* is between *glyph1* and *glyph3* on at least one of the voronoi diagrams containing both glyphs.

5 POSITIONAL RELATIONS

5.1 ABOUT THE GLYPHS

(above *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that *glyph1* is above *glyph2* in the sketch coordinate system (Y-values increase as you go upwards; higher values are above lower values).

(below *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that *glyph1* is below *glyph2* in the sketch coordinate system (Y-values increase as you go upwards; higher values are above lower values). Note that above is our canonical representation -- Calling `nusketch:compute-positional-relations` where some glyph A is below of some other glyph B will not generate a below fact but will instead generate (above B A).

(rightOf *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that *glyph1* is to the right of *glyph2* in the sketch coordinate system (X-values increase as you go towards the right).

(leftOf *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that *glyph1* is to the left of *glyph2* in the sketch coordinate system (X-values increase as you go towards the right). Note that `rightOf` is our canonical representation -- Calling `nusketch:compute-positional-relations` where some glyph A is left of some other glyph B will not generate a leftOf fact but will instead generate (`rightOf B A`).

(positionalRelationFor *glyph1 glyph2 rel*)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two glyphs. For glyphs, *rel* will be one of above, below, `rightOf`, or `leftOf`.

(enclosesVertically *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that *glyph2* is completely within the vertical bounds determined by the minimum Y-coordinate and maximum Y-coordinate of *glyph1*.

(enclosesHorizontally *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that *glyph2* is completely within the horizontal bounds determined by the minimum X-coordinate and maximum X-coordinate of *glyph1*.

(directionalSignature *glyph1 glyph2 sig*)

Can be generated on demand by fire:ask.

Low-level presentation of the position relation between two glyphs. The signature is a set of one or more numbers indicating the region in which *glyph2* is, relative to *glyph1*. 1 is directly right of *glyph1*, 2 is right and above, 3 is directly above, etc.

(occludes *glyph1 glyph2 glyph3*)

Can be generated on demand by fire:ask.

Says that *glyph1* is in a position between *glyph2* and *glyph3* such that it occludes each from the other. In cases of partial occlusion, this relationship holds if any of the following three conditions is true: (1) More than 50% of the area of *glyph1* lies in the “visibility region” between *glyph2* and *glyph3*, i.e. more than 50% of *glyph1* participates in the occlusion, (2) *glyph1* occludes more than 50% of *glyph2* from *glyph3*, or (3) *glyph1* occludes more than 50% of *glyph3* from *glyph 2*.

5.2 ABOUT THE OBJECTS REPRESENTED BY THE GLYPHS

5.2.1 PHYSICAL-VIEW GENRE, LOOKING-FROM-SIDE POSE

(above *obj1 obj2*)

Can be generated on demand by fire:ask.

Says that *obj1* is above *obj2*.

(below *obj1 obj2*)

Can be generated on demand by fire:ask.

Says that *obj1* is above *obj2*. Note that above is our canonical representation -- Calling `nusketch:compute-positional-relations` where some object A is below of some other object B will not generate a below fact but will instead generate (above B A).

(rightOf *obj1 obj2*)

Can be generated on demand by fire:ask.

Says that *obj1* is to the right of *obj2*.

(leftOf *obj1 obj2*)

Can be generated on demand by fire:ask.

Says that *obj1* is to the left of *obj2*. Note that `rightOf` is our canonical representation -- Calling `nusketch:compute-positional-relations` where some object A is left of some other object B will not generate a leftOf fact but will instead generate (rightOf B A).

(positionalRelationFor *obj1 obj2 rel*)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two objects.

(enclosesVertically *obj1 obj2*)

Can be generated on demand by fire:ask.

Says that *obj2* is completely within the vertical bounds determined by the minimum Y-coordinate and maximum Y-coordinate of *obj1*.

(enclosesHorizontally *obj1 obj2*)

Can be generated on demand by fire:ask.

Says that *obj2* is completely within the horizontal bounds determined by the minimum X-coordinate and maximum X-coordinate of *obj1*.

5.2.2 PHYSICAL-VIEW GENRE, LOOKING-FROM-TOP POSE

(positionalRelationFor *obj1 obj2 rel*)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two objects.

5.2.3 PHYSICAL-VIEW GENRE, LOOKING-FROM-BOTTOM POSE

(positionalRelationFor obj1 obj2 rel)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two objects.

5.2.4 GEOSPATIAL-VIEW GENRE, LOOKING-FROM-TOP POSE

(eastOf obj1 obj2)

Can be generated on demand by fire:ask.

(northEastOf obj1 obj2)

Can be generated on demand by fire:ask.

(northOf obj1 obj2)

Can be generated on demand by fire:ask.

(northWestOf obj1 obj2)

Can be generated on demand by fire:ask.

(westOf obj1 obj2)

Can be generated on demand by fire:ask.

(southOf obj1 obj2)

Can be generated on demand by fire:ask.

(southWestOf obj1 obj2)

Can be generated on demand by fire:ask.

(southEastOf obj1 obj2)

Can be generated on demand by fire:ask.

(positionalRelationFor obj1 obj2 rel)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two objects.

(compassPositionalRelationFor obj1 obj2 rel)

Can be generated on demand by fire:ask.

rel will be one of eastOf, northEastOf, northOf, northWestOf, westOf, southWestOf, southOf, or southEastOf.

(compassCentroidRelationFor obj1 obj2 rel)

Can be generated on demand by fire:ask.

This is similar to compassPositionalRelationFor but only the centroids of the two glyphs are used to compute the compass positional relation, ignoring the blob boundaries.

5.2.5 GEOSPATIAL-VIEW GENRE, LOOKING-FROM-SIDE POSE

(positionalRelationFor obj1 obj2 rel)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two objects.

5.2.6 GEOSPATIAL-VIEW GENRE, LOOKING-FROM-BOTTOM POSE

(positionalRelationFor obj1 obj2 rel)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two objects.

5.2.7 ABSTRACT-VIEW GENRE, UNSPECIFIED-VIEWPOINT POSE

(positionalRelationFor obj1 obj2 rel)

Can be generated on demand by fire:ask.

Says that the given positional relation holds between the two objects.

6 GLYPH-GROUPS

6.1 CONTAINMENT

(isa (ContainedGlyphGroupFn *outside-glyph* (TheList *inside-glyph1 inside-glyph2 ...*)) ContainedGlyphGroup)

Automatically computed between glyphs on a subsketch.

Reifies the glyphs contained inside another glyph, thus allowing us to reason about the group as an entity.

(containedGlyphGroupInsider *inside-glyph glyph-group*)

Automatically computed between glyphs on a subsketch.

Says that *inside-glyph* is one of the glyphs contained inside in the specified *ContainedGlyphGroup*.

(containedGlyphGroupTangentialInsider *inside-glyph glyph-group*)

Automatically computed between glyphs on a subsketch.

Says that *inside-glyph* is one of the glyphs contained inside in the specified *ContainedGlyphGroup* and is touching the interior wall of the containing glyph.

(containedGlyphGroupContainer *outside-glyph glyph-group*)

Automatically computed between glyphs on a subsketch.

Says that *outside-glyph* is the glyph containing the inside glyphs in the specified *ContainedGlyphGroup*.

6.2 CONNECTNESS

(isa (ConnectedGlyphGroupFn (TheList *glyph1 glyph2 ...*)) ConnectedGlyphGroup)

Automatically computed between glyphs on a subsketch.

Reifies a group of connected glyphs.

(connectedGlyphGroupMember *glyph glyph-group*)

Automatically computed between glyphs on a subsketch.

Says that *glyph* is one of the glyphs contained inside in the specified *ConnectedGlyphGroup*.

(connectedGlyphGroupTangentialConnection *glyph1 glyph2 glyph-group*)

Automatically computed between glyphs on a subsketch.

Says that *glyph1* and *glyph2* are connected because their outsides are touching and that they belong to the specified *ConnectedGlyphGroup*.

(glyphGraphEdgesFor *glyph-graph glyph* (TheList *connected-glyph1 connected-glyph2 ...*))

Automatically computed between glyphs on a subsketch.

Says that *glyph* is a node in *glyph-graph* whose arcs consist of links to the glyphs in the given list.

7 MISCELLANEOUS GEOMETRY

(areaOfObject *object area*)

Can be generated on demand by fire:ask.

Gives the area of the object in "real-world" units (i.e. if the glyph is a square that is one unit wide by one unit tall, and each unit represents 10 Km, then the area would be (Kilometer 100)). The area is computed using the blob boundary of the glyph that represents the specified object.

(centralReferencePoint *object point*)

Can be generated on demand by fire:ask.

Specifies the centroid of the object, in "real-world" units. The centroid is computed from blob boundary of the glyph that represents the specified object.

(distanceBetween *obj1 obj2 distance*)

Can be generated on demand by fire:ask.

Returns the distance between the glyphs representing the two objects.

(entityCentroidOnPath *obj path-glyph*)

Can be generated on demand by fire:ask.

(entityCentroidOnPath ?probe ?path) is true exactly when ?probe is close enough to some point on ?path, as determined by ?path's width.

(entityLocatedAt *obj location-obj*)

Can be generated on demand by fire:ask.

Object is located at location, meaning inside or overlapping or touching.

(entityLocatedInside *obj location-obj*)

Can be generated on demand by fire:ask.

Object is located inside location.

(facingRelation *obj1 obj2 facingRelationSpecifier*)

Can be generated on demand by fire:ask.

Says that the specified relation holds between the facing directions of Obj1 and Obj2. Acceptable relations here are onLeftFlank-Facing, onRightFlank-Facing, onRear-Facing, and onFront-Facing.

(fixedAxisRotation *situation1 situation2 obj1 origin*)

Can be generated on demand by fire:ask.

Indicates that, in situation2, obj1 has been rotated around origin without translation from its orientation in situation1.

(blobIntersectsConvexHull *glyph1 glyph2*)

Can be generated on demand by fire:ask.

Says that the blob boundary of glyph1 intersects the convex hull of glyph2.

(lengthAlongMajorAxis *obj distance*)

Can be generated on demand by fire:ask.

Gives the length of an object along its major axis in "real-world" units.

(widthAcrossMajorAxis *SpatialThing* Distance)

Can be generated on demand by fire:ask.

Gives the width of an object across its major axis in "real-world" units.

(majorAxisAngle *glyph* angle)

Can be generated on demand by fire:ask.

Represents the major axis angle, relative to the current 2D orientation of the glyph.

(outsideNormal *glyph* surface *qualitative-vector*)

Can be generated on demand by fire:ask.

Says that the vector is the outside normal for the specified surface of a glyph. The surface is an outside edge of a glyph computed via glyph decomposition.

(overlappingParts *glyph1* segment1 *glyph2* segment2)

Can be generated on demand by fire:ask.

Says that glyph1 and glyph2 overlap and specifies the line segments where the overlap occurs.

(qualitativeVectorBetween *NuSketchPoint* *NuSketchPoint* *QualitativeVector*)

Can be generated on demand by fire:ask.

qualitativeDirection is true iff the third argument is the qualitative direction from the first argument to the second argument.

(relativePositionAlong *Path-Spatial* *SpatialThing-Localized* *SpatialThing-Localized* *PathRelativePositionRelation*)

Can be generated on demand by fire:ask.

(relativePositionAlong ?path ?probe ?ref ?relation) states that ?relation holds for ?probe relative to ?ref along ?path.

(relativePositionChange *situation1* *situation2* *obj1* *obj2* *qualitative-vector*)

Can be generated on demand by fire:ask.

Gives the qualitative change in the vector difference between obj2 and obj1 that happened between situation1 and situation2.

(shortestRotationDir *situation1* *situation2* *obj* *rotation-dir*)

Can be generated on demand by fire:ask.

Indicates the direction in which obj rotated between situation1 and situation2.

(surfaceOverlapDirToPoint *QMSurface* *QMSurface* *QMPoint* *QualitativeVector*)

Can be generated on demand by fire:ask.

surfaceOverlapDirToPoint is true iff the qvector is the direction from the midpoint of the overlap of the two surfaces to the qpoint.

(ConvexHullFn *glyph*)

A functional wrapper that can be wrapped around any glyph when querying for a topological relationship. The query will effectively replace the glyph in the query with its convex hull.

(surfaceContactDirection *glyph1* *glyph2* *direction*)

Can be generated on demand by fire:ask.

Says that glyph1 has a surface contact with glyph2, where the direction of contact is in the specified qualitative direction.

(glyphFromGlyphIntersection *glyph1 glyph2 layer new-glyph*)

Can be generated on demand by fire:ask.

Says that the new-glyph, to be placed on layer, is made from the intersection of the regions of glyph1 and glyph2

(glyphFromGlyphUnion *glyph1 glyph2 layer new-glyph*)

Can be generated on demand by fire:ask.

Says that the new-glyph, to be placed on layer, is made from the union of the regions of glyph1 and glyph2

(glyphFromGlyphDifference *glyph1 glyph2 layer new-glyph*)

Can be generated on demand by fire:ask.

Says that the new-glyph, to be placed on layer, is made from the region of glyph1 that isn't overlapping glyph2

8 VISUAL/CONCEPTUAL RELATIONS

For many reasoning tasks it is helpful to clarify for CogSketch what relationship holds between the objects depicted based on the visual relationships that hold between the glyphs that depict them. We call these visual/conceptual relationships, since they are derived from both kinds of information. For example, two glyphs that touch could indicate that they are rigidly connected, hinged, or any of a number of other possibilities, depending on the specific kinds of entities involved. To specify these relationships for a sketch, click on the  icon. A browser window will open, providing a form which enables you to choose a specific relationship for each pair of entities that have a form of visual relationship. When you are finished selecting relationships, click the submit button. If you need to change any of the VCR relationships, check the retract box underneath that relationship and click the submit button. You should get the drop-down menu again and you can re-assign the relationship between the involved glyphs.

Some things to know about this computation:

- The set of possible candidates can be quite large or quite small, depending on the visual and conceptual properties of the entities involved. Having over one hundred possibilities is not uncommon. Sorting through them can be complex, and we recommend having a KB Browser window open on the side while you are familiarizing yourself with the options.
- Only relations whose argument type constraints are consistent with the declared types of the entities are presented as possibilities. No other information is currently used to filter the set, e.g., it does not try to derive each of the possibilities and its negation using the information in the sketch plus the KB knowledge.
- The only visual relationships between glyphs that currently trigger this computation are touching and insideness (i.e., RCC8-EC, RCC8-PO, RCC8-TPP, RCC8-NTPP). If you do not get possible relationships for a pair of glyphs, check to see if one of these visual relationships holds, and if not, redraw or move one of them.
- If the set of relationship options does not include something that you think should be there, check to see if that relationship is consistent with the types of entities involved, using the KB Browser.

9 RELATIONS USED IN SPATIAL ROUTINES

The following four tables describe the attributes and relations used by Spatial Routines during cognitive modeling simulations (e.g., see Perceptual Sketchpad and Geometric Analogy in the User Manual). The first two tables describe the attributes and relations used to represent an image, i.e., a sketch drawn in CogSketch or a psychological stimulus imported into CogSketch. The latter two tables describe how routines represent a *pattern-of-variance*. A pattern-of-variance describes the differences found between images. It is used by Spatial Routines in some problem-solving tasks, such as geometric analogy and Raven’s Progressive Matrices.

9.1 OBJECT ATTRIBUTES

Each object in an image (i.e., each glyph in CogSketch) is assigned a set of attributes from the following list.

Type	Term	Description
General Shape Type	2D-Shape-Generic ^A	Any visible 2D shape
	Implicit-Shape ^A	A shape implied by negative space
	Proximal-Similar-Shape-Group ^A	A group formed of several similar closed shapes that are about equally distant from each other
Specific Shape Type	Dot-Shape ^A	Special shape: dot (any very small glyph)
	VerticalEdge/ HorizontalEdge ^{A,S}	Shape consisting of a single straight edge, horizontally or vertically aligned
Closedness	2D-Shape-Closed ^{A,S}	Any closed shape
	2D-Shape-Open ^{A,S}	Any open shape
Convexity	2D-Shape-Convex ^{A,S}	Closed shape without any concavities
Curvedness	2D-Shape-Curved ^{A,S}	Shape with only curved edges
	2D-Shape-Straight ^{A,S}	Shape with only straight edges
Junctions	2D-Shape-Forked ^{A,S}	Shape with junctions where 3+ edges meet
Symmetry	Symmetric-Shape ^{A,S}	Shape with one axis of symmetry
	Perpendicular-Symmetric-Shape ^{A,S}	Shape with two perpendicular axes of symmetry
	Fully-Symmetric-Shape ^{A,S}	Shape with two perpendicular axes of symmetry, plus at least one more axis, and with a fairly even aspect ratio

	Multiply-Symmetric-Shape ^{A,S}	Other shape with multiple axes of symmetry
	Symmetric-Blob	Shape with no detected symmetry axes, but with no axes of elongation, suggesting an overall regular shape
Alignment	2D-Shape-AxisAligned ^A	Shape whose edges are aligned with x- and y-axes
	2D-Shape-Oblique ^A	Shape whose edges are diagonal (non-axis-aligned)
Relative Size	TinySizeGlyph ^A	Tiny closed shape (based on distribution of sizes in a context)
	Small/Medium/LargeSizeGlyph ^A	„
Relative Location	Centered-Element ^A	Element located at the center of an image
	OnLeft-Element/OnTop-Element ^A	Element located at the left/top side of an image
Relative Edge Width	narrowEdged/wideEdged	Describes shapes whose edges are narrow or wide, relative to other shapes in the context
Fill Color	(ObjectsColoredFn X)	Shape with fill color X
Edge Color	(ObjectsBorderColoredFn X)	Shape with edges of color X
Texture	TexturedObject	Object with some fill texture (a set of parallel straight lines inside it)

A: These attributes describing shape or location are important in guiding the comparison between images. However, when Spatial Routines represent the pattern-of-variance *between* images, they are abstracted out. They are replaced with changes in spatial relations and with shape transformations (see below).

S: These attributes describe rotation-invariant features of an object's shape.

9.2 SPATIAL RELATIONS

These are the relations used by spatial routines.

Type	Term	Description
Relative position	(above X Y)	Object X is above object Y
	(rightOf X Y)	Object X is right of object Y
Topology	(elementContains X Y)	Closed shape X contains object Y
	(elementsIntersect X Y) ^S	The edges of objects X and Y intersect
	(elementsOverlap X Y) ^S	The interiors of closed shapes X and Y overlap

Frame of reference relations	(centeredOn X Y)	Object X contains object Y. Object X creates a frame of reference in which object Y's relative location can be encoded. In this case, object Y is located at the center of object X.
	(onLeft/Right/Top/BottomHalfOf X Y)	''
Alignment relations	(parallelElements X Y) ^S	X and Y are single edges (are rows of objects). They are parallel
	(perpendicularElements X Y) ^S	''
	(collinearElements X Y) ^S	X and Y are single edges and are collinear, or X is a single edge and Y is a small object that lies along its extension.
	(centeredOn X Y)	This relation can also indicate X is a single edge (or set of edges) and Y lies at its center.
Transformation relations	(reflectedShapes-XAxis X Y)/ (reflectedShapes-YAxis X Y) ^S	Indicates that there is a reflection between the two objects' shapes.
	(reflectedShapes X Y) ^S	Indicates that there is some other reflection.
	(rotatedShapes-90 X Y)/ (rotatedShapes-180 X Y) ^S	Indicates there is a rotation between the two objects' shapes.
	(rotatedShapes X Y) ^S	Indicates that there is some other rotation.

S: Symmetric relations in which the order of the arguments is irrelevant. E.g., (elementsOverlap X Y) => (elementsOverlap Y X)

9.3 PATTERN OF VARIANCE RELATIONS

When a spatial routine computes a pattern of variance between images, it compares the images' visual representations, containing the attributes and relations described above. It produces a set of relations describing changes between the images. These relations are given below.

Term	Description
(changeBetweenImages fact Image-X Image-Y)	Indicates that a fact holds in Image-Y but not in Image-X.
(reversalBetweenImages fact-X fact-Y Image-X Image-Y)	Indicates that a relation reverses between Images X and Y. For example, Object-A may be above Object-B in Image-X, but below Object-B in Image-Y.
(changeBetweenImagesFromTo fact-X fact-Y Image-X Image-Y)	Indicates an object transformation between Images X and Y. For example, an object might rotate, or it might change shape entirely. See the next table for a list of possible transformations.

(holdsInImage fact Image-X)

Indicates a that fact holds in Image-X. This relation may be used instead of changeBetweenImages in special cases.

9.4 SPATIAL TRANSFORMATION ATTRIBUTES

When a spatial routine computes a pattern of variance between images, it represents changes to an object's shape with the relation:

(changeBetweenImagesFromTo

(isa Element-1 Spatial-trans-attribute)

(isa Element-1 Spatial-trans-attribute)

Image-X Image-Y)

The attributes may describe a transformation such as a rotation, a deformation such as becoming longer, or a total change in shape. A generalized form allows the Structure-Mapping Engine (our model of comparison) to generalize when comparing representations. For example, it may be possible to align (isa Object-A ScaledShape-Bigger) with (isa Object-1 DeformedShape-Longer) because the two attributes share the generalized form TransformedShape-Larger.

Type	Generalized Form	Term	Description
Shape Type	ShapeType	(ShapeTypeFn id)	A shape of type <i>id</i> (<i>id</i> 's are arbitrary numbers assigned to the shape types encountered in a given context).
		(ShapeTransFn id trans scaling)	A shape of type <i>id</i> that has been transformed and/or scaled from the prototype for that type (e.g., a circle that's bigger than the circles we've seen before).
Rotation	RotatedShape	RotatedShape-90	A shape that's been rotated 90 degrees.
		RotatedShape-X	Some other rotation (rounds to the nearest 45 degrees).
Reflection	ReflectedShape	ReflectedShape-XAxis	A shape that's been reflected over the x-axis.
		ReflectedShape-YAxis	A shape that's been reflected over the y-axis.
		ReflectedShape-DiagAxis	A shape that's been reflected over one of the two diagonal, 45-degree axes.
		ReflectedShape-Other	A shape that's been reflected over some other axis.
Scaling	Transformed Shape-Larger	ScaledShape-Bigger	A shape that's become bigger.
	Transformed Shape-Smaller	ScaledShape-Smaller	A shape that's become smaller.

Deformation	Transformed Shape-Larger	DeformedShape-Longer	A shape that's become longer along one dimension.
	Transformed Shape-Larger	DeformedShape-LongerPart	One part of a shape has become longer.
	Transformed Shape-Larger	DeformedShape-AddedPart	A shape that's had a part added to it.
	Transformed Shape-Smaller	DeformedShape-Shorter	A shape that's become shorter along one dimension.
	Transformed Shape-Smaller	DeformedShape-ShorterPart	One part of a shape has become shorter
	Transformed Shape-Smaller	DeformedShape-RemovedPart	A shape that's had a part removed from it.
Addition	-----	AddedShape	A shape that's been added.
		RemovedShape	A shape that's been removed.
Other	-----	ConstantShape	A shape that's remained unchanged.

NOTE: If a shape remains constant throughout the images being compared, it is not represented at all in the pattern of variance. On the other hand, if a shape remains constant between two images and then transforms in a third image, then its remaining constant between the first two images will be represented using ConstantShape.

10 DECOMPOSITIONS

CogSketch can visually decompose a glyph into networks of edges/junctions and edge-cycles. Edges are segments of ink with relatively constant curvature that meet at junctions, and edge-cycles are closed sequences of edges that surround regions of whitespace and perimeters of edge-connected objects - islands of connected ink within the glyph. Viewing an edge/junction decomposition as a graph embedding, the edge-cycles correspond to its faces and the edge-connected objects correspond to its connected components.

A set of edge-cycle representations, which include some of the shape attributes from Section 9.1, can be generated for a glyph directly. A separate predicate is available for computing edge-cycle representations in which perceptually similar nearby cycles are grouped into texture regions, which are also described in terms of their edge-cycles. Edge representations can be generated for an edge-cycle, either by describing the relationships between, and attributes of, edges as they trace around the cycle, or by constructing a skeleton using the medial axis transform of the edge-cycle polygon. The next section outlines the predicates that generate these representations and Section 10.2 details the attributes and relations that show up in the generated representations.

10.1 PREDICATES FOR GENERATING DECOMPOSITIONS

The following predicates can be queried to generate decomposition representations. In general, they take six arguments. To cause the decomposition to be constructed, the first three arguments should be ground and the latter three should be variables. The first argument is the object to be decomposed into parts. The second and third are parameters that control the flexibility with which CogSketch will consider (a) edges to be perpendicular or parallel, and (b) objects to be the same size². They should be integers ranging from [-1,2]. The fourth, fifth, and sixth arguments will be bound respectively to the microtheory (i.e. context) where the representations were stored, the set of names for perceptual entities (edge-cycles or edges) mentioned in the generated representations, and the number of facts generated.

(edgeCycleRepresentationsFor *glyph angle-mod size-mod microtheory cycle-names num-facts*)

Can be generated on demand by fire:ask.

Says that the structured representations of the edge-cycles in *glyph*, as generated with angle-threshold modifier *angle-mod* and size-threshold modifier *size-mod* (described above), are stored in the context *microtheory*, describe the edge-cycles *cycle-names*, and span the number of facts *num-facts*.

(edgeCycleRepresentationsFor-Textured *glyph angle-mod size-mod microtheory cycle-names num-facts*)

Can be generated on demand by fire:ask.

Says that the structured representations of the edge-cycles in *glyph*, as generated with angle-threshold modifier *angle-mod* and size-threshold modifier *size-mod* (described above) and grouped into textures based on local perceptual similarities (e.g. orientation, area, complexity, edge-continuity), are stored in the context *microtheory*, describe the edge-cycles *cycle-names*, and span the number of facts *num-facts*.

² CogSketch uses a simple linear thresholding scheme to put relative sizes into four buckets (e.g. lengthTiny, lengthShort, lengthMedium, lengthLong). However, if it considers two objects to be close enough to the same size and they straddle a threshold, it will avoid splitting them into two separate buckets by allowing the threshold to shift temporarily.

(tracingEdgeRepresentationsForEdgeCycle *edge-cycle angle-mod size-mod microtheory edge-names num-facts*)

Can be generated on demand by fire:ask.

Says that the structured representations of the edges in an *edge-cycle*, as generated with angle-threshold modifier *angle-mod* and size-threshold modifier *size-mod* (described above), are stored in the context *microtheory*, describe the edges *edge-names*, and span the number of facts *num-facts*.

(medialAxisRepresentationsForEdgeCycle *edge-cycle angle-mod size-mod microtheory cycle-names num-facts*)

Can be generated on demand by fire:ask.

Says that the structured representations of the edges along the skeleton of the closed regions in *edge-cycle*, as generated with angle-threshold modifier *angle-mod* and size-threshold modifier *size-mod* (described above), are stored in the context *microtheory*, describe the edges *edge-names*, and span the number of facts *num-facts*. The skeleton is generated using a version of the medial axis transform that is filtered using the exterior segmentation (the edges in *edge-cycle*) and carved at qualitative transitions in the radius function (the distance from each point in the skeleton to the closest point along the exterior).

10.2 EDGE-CYCLE ATTRIBUTES

Edge-cycles are assigned attributes from the following catalog. There is significant overlap with the object attributes from Section 9.1.

Type	Attribute	Description
General Shape Type	PerceptualEdgeCycle	Any visible edge-cycle
	PerceptualEdgeCycle-Perimeter	An edge-cycle that traces the perimeter of an edge-connected object or a texture
	PerceptualEdgeCycle-Atomic	An edge-cycle that does not contain any other edge-cycles from the same edge-connected object (it may contain other edge-connected objects, and thus, their edge-cycles)
Specific Shape Type	Dot-Shape	Special shape: dot (any very small glyph)
Closedness	2D-Shape-Closed	Any edge-cycle that forms a closed shape
	2D-Shape-Open	Any edge-cycle that forms an open shape
	2D-Shape-PartiallyClosed	Any edge-cycle that forms an open shape with some closed parts
Convexity	2D-Shape-Convex	Closed shape without any concavities

Curvedness	2D-Shape-Curved	Shape with only curved edges
	2D-Shape-Straight	Shape with only straight edges
Junctions	2D-Shape-Forked	Shape with junctions where 3+ edges meet
Symmetry	Symmetric-Shape	Shape with one axis of symmetry
	Perpendicular-Symmetric-Shape	Shape with two perpendicular axes of symmetry
	Fully-Symmetric-Shape	Shape with two perpendicular axes of symmetry, plus at least one more axis, and with a fairly even aspect ratio
	Multipley-Symmetric-Shape	Other shape with multiple axes of symmetry
Alignment	Symmetric-Blob	Shape with no detected symmetry axes, but with no axes of elongation, suggesting an overall regular shape
	2D-Shape-AxisAligned	Shape whose edges are aligned with x- and y-axes
Relative Size	2D-Shape-Oblique	Shape whose edges are diagonal (non-axis-aligned)
	areaTiny	Tiny closed shape (based on distribution of sizes in a context)
Relative Complexity	areaSmall/areaMedium/areaLarge	„
	edgeComplexityVeryLow	Edge-cycle with very few edges (based on distribution of complexities in a context)
	edgeComplexityLow/edgeComplexityMedium/edgeComplexityHigh	„
Major Axis Orientation	2D-Shape-VerticalMajorAxis	Shape whose major axis is vertical
	2D-Shape-HorizontalMajorAxis	Shape whose major axis is horizontal
	2D-Shape-ObliqueMajorAxis	Shape whose major axis is oblique

10.3 EDGE-CYCLE RELATIONS

Edge-cycles are related to one another using relations from the following catalog.

Type	Relation	Description	
Connectivity	(cyclesShareEdge ?c1 ?c2)	The cycles share an edge	
	(cyclesShareJunction ?c1 ?c2)	The cycles share a junction	
	(cornerAdjacent-Dominates-TJunction ?c1 ?c2)	There exists a T-junction where ?c1 is the dominant cycle (along the crossbar of the T) and ?c2 is one of the smaller cycles in the T.	
	(cornerAdjacent-Codominated-TJunction ?c1 ?c2)	There exists a T-junction where ?c1 and ?c2 are the smaller corners in the T	
	(cornerAdjacent-Dominates-ArrowJunction ?c1 ?c2)	There exists an arrow-junction where ?c1 supplies the dominant cycle (along the front of the arrow) and ?c2 supplies one of the smaller corners in the arrow.	
	(cornerAdjacent-Codominated-ArrowJunction ?c1 ?c2)	There exists an arrow-junction where ?c1 and ?c2 are the smaller corners in the arrow	
	(cornerAdjacent-YJunction ?c1 ?c2)	There exists a Y-junction that contains corners from ?c1 and ?c2	
	(cornerAdjacent-Dominates-LJunction ?c1 ?c2)	There exists an L-junction where the larger corner comes from ?c1 and the smaller comes from ?c2	
	Positional	(above ?c1 ?c2)	?c1 is above ?c2
		(rightOf ?c1 ?c2)	?c1 is to the right of ?c2
Relations to parent objects	(objectContains ?c ?o)	The edge-cycle ?c contains the object ?o. ?o is either an edge-connected object or a hole in a texture region	
	(hasEdgeCycle ?eco ?c)	Edge-cycle ?c is an edge-cycle in the edge-connected object ?eco	
	(hasPerimeterEdgeCycle ?o ?c)	Edge-cycle ?c is the perimeter edge-cycle for ?o, which is an edge-connected object, or a hole in a texture region	
	(hasHole ?r ?h)	?h is a hole in the texture region ?r	

10.4 EDGE ATTRIBUTES

Edges are assigned attributes from the following catalog.

Type	Attribute	Description
Curvature	StraightEdge	Any straight edge
	CurvedEdge	Any curved edge
	EllipseEdge	Any curved edge whose endpoints connect
	MajorArcEdge/MinorArcEdge	A major/minor arc
Convexity	SemicircleEdge	A semicircle
	ConvexEdge	A curved edge that forms a convexity in the parent cycle
	ConcaveEdge	A curved edge that forms a concavity in the parent cycle
Orientation	VerticalEdge/HorizontalEdge/ObliqueEdge	A straight edge that is vertical/horizontal/diagonal
	CurvedEdge-UpBumped, CurvedEdge-DownBumped, CurvedEdge-LeftBumped, CurvedEdge-RightBumped	A curved edge whose apex points upward/downward/left/right
Relative Size	lengthTiny	Tiny edge (based on distribution of sizes in a context)
	lengthShort/lengthMedium/lengthLong	''
Radius function behavior (Medial Axis edges)	Directed/Undirected	A skeleton edge along which the radius function is relatively stable / narrowing
	Concave/Linear/Convex	A directed skeleton edge along which the second derivative of the radius function is $>/\approx/< 0$.
	Obtuse/Right/Acute	A directed skeleton edge along which the first derivative of the radius function is $>/\approx/< -1$.
	Source/Sink	An undirected skeleton edge whose directed neighbors are exclusively directed away from / toward it
	matRadiusVeryNarrow	A skeleton edge with a very narrow radius function relative to the distribution of edges in the medial axis
	matRadiusNarrow, matRadiusMedium, matRadiusThick	''

10.5 EDGE RELATIONS

Edges are related to one another using relations from the following catalog.

Type	Relation	Description
Relative Orientation/Position	(parallelElements ?e1 ?e2)	The edges are parallel
	(perpendicularElements ?e1 ?e2)	The edges are perpendicular
	(collinearElements ?e1 ?e2)	The edges are collinear
Corners	(convexAngleBetweenEdges ?e1 ?e2)	The corner going from ?e1 to ?e2 in the cycle is convex wrt the cycle
	(concaveAngleBetweenEdges ?e1 ?e2)	The corner going from ?e1 to ?e2 in the cycle is concave wrt the cycle
	(acuteCorner (convexAngleBetweenEdges ?e1 ?e2))	The corner going from ?e1 to ?e2 in the cycle forms an acute angle
	(obtuseCorner (convexAngleBetweenEdges ?e1 ?e2))	The corner going from ?e1 to ?e2 in the cycle forms an obtuse angle
	(perpendicularCorner (convexAngleBetweenEdges ?e1 ?e2))	The corner going from ?e1 to ?e2 in the cycle forms a right angle
Corner Relations	(cycleAdjacentAngles (convexAngleBetweenEdges ?e1 ?e2) (concaveAngleBetweenEdges ?e3 ?e4))	The corner going from ?e3 to ?e4 follows the corner going from ?e1 to ?e2 in the cycle
Radius function behavior (Medial Axis edges)	(weaklyDirectedConnection (directedConnection ?e1 ?e2))	Either ?e1 is directed toward ?e2, which is undirected, or ?e2 is directed away from ?e1, which is undirected. ?e1 and ?e2 must be connected
	(weaklyDirectedConnection (directedConnection ?e1 ?e2))	?e1 is directed towards ?e2, which is directed in the same direction. The two edges are connected.
	(sourceConnection (elementsConnected ?e1 ?e2))	?e1 and ?e2 are connected, and directed away from one another
	(sinkConnection (elementsConnected ?e1 ?e2))	?e1 and ?e2 are connected, and directed toward one another
	(clockwiseNeighborAtJunction ?e1 ?e2)	There exists a junction in which, going around it in the clockwise direction, ?e2 follows ?e1