Diagrammatic Reasoning and System Visualisation

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Session Overview

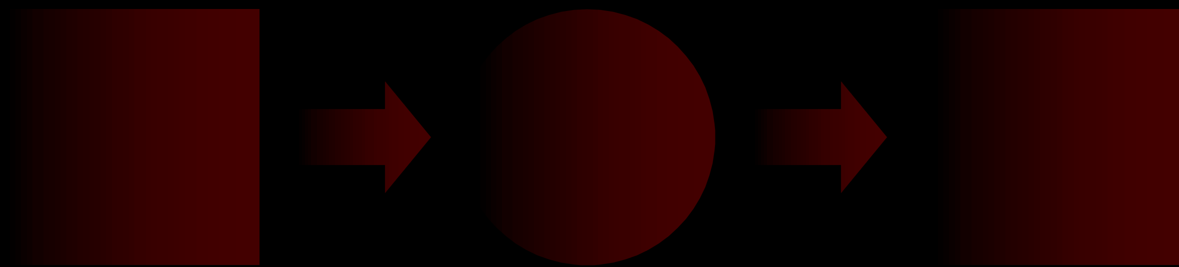
- The nature of diagrams
- Human understanding of diagrams
- Diagrammatic reasoning systems
- Future research goals
- Resources

Motivation

- Diagrams are human artefacts, constantly evolving to support human activity.
- They are “qualitative” in the sense that they have (to date) escaped mathematical formalisation.
- They are a rich domain for research:
  - Drawing lessons from human perception and reasoning
  - As a well-understood class of representational model
  - As a source of novel computation techniques
- This lecture therefore draws from psychology & graphic design in addition to computer science.

Background / Biases / Perspective

- B.Eng. 1982: major in control theory
- 6 years industrial automation development
- Comp. Sci. M.Sc. dissertation 1987: *Spatial reasoning for robots: A qualitative approach*
- 6 years AI engineering (diagnosis) and product design
- Psychology Ph.D. 1999: *Metaphor in Diagrams*
- Senior research associate, project leader: *New Paradigms for Visual Interaction*



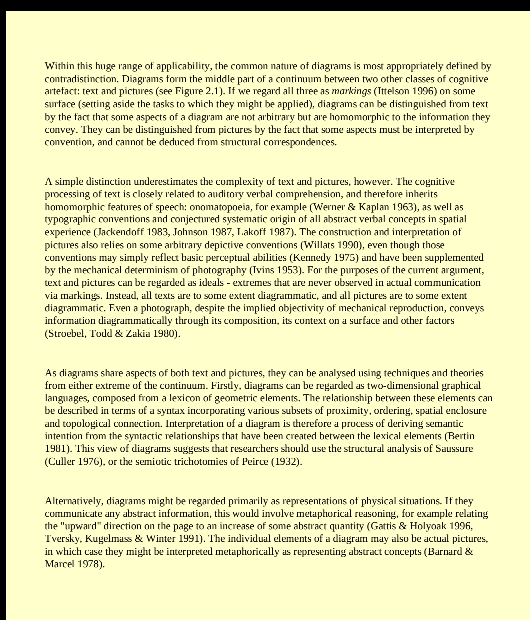
I. The Nature and Study of Diagrams

Research approaches to diagrams

- Diagrams as external representations
- Diagrams as internal representations
  - mental representations (humans)
  - computational representations (machines)
- Range of schematicity / representation taxonomy
- Diagrams as language
  - elements & configuration versus lexicon & syntax
- Diagrams as qualitative models of the world

Defining qualitative nature of diagrams

- Diagrams are unlike text; they share structure with what they describe.
- Diagrams are unlike pictures; they must be interpreted by convention.



Within this huge range of applicability, the common nature of diagrams is most appropriately defined by contradistinction. Diagrams form the middle part of a continuum between two other classes of cognitive artefact: text and pictures (see Figure 2.1). If we regard all three as *markings* (Ittelson 1996) on some surface (setting aside the tasks to which they might be applied), diagrams can be distinguished from text by the fact that some aspects of a diagram are not arbitrary but are homomorphic to the information they convey. They can be distinguished from pictures by the fact that some aspects must be interpreted by convention, and cannot be deduced from structural correspondences.

A simple distinction underestimates the complexity of text and pictures, however. The cognitive processing of text is closely related to auditory verbal comprehension, and therefore inherits homomorphic features of speech: onomatopoeia, for example (Werner & Kaplan 1963), as well as typographic conventions and conjectured systematic origin of all abstract verbal concepts in spatial experience (Jackendoff 1983, Johnson 1987, Lakoff 1987). The construction and interpretation of pictures also relies on some arbitrary depictive conventions (Willats 1990), even though those conventions may simply reflect basic perceptual abilities (Kennedy 1975) and have been supplemented by the mechanical determinism of photography (Ivins 1953). For the purposes of the current argument, text and pictures can be regarded as ideals - extremes that are never observed in actual communication via markings. Instead, all texts are to some extent diagrammatic, and all pictures are to some extent diagrammatic. Even a photograph, despite the implied objectivity of mechanical reproduction, conveys information diagrammatically through its composition, its context on a surface and other factors (Stroebel, Todd & Zakia 1980).

As diagrams share aspects of both text and pictures, they can be analysed using techniques and theories from either extreme of the continuum. Firstly, diagrams can be regarded as two-dimensional graphical languages, composed from a lexicon of geometric elements. The relationship between these elements can be described in terms of a syntax incorporating various subsets of proximity, ordering, spatial enclosure and topological connection. Interpretation of a diagram is therefore a process of deriving semantic intention from the syntactic relationships that have been created between the lexical elements (Bertin 1981). This view of diagrams suggests that researchers should use the structural analysis of Saussure (Culler 1976), or the semiotic trichotomies of Peirce (1932).

Alternatively, diagrams might be regarded primarily as representations of physical situations. If they communicate any abstract information, this would involve metaphorical reasoning, for example relating the "upward" direction on the page to an increase of some abstract quantity (Gattis & Holyoak 1996, Tversky, Kugelmass & Winter 1991). The individual elements of a diagram may also be actual pictures, in which case they might be interpreted metaphorically as representing abstract concepts (Barnard & Marcel 1978).

The graphic / linguistic distinction

- Many elements of typographic “texts” are diagrammatic.
- The study of diagrams is the study of meaning in qualitative visual structure.


Chapter 2: Diagram and Metaphor as Tools

Diagrams

External diagrams as markings

- Markings appear on a surface, but do not refer to the surface.
- Information in markings is decoupled from the real world, as are the markings themselves - because everything in the real world has three dimensions, but markings only have two.
- Markings do not occur “naturally” - they are intentional, expressive and communicative human artefacts.
  - W.H. Ittelson (1996). Visual perception of markings. *Psychonomic Bulletin & Review*, 3(2), 171-187

External diagrams as artefacts

- Information artefacts constitute
  - i) a notation
  - ii) tools & environment for manipulating notation
- They support cognitive processes of:
  - communication
  - cognitive synchronisation
  - problem solving
  - reflection and creativity

Diagrams as internal representations

- Exploiting visuo-spatial working memory
  - metric images
    - S.M. Kosslyn, T.M. Ball & B.J. Reiser (1978). Visual images preserve metric spatial information. *Journal of Experimental Psychology: Human Perception & Performance* 4, 47-60.
  - mental models of syllogisms
    - P.N. Johnson-Laird (1983). *Mental Models*. Harvard University Press.
  - mnemonic dual-coding
    - A. Paivio (1971). *Imagery & Verbal Processes*. Holt, Rhinehart & Wilson
- Ammunition in the image/logic debate
  - the origin of meaning in visual experience
  - the adequacy of propositional representations

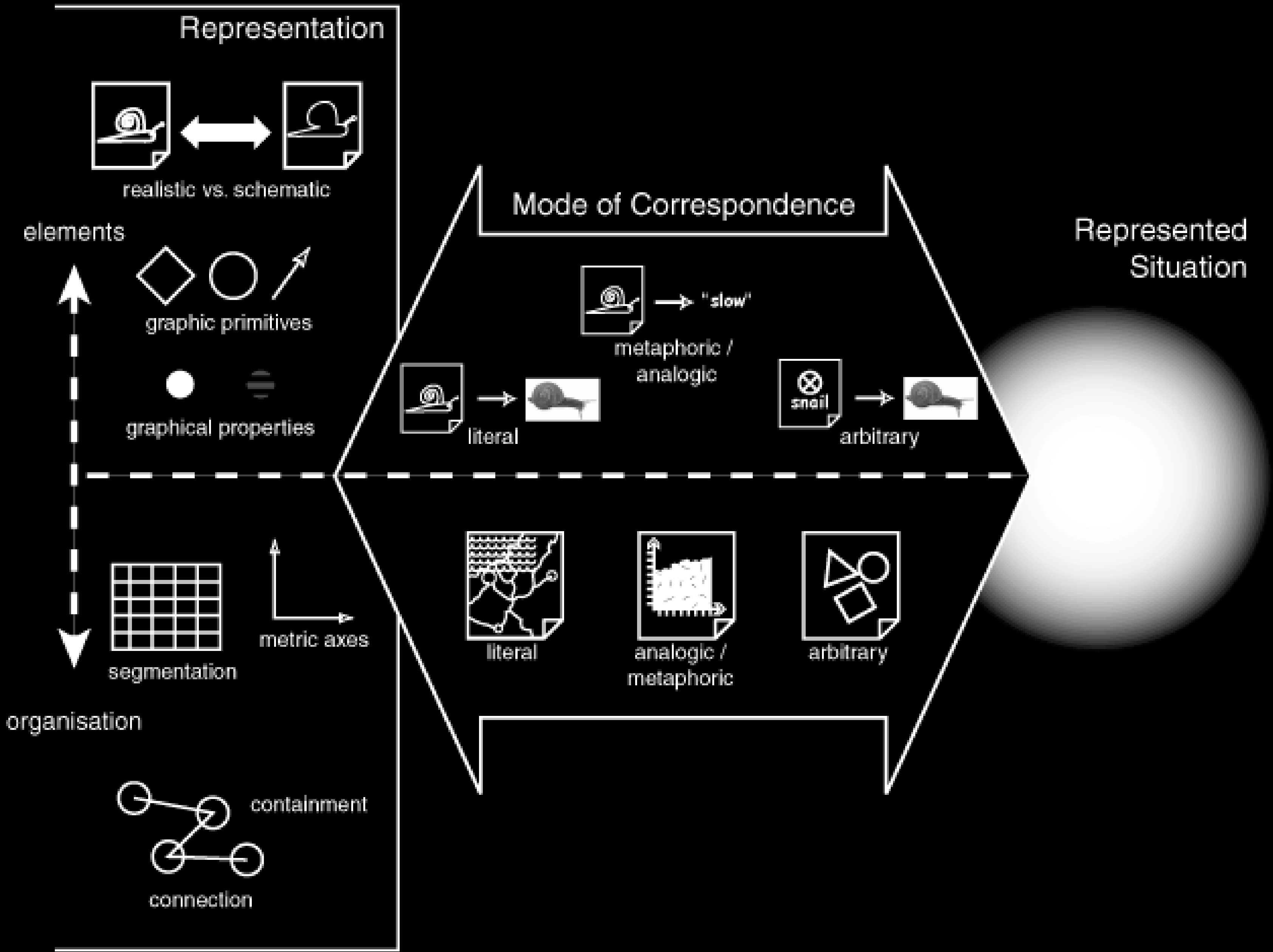
Schematicity: qualitative representation

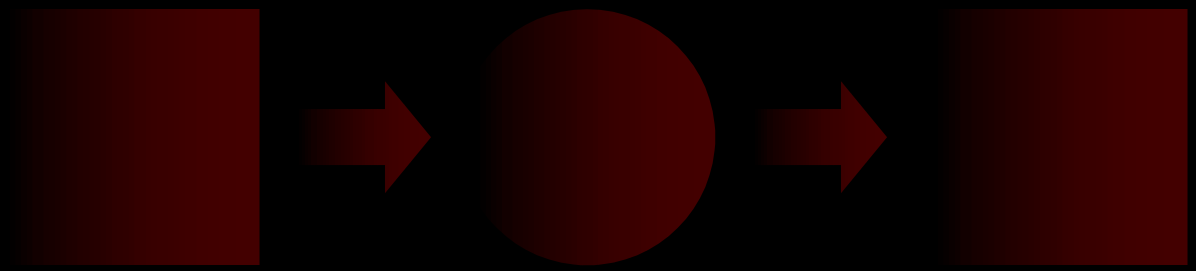
- Diagrammatic representations of physical situations are *models*:
  - representing some dimensions faithfully
  - stylising and simplifying other dimensions
    - e.g. maps - is the London Underground diagram a map?
- Diagrammatic representations of abstraction
  - present abstract elements and relations through metaphor and isomorphism
  - allow freer allocation of representational dimensions

Diagrams as language

- Elements and configuration appear (naively) as lexicon and syntax in many taxonomies.
- Further semiotic analysis identifies:
  - geometric or pictorial properties of representation
  - ontology of represented situation
  - mode of correspondence: literal vs. metaphorical
  - interaction tools, cognition and social context
    - A.F. Blackwell & Y. Engelhardt (1998). A taxonomy of diagram taxonomies. In *Proceedings Thinking with Diagrams 98*, 60-70. (also forthcoming in Olivier, Anderson & Meyer 2000)

Diagrams as models of the world





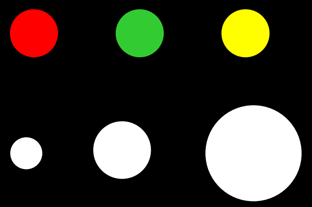
II. Examining Human Performance with Diagrammatic Models

Cognitive diagram features - overview

- What lessons can be drawn from human perception and reasoning?
- Qualitative perceptual properties
  - visual systems
  - graphic design
- Qualitative cognitive properties
  - symbolic consequences
  - ambiguity and images
- Cognitive dimensions of notations

Qualitative perceptual properties

- Visual routines
  - Algorithms can be identified to account for fundamental properties of line drawings:
    - containment, inclusion, linking
      - Ullman, S. (1984). Visual Routines. Cognition 18:97-159.
- Gestalt “laws”
  - We perceive shape from configuration



- Variables of the plane (Bertin)
  - Ink distribution is constrained by information type
    - two plane dimensions, a few ordinal dimensions & a few more nominal dimensions
      - Bertin, J. (1981). Graphics and Graphic Information Processing. Berlin: Walter de Gruyter.

Cognitive properties: symbolic processes

- Indexing and locality
  - Larkin & Simon
- Specificity
  - Stenning & Oberlander
- Free rides
  - Shimojima

Symbolic processes 1: Indexing & locality

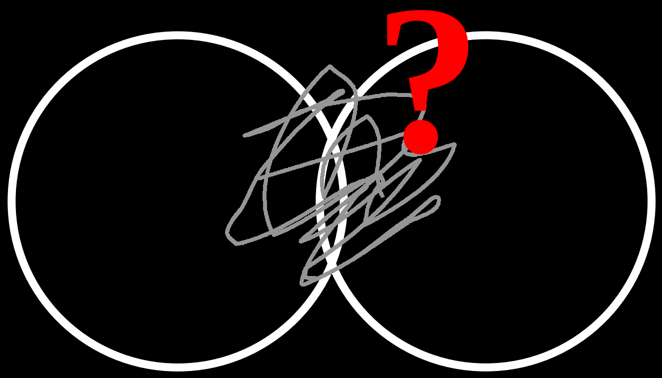
- Compare systems built to reason with:
  - propositional representation
  - diagram whose elements are located in a plane.
- Diagrams have computational advantages:
  - group information that is needed at the same time
  - establish correspondence without labels
  - support direct “perceptual inference”
    - J.H. Larkin & H.A. Simon (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science* 11, 65-99.

Symbolic processes 2: Specificity

- Can a representation be interpreted to represent more than one model? If so, it is less specific.
  - ***M****inimal* ***A****bstraction* ***R****epresentational* ***S****ystems* can only be interpreted as representing a single model.
  - ***L****imited* ***A****bstraction* ***R****epresentational* ***S****ystems* have one dimension that can be mapped to multiple models.
  - ***U****nlimited* ***A****bstraction* ***R****epresentational* ***S****ystems* also allow multiple interpretations of higher order relations.
- Computational advantages arise from specificity
  - K. Stenning & J. Oberlander (1995). A cognitive theory of graphical and linguistic reasoning: logic and implementation. *Cognitive Science* 19,97-140.

Symbolic processes 3: Free rides

- A *free ride* occurs where:
  - diagram conventions constrain operations
  - as a result of constraints, the diagram then expresses some fact which was not explicitly encoded
    - A. Shimojima (1996). Operational constraints in diagrammatic reasoning. In Allwein & Barwise (Eds), *Logical reasoning with diagrams*. Oxford University Press, 27-48.
- But diagram constraints can impede reasoning:
  - *Overdetermined alternatives* occur where it is not possible to construct a diagram without encoding an undesired fact
    - e.g. Euler sets must either be joint or disjoint.

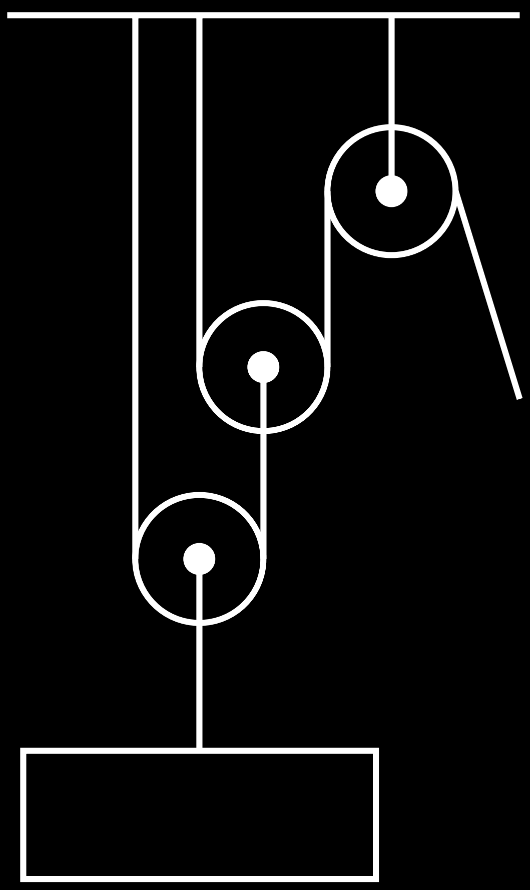


Cognitive properties: pictorial processes

- Must diagrammatic reasoning be analysed in terms of symbolic processes?
- Mental animation
  - Hegarty: attention and the causal chain
  - Schwartz: effect of pictorial realism on strategy
- Sketch ambiguity
  - Fish & Scrivener: ambiguity as a cognitive property
  - Goldschmidt: creative strategies

Mental animation: Hegarty

- Human reasoning about mechanical diagrams involves a locus of visual attention that follows the causal chain.
  - M. Hegarty (1992). Mental animation: Inferring motion from static displays of mechanical systems. *Journal of Experimental Psychology: Learning, Memory and Cognition* 18, 1084-1102.



Mental animation: Schwartz

- Choice of analytic or image strategies for isomorphic problems is influenced by pictorial representation.
  - D.L. Schwartz (1995). Reasoning about the referent of a picture versus reasoning about the picture as the referent: An effect of visual realism. *Memory and Cognition* 23:709-722.

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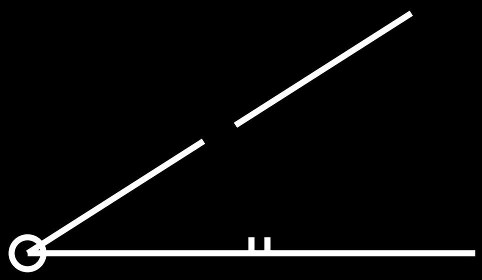

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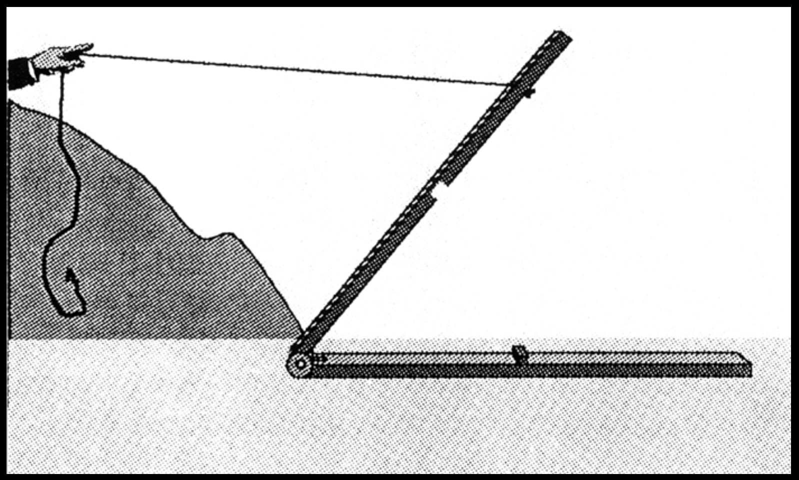


Sketch ambiguity

- Indeterminacy enables discovery
  - missing or alternative contours, wobbles, mysterious shadows, suggestive scribbles, smudges …
    - J. Fish & S. Scrivener (1990). Amplifying the mind's eye: Sketching and visual cognition. *Leonardo* 23, 117-126.
- Designers engage in a dialogue with their sketches
  - alternate generation and inspection
    - G. Goldschmidt (1991). The dialectics of sketching. *Creativity Research Journal* 4(2), 123-143.

M. Trinder (1999). The computer's role in sketch design: A Transparent Sketching Medium. CAAD Futures 99

Cognitive dimensions of notations

- How can new notations be designed to be appropriate to human activity?
- Vocabulary for describing the design trade-offs between properties of notational systems:
  - Viscosity: resistance to change.
  - Diffuseness: verbosity of notational language.
  - Provisionality: degree of commitment to actions or marks.
  - Hidden dependencies: links between entities are not visible.
  - + many more …
    - Green, T.R.G. & Blackwell, A.F. (1998). Tutorial on Cognitive Dimensions. **`http://www.cl.cam.ac.uk/~afb21/publications/CDtutSep98.pdf`**

III. Diagrammatic Reasoning Systems

Why build diagrammatic reasoners?

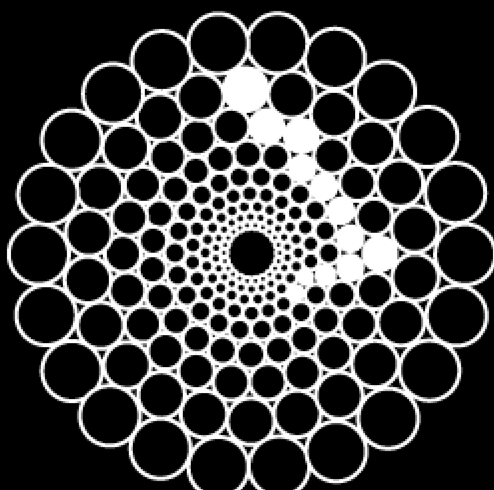
- What novel computational techniques can be developed and investigated:
  - through simulation of human perceptual and pictorial strategies?
  - through attempts to use non-symbolic representations?
- How can we exploit the well-understood characteristics of representational models:
  - where diagrams accompany text?
  - where diagrams are conventionally employed as problem-solving tools?

Computing with pictorial representations

- Funt - a model of computation in the retina
- Furnas - computation with graphical rewrite rules
- Glasgow - spatial geometry
- Olivier - variant scale and resolution
- Cypher - graphical programming for kids
- Citrin - a graphical lambda calculus

Funt’s *Whisper* system

- Qualitative physical analysis and envisionment based on visual operations in a “retina” model



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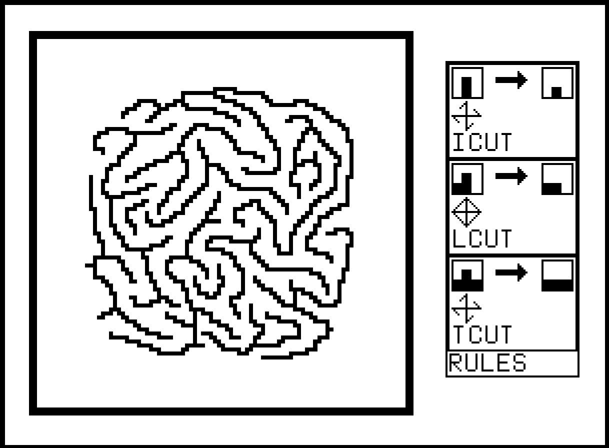
B.V. Funt (1980). Problem-solving with diagrammatic representations. *Artificial Intelligence* 13(3), 201-230.

Furnas's *BITPICT* system

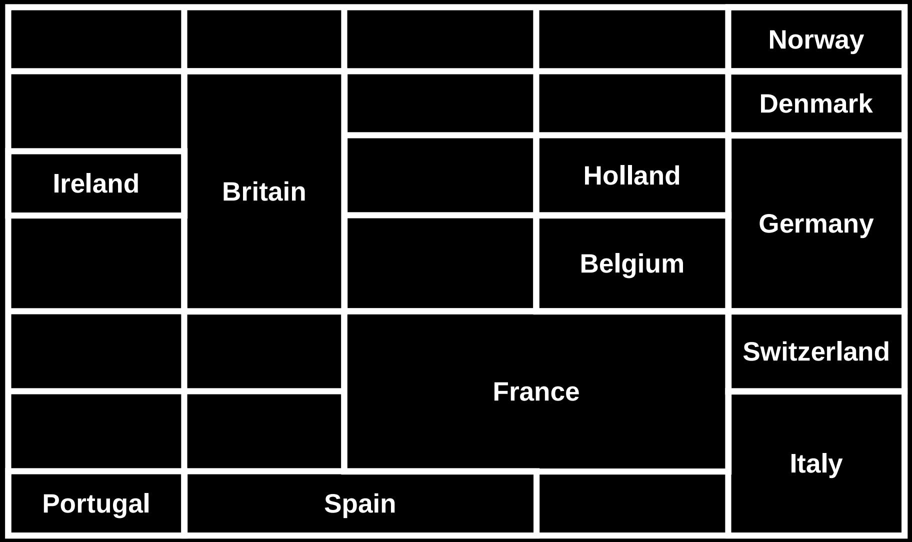
- Graphical rewrite rules specify inferential transformations on visual representations.



G. Furnas (1990). Formal Models for Imaginal Deductions. *Proc. 12th Annual Conference of the Cognitive Science Society*, 622-669.

Jenkins & Glasgow's *Nial* language

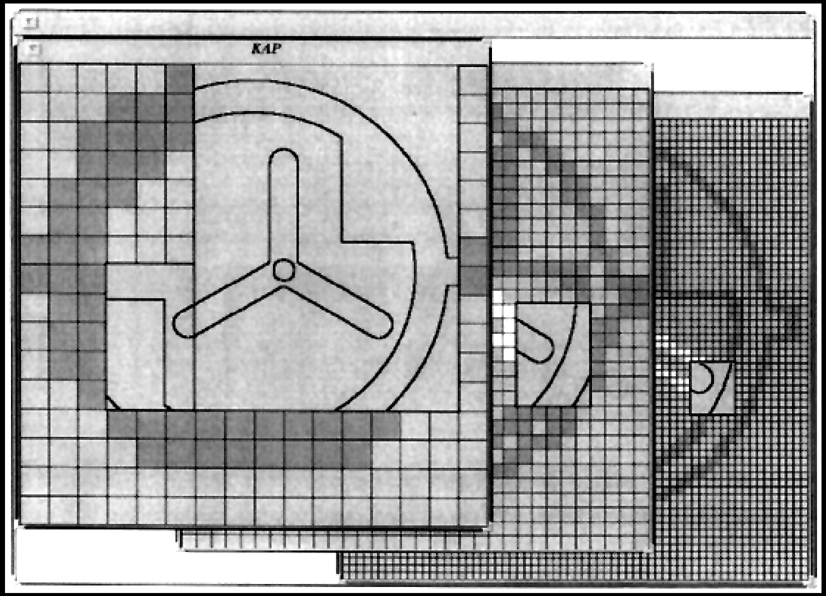
- Nested occupancy arrays make spatial relations explicit where they are relevant to the problem.



J.I. Glasgow & D. Papadias (1995). Computational imagery. In Glasgow, Narayanan & Chandrasekaran, *Diagrammatic Reasoning*. AAAI Press, pp. 435-480.

Olivier's *KAP* system

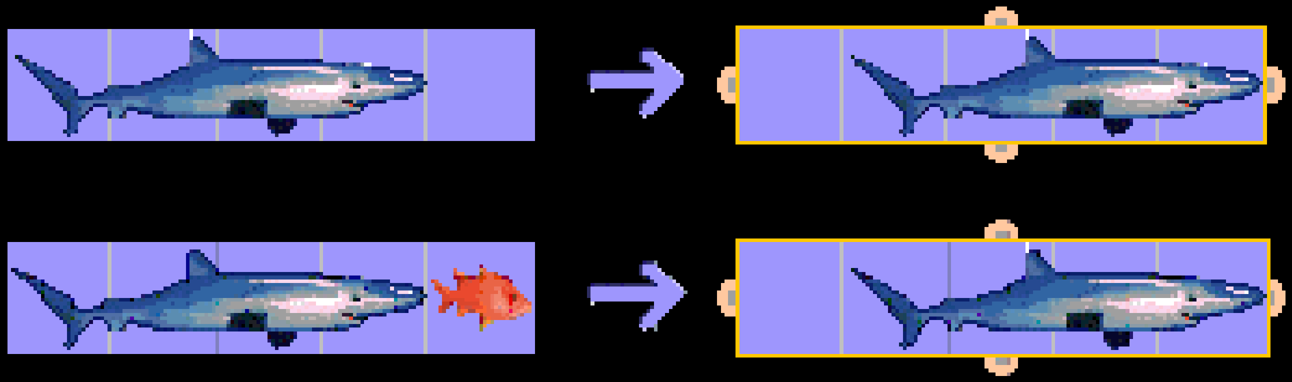
- Hierarchical representation of mechanical components used to focus attention for kinematic reasoning.



P. Olivier, K. Nakata & A.R.T. Ormsby (1996). Occupancy array-based kinematic reasoning. *Engineering Applications of Artificial Intelligence* 9(5), 541-549.

Stagecast *Creator* product

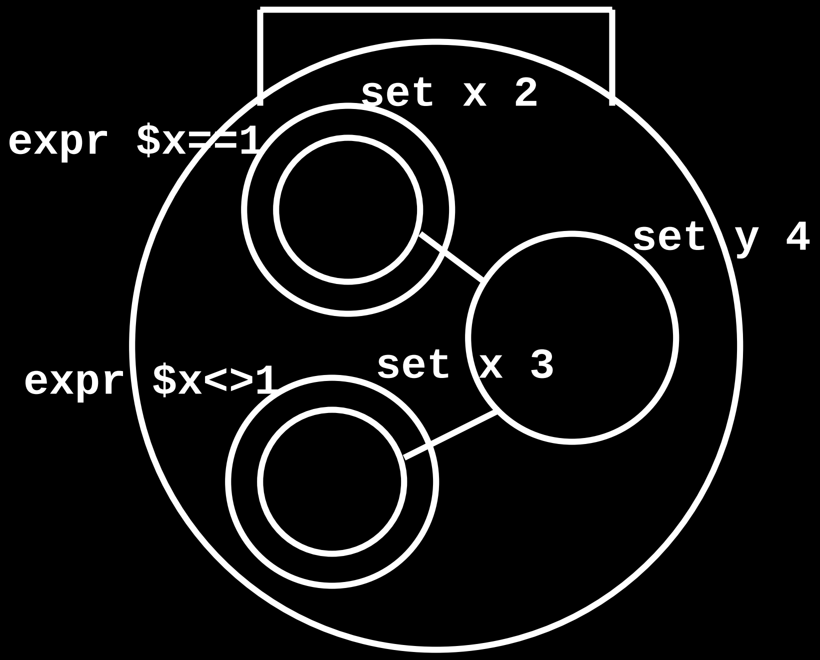
- Graphical programming for kids
  - (originally Apple KidSim/Cocoa project)
- Create simulations by demonstration, using graphical rewrite rules.



A. Cypher & D.C. Smith (1995). KidSim: End User Programming of Simulations. *Proceedings of ACM Conference on Human Factors in Computing Systems*, 27-34

Citrin's *VIPR* language

- Graphical isomorph to the lambda calculus, with beta reduction defined as a graphical rewrite rule.



W. Citrin, M. Doherty & B. Zorn (1994). Formal semantics of control in a completely visual programming language. *IEEE Symposium on Visual Languages*, 208-215

Issue: What is special here?

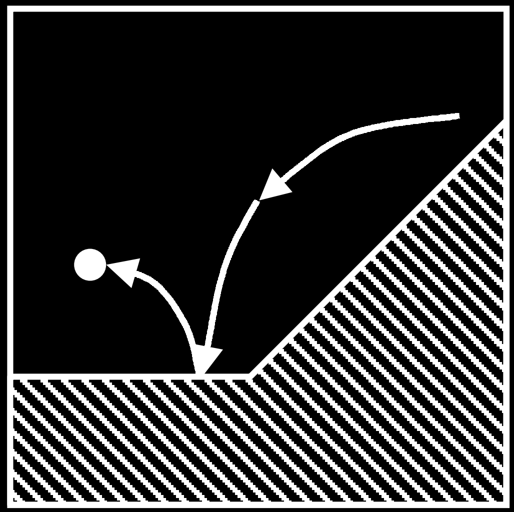
- Most of these languages and systems were designed to challenge the predominance of symbolic representations.
  - Is it true that they aren't symbolic?
- Some are now mainstream products.
  - Is there anything special about programming with qualitative pictorial representations?

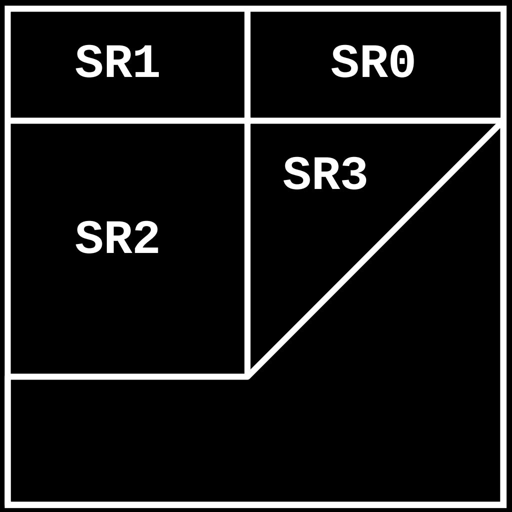
Diagrams as qualitative physical models

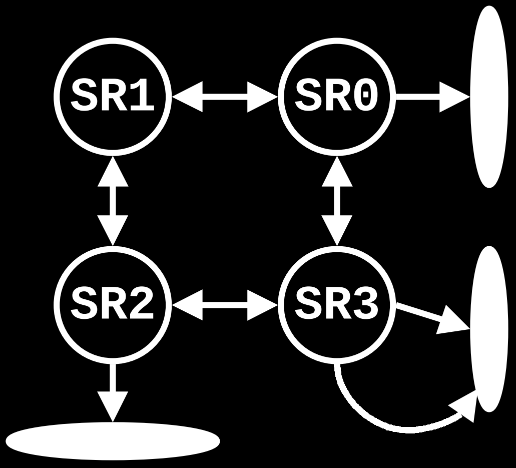
- Three early categories of qualitative spatial reasoning:
  - dynamic simulation in two dimensions
    - Forbus 1980, 1983
  - kinematic analysis of 2D mechanisms
    - Stanfill 1983, Faltings/Forbus 1987, Joscowicz 1987, Nielsen 1988
  - complex path planning in two dimensions
    - Blackwell 1987, 1989

Dynamic simulation in 2D

- Forbus's FROB (1980,1983) reasoned about dynamics in a bouncing ball world.







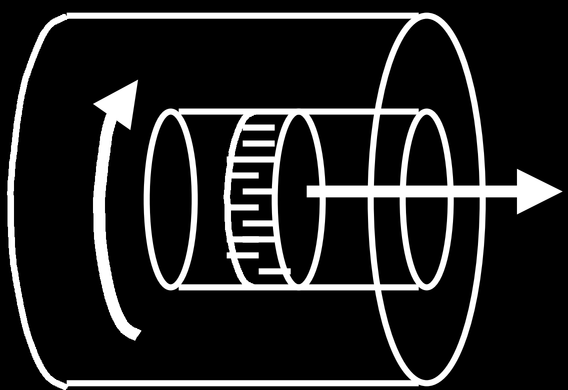
Architecture of FROB

- Metric diagram records geometric information.
- Space graph encodes relations between qualitative places.
- Action sequence describes a dynamic motion schema.

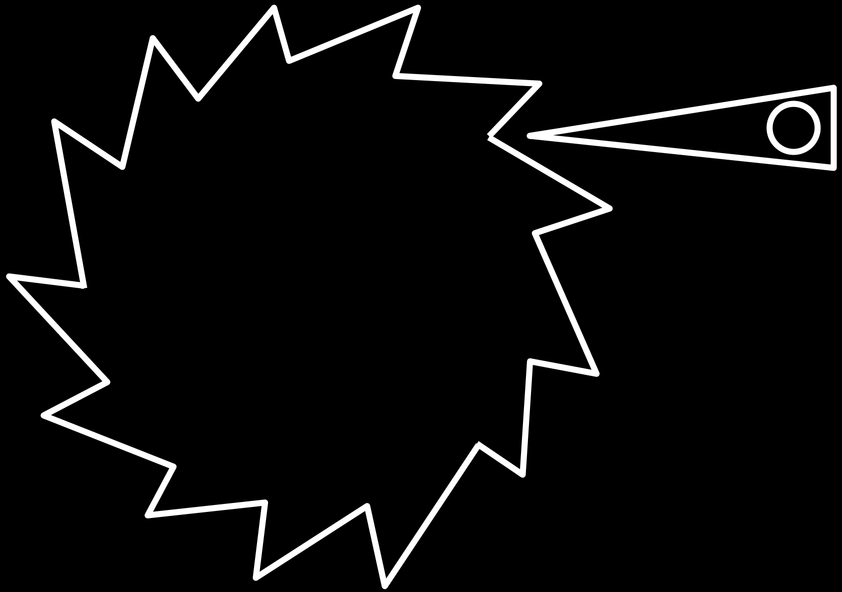
- K.D. Forbus (1980). Spatial and qualitative aspects of reasoning about motion. *AAAI 80*, 170-173.
- K.D. Forbus (1983). Qualitative reasoning about space and motion. In Gentner & Stevens, *Mental Models*. LEA, 53-73.

Kinematic analysis of mechanisms

- Analyse shape to identify kinematic function.
- Describe local constraint in configuration space.
- Derive system behaviour from related pairs.



Stanfill's "Mack" (1983)



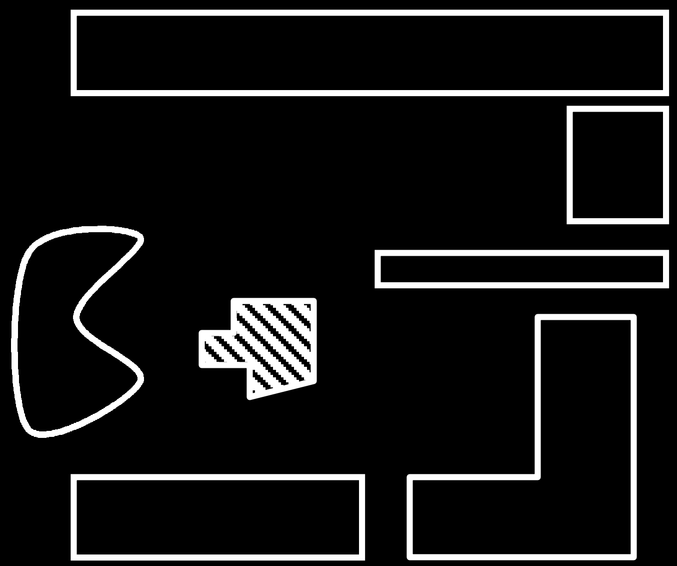
Faltings' "CLOCK" (1987)

Mechanism analysis techniques

- Stanfill's *Mack* described physical processes acting on primitive mechanical pairs.
  - C. Stanfill. (1983). The decomposition of a large domain: Reasoning about machines. *Proceedings of AAAI 83*, 387-390.
- Faltings' ***CLOCK*** develops Forbus' space graph into Place Vocabulary of configuration space.
  - K.D. Forbus, P. Nielsen & B. Faltings (1987). Qualitative Kinematics: A framework. *Proceedings of IJCAI 87*, 430-435.
- Other developments of logic and geometry in qualitative configuration space:
  - P. Nielsen (1988). A qualitative approach to mechanical constraint. *AAAI 88*.
  - L. Joskowicz (1989). Simplification and abstraction of kinematic behaviours. *Proceedings of IJCAI 89*, 1337-1342.

Complex path planning

- Blackwell's EPB/PDO (1987/1989) solved the piano-mover's problem in two dimensions.



EPB/PDO implementation approach

- Describe qualitative shape at multiple levels of detail in extended polygon boundary (including curves and other non-line segments).
- Scene constructed from boundary proximity maintained in a partial distance ordering.
- Reason about motion constraints using qualitative trigonometry.
    - A.F. Blackwell (1987). Qualitative geometric reasoning using a partial distance ordering. *Proceedings Australian Joint AI Conference AI'87*, 433-444.
    - A.F. Blackwell (1989). Spatial reasoning with a qualitative representation. *Knowledge-Based Systems*, 2(1), 37-45.

Issue: What can we do with this?

- Most of these systems were motivated by cognitive science goals.
- What can be achieved with these techniques?
  - Metric Diagram / Place Vocabulary methods have achieved general currency for qualitative applications.
  - CAD “design experts” can provide qualitative critiques.
  - Qualitative planning methods may be more robust, or operate with incomplete data.
- Integrate with conventional (propositional) models of expertise.

Integrated models of expertise

- Physics expertise
  - Narayanan, Suwa & Motoda
  - Gardin & Meltzer
  - Novak
- Geometry expertise
  - Koedinger & Anderson
  - McDougal & Hammond
- Economic expertise
  - Schijf, Leonardo & Simon

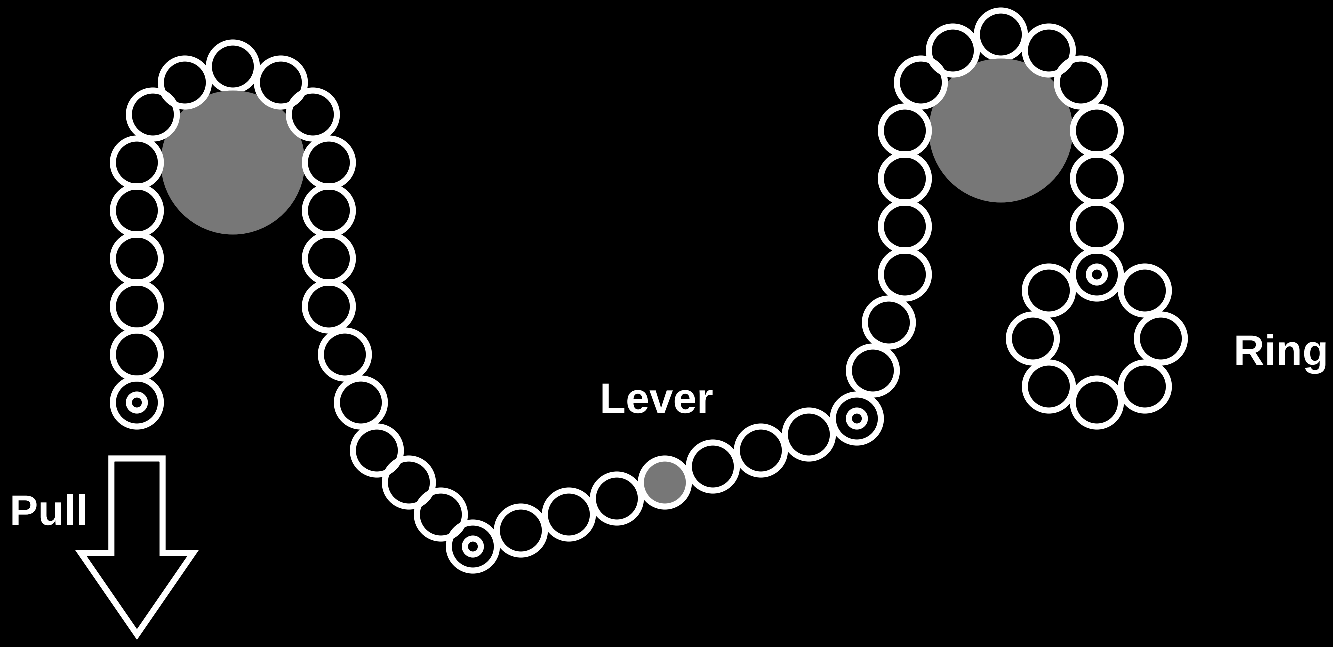
Physics expertise I

- Hypotheses about how things work can be indexed and combined via focus on a diagram.

N.H. Narayanan, M. Suwa & H. Motoda (1995). Hypothezing behaviors from device diagrams. In Glasgow, Narayanan & Chandrasekaran, *Diagrammatic Reasoning*.

Physics expertise II

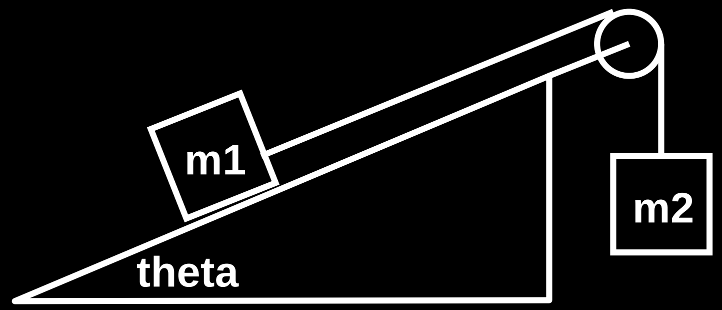
- Extend the “retina” of Funt’s *Whisper* so that cells move and interact like molecules or fluids.



F. Gardin & B. Meltzer (1995). Analogical representations of naïve physics. In Glasgow, Narayanan & Chandrasekaran, *Diagrammatic Reasoning*.

Physics expertise III

- Coreference between problem statement and diagram used to exploit illustrative conventions.



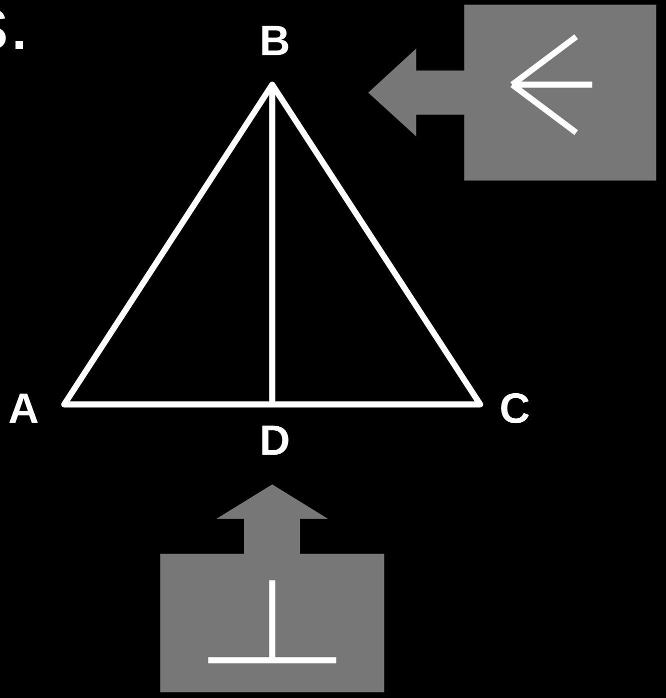
Two masses are connected by a light string as shown in the figure. The incline and peg are smooth. Find the acceleration of the masses and the tension in the string for theta = 30 degrees and m1 = m2 = 5kg.

G.S. Novak Jr. (1995). Diagrams for solving physical problems. In Glasgow, Narayanan & Chandrasekaran, *Diagrammatic Reasoning*.

Geometry expertise I

- Prune solution search space based on diagram configuration schemas.

Given:	**right angle ADB**
	BD bisects ABC
Prove:	**D midpoint of AC**



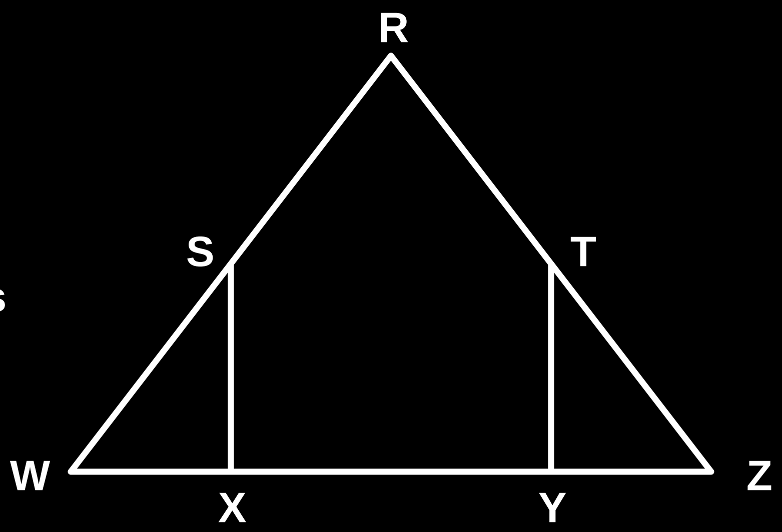
K.R. Koedinger & J.R. Anderson (1995). Abstract planning and perceptual chunks. In Glasgow, Narayanan & Chandrasekaran, *Diagrammatic Reasoning*.

Geometry expertise II

- Use diagram features to index existing similar solution plans for case-based reasoning.

Given: **SX=TY**
SW=TZ
WX=YZ

Prove: **WRZ is isosceles**



T.F. McDougal & K.J. Hammond (1995). Using diagrammatic features to index plans for geometry theorem proving. In Glasgow, Narayanan & Chandrasekaran, *Diagrammatic Reasoning*.

Economic expertise

- Based on observation of an economics expert (actually Herb Simon).
- The CaMeRa system:
  - constructs diagrams in a low resolution “visual memory”.
  - remembers semantic signficance of the lines.
  - notices features (eg intersection) in visual inspection.
  - interprets those features in the application domain.

H.J.M. Tabachnek-Schijf, A.M. Leonardo & H.A. Simon (1997). CaMeRa: A computational model of multiple representations. *Cognitive Science*, **21**(3), 305-350.

IV. Future Research Goals

Future research goals

- Further analysis of evolved specialist notations
  - music notation
  - design drawings
  - mathematical notations
- Further development of evolving notations
  - electronic circuit schematics
  - visual programming languages and UML
  - graphical user interfaces
- Interactive diagrammatic reasoning
  - integrating system inference with user's perceptions

Some work on existing notations

- Music combines analog and discrete, obligatory and optional conventions.
  - D. Blostein & L. Haken (1999). Using diagram generation software to improve diagram recognition: a case study of music notation. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 21(11), 1121-1135.
- Architectural sketches can form a natural user interface to more formal CAD systems.
  - M.D. Gross (1996). The Electronic Cocktail Napkin: A computational environment for working with design diagrams. *Design Studies*, 17(1), 53-69.
- Notational environment has dramatic effects on designers.
  - A. Black (1990). Visible planning on paper and on screen: The impact of working medium on decision-making by novice graphic designers. *Behaviour and Information Technology,* 9(4), 283-296

Some work on evolving notations

- Electronic circuit schematics: pragmatic context must be examined at time of rapid change.
  - J. Oberlander (1996). Grice for graphics: pragmatic implicature in network diagrams. *Information Design Journal*, 8(6), 163-179.
- Visual languages and UML: apparently designed without any analysis of cognitive ergonomics.
  - A.F. Blackwell (1996). Metacognitive theories of visual programming: What do we think we are doing? In *Proc. IEEE Visual Languages VL'96*, 240-246.
- Graphical user interfaces: ongoing demo culture involves very little thoughtful analysis of any kind.
  - C. & T. Strothotte (1997). *Seeing between the pixels: Pictures in interactive systems*. Springer.

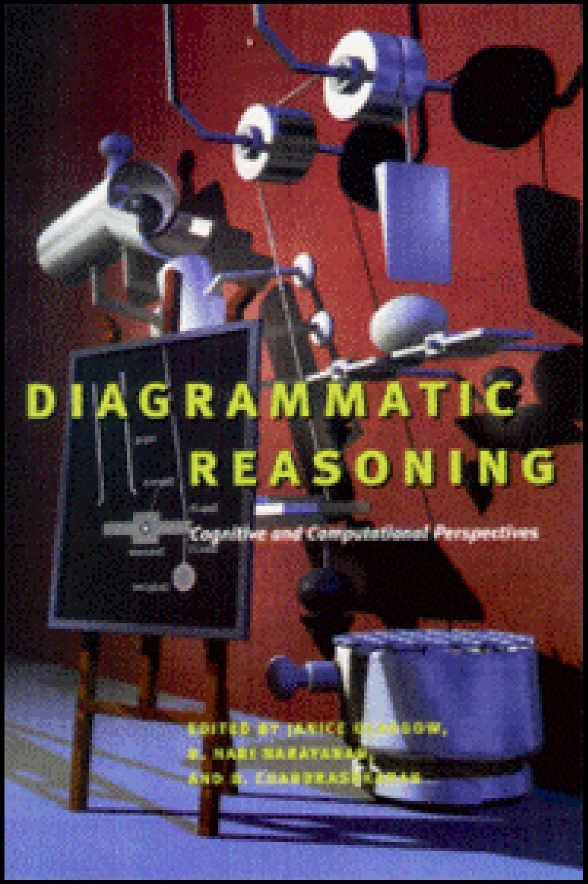
Related but different

- Wayfinding and navigation
  - human (landmarks and use of maps)
  - robot (integrating visual data, cumulative accuracy)
- Spatial language
  - mental models of texts
  - interpreting abstract spatial metaphors
- Simulation and diagnosis of physical systems
  - in cases where the systems can be adequately modeled in terms of circuit topology.

V. Resources

Suggested reading

- Janice Glasgow, Hari Narayanan & B. Chandrasekaran
  - Diagrammatic Reasoning: Computational and Cognitive Perspectives on Problem Solving with Diagrams.
  - AAAI Press / MIT Press 1995.
  - ISBN 0-262-57112-9



Forthcoming books

- Thinking with Diagrams
  - Ed. Blackwell
  - Kluwer Academic 2000
    (also special issue of AI Review)
- Diagrammatic Representation and Reasoning
  - Eds. Olivier, Anderson & Meyer
  - Springer-Verlag 2000

Online resources

- The Diagrammatic Reasoning Site
  - **www.hcrc.ed.ac.uk/gal/Diagrams/**
- Thinking with Diagrams workshop archives
  - **www.mrc-cbu.cam.ac.uk/projects/twd/Workshop.html**
  - **www.aber.ac.uk/~plo/TwD98/**

Forthcoming research meeting

- Diagrams 2000 - International Conference on the Theory and Application of Diagrams
  - September 1-3, University of Edinburgh (in cooperation with AAAI)
  - **`http://www-cs.hartford.edu/~d2k/`**

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