Studying the Use of Diagrams in Science

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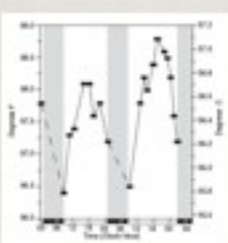
Outline

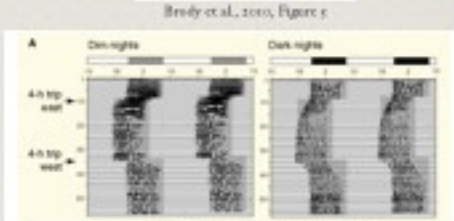
1. Examples of use of diagrams in science
2. Psychological research on mental versus drawn images
3. Psychological research on using drawings and diagrams in problem solving and scientific discovery
4. Diagrams and mechanistic explanations
5. Conclusions

Diagrams to Represent Phenomena

Brody et al., 2010, Figure 5



Koukkari and Sothern, 2006, Figure 1.3



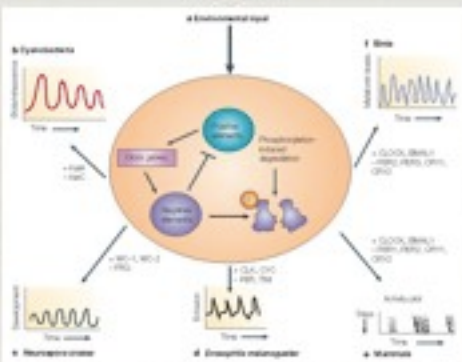
Evans, Elliott, and Gorman, 2009, Figure 1

Diagrams to Represent Experimental Procedures

Classic experiment of Konopka and Benzer, 1971: Discovery of the first circadian clock gene--period

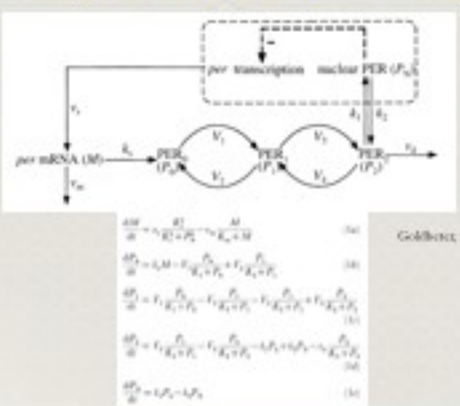
Konkkari and Southern, 2006, Figure 2.9

Diagrams to Represent Mechanisms/Explanations



Bell-Pedersen et al, 2005, Figure 1

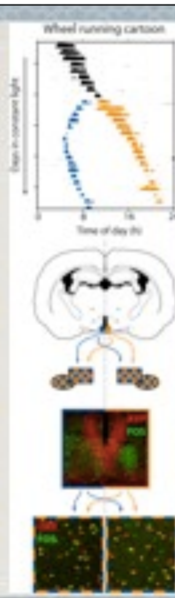
Diagrams to Guide Computational Modeling



Goldbeter, 1995

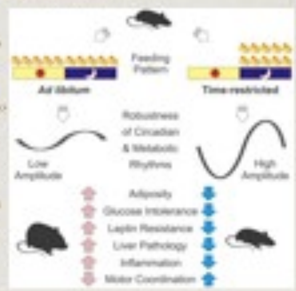
Recent Practice - Graphical Abstracts I

- Butler, M. P., Rainbow, M. N., Rodriguez, E., Lyon, S. M., & Silver, R. (2012). Twelve-hour days in the brain and behavior of split hamsters. *European Journal of Neuroscience*, 36, 2556-2566.
- Abstract: Hamsters will spontaneously 'split' and exhibit two rest–activity cycles each day when housed in constant light (LL). The suprachiasmatic nucleus (SCN) is the locus of a brain clock organizing circadian rhythmicity. In split hamsters, the right and left SCN oscillate 12 h out of phase with each other, and the twice-daily locomotor bouts alternately correspond to one or the other. This unique configuration of the circadian system is useful for investigation of SCN communication to efferent targets. To track phase and period in the SCN and its targets, we measured wheel running and FOS expression in the brains of split and unsplit hamsters housed in LL or light–dark cycles. The amount and duration of activity before splitting were correlated with latency to split, suggesting behavioral feedback to circadian organization. LL induced a robust rhythm in the SCN core, regardless of splitting. The split hamsters' SCN exhibited 24-h rhythms of FOS that cycled in antiphase between left and right sides and between core and shell subregions. In contrast, the medial preoptic area, paraventricular nucleus of the hypothalamus, dorsomedial hypothalamus and orexin-A neurons all exhibited 12-h rhythms of FOS expression, in-phase between hemispheres, with some detectable right–left differences in amplitude. Importantly, in all conditions studied, the onset of FOS expression in targets occurred at a common phase reference point of the SCN oscillation, suggesting that each SCN may signal these targets once daily. Finally, the transduction of 24-h SCN rhythms to 12-h extra-SCN rhythms indicates that each SCN signals both ipsilateral and contralateral targets.



A Recent Practice: Graphical Abstracts - 2

- Hatori, M., Vollmers, C., Zarrinpar, A., DiTacchio, L., Bushong, E. A., Gill, S., et al. (2012). Time-Restricted Feeding without Reducing Caloric Intake Prevents Metabolic Diseases in Mice Fed a High-Fat Diet. *Cell Metabolism*, 15, 848-860.
- Highlights
  ▶ Time-restricted feeding improves clock and nutrient sensor functions
  ▶ tRF prevents obesity, diabetes, and liver diseases in mice on a high-fat diet
  ▶ Nutrient type and time of feeding determine liver metabolome and nutrient homeostasis
  ▶ tRF raises bile acid production and energy expenditure and reduces inflammation
- Summary: While diet-induced obesity has been exclusively attributed to increased caloric intake from fat, animals fed a high-fat diet (HFD) ad libitum (ad lib) eat frequently throughout day and night, disrupting the normal feeding cycle. To test whether obesity and metabolic diseases result from HFD or disruption of metabolic cycles, we subjected mice to either ad lib or time-restricted feeding (tRF) of a HFD for 8 hr per day. Mice under tRF consume equivalent calories from HFD as those with ad lib access yet are protected against obesity, hyperinsulinemia, hepatic steatosis, and inflammation and have improved motor coordination. The tRF regimen improved CREB, mTOR, and AMPK pathway function and oscillations of the circadian clock and their target genes' expression. These changes in catabolic and anabolic pathways altered liver metabolome and improved nutrient utilization and energy expenditure. We demonstrate in mice that tRF regimen is a nonpharmacological strategy against obesity and associated diseases.



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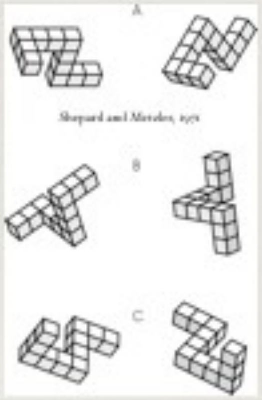
The Imagery Debates - I



Kosslyn, Ball, & Reiser, 1978

The Imagery Debates - II

- Pylyshyn's challenge: chronometric measures are not sufficient to demonstrate that people process image-like representations
  - They could be employing propositionally encoded information
    - But delaying their responses appropriate to simulate rotating an object or moving in space
- Anderson: because representations and processing are always coupled, this debate cannot be settled by appeals to behavioral measures
- With the advent of appropriate techniques, Kosslyn and others sought to invoke neural evidence to settle the issue by demonstrating
  - The same brain areas are active in visual and mental imagery tasks
  - Parametric relations between activations and the size of objects imagined (Behrmann, 2000)

The Imagery/Drawing Debates-1

- Chambers and Reisberg (1985):
  - Is imagining as similar to seeing as Kosslyn et al. suggest?
  - Contend the imagining is intentional--images are interpreted in one specific way
- Experimental task:
  - Ambiguous figure A was presented briefly
  - Subjects were then trained to find alternative interpretations of B
  - They were then asked whether they could find an alternative interpretation of A
    - First relying on imagery alone
    - Then when allowed to draw A

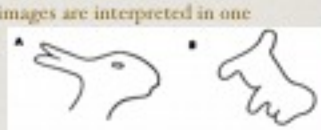


Table 1
Summary of Results

Experiment and test stimulus	N	Number of reversals: From image	From own drawing
1 Duck/rabbit	15	0	15
2 Duck/rabbit	10	0	10
4 Duck/rabbit	10	0	10
Necker cube	10	0	10
Schroder staircase	10	0	6

The Imagery/Drawing Debates-II

- Response by Finke, Pinker, and Farah (1989)
  - Task:
    - Construct images from stimuli
    - Report any emergent forms

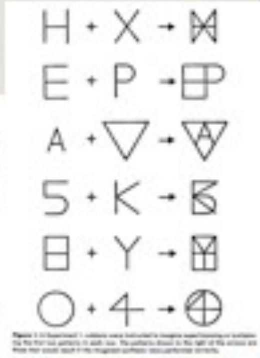


TABLE 1
Number of Correct Reports of Emergent Patterns in Experiment 1 For Each Pair of Stimulus Patterns

Stimulus Patterns	Type of Emergent Pattern: Image		Drawing	
	Geometric	Symbolic	Geometric	Symbolic
"H" + "X"	16	14	2	7
"E" + "P"	12	8	1	1
"A" + Triangle	22	3	2	6
"5" + "K"	16	4	5	8
Square + "Y"	29	4	0	4
Circle + "4"	15	4	1	5

Note. The number of reports are summed over the 12 experimental subjects. The emergent patterns reported in the drawings include only those that were not detected in the subjects' mental images.

The Imagery/Drawing Debate - III

- Finke, Pinker, and Farah also asked subjects to perform a sequence of manipulations and report the result:
  - "Imagine the number '7'. Make the diagonal line vertical. Move the horizontal line down to the middle of the vertical line. Now rotate the figure 90 degrees to the left."
  - Those whose drawing were correct mostly made the correct identification
    - If they were wrong when relying on the image, most got it right when they drew it

TABLE 2
Emergent Pattern Identifications According to Accuracy of Mental Transformations in Experiment 2

Pattern Identifications	Accuracy of Transformation: Correct	Partial	Wrong
	Based on Mental Image		
Correct	20	2	0
Alternative	3	0	0
Wrong	13	8	14
	Based on Drawing		
Correct	13	8	0
Alternative	0	0	0
Wrong	3	0	14

Note. Responses are summed across the 12 experimental subjects. Identifications of emergent patterns in the drawings were attempted only when the patterns were not correctly identified in the mental images.

Creativity with Images

- Finke and Slayton (1988) asked subjects to combine three simple shapes creatively, name it, and draw it
- Experimenters evaluated the recognizability of the drawing
- On 119 of 312 trials (38%) subjects produced recognizable drawings, of which 19 were judged highly creative

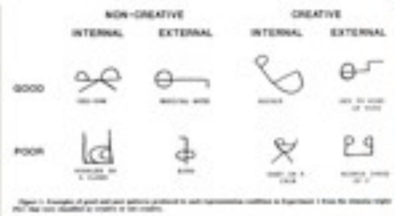
Creativity with Images -2

- Does drawing help? Anderson and Helstrup (1993) followed the procedures of Finke and Slayton (1988), except they added the option to draw on some trials
  - Allowing subjects to draw had no detectable effect on their ability
    - to generate a pattern
    - to produce a recognizable correspondence of name with drawing
    - to generate a creative pattern

Table 1
Mean Performance Measures for Experiment 1

Measure	Representation Condition: Internal	Representation Condition: External
Trials with pattern (max = 5)	4.29	4.52
Good pattern trials	1.62	1.71
Wrong parts trials	.05	.19
*No-pattern trials	.67	.28
Correspondence rating (max = 5)	3.55	3.57
Transformation complexity (max = 13)	2.91	2.72
Creative pattern trials (max = 5)	.62	.67
Total subjects producing at least one creative pattern (max = 21)	10	12

*A significant difference at the .05 level or beyond.



Creativity with Images -3

- Anderson and Helshup (1993) then examined the effects of drawing when subjects were asked to develop as many patterns as they could
  - Drawing resulted in significantly greater
    - Production of at least one pattern
    - Number of good patterns
    - Number of creative patterns

Table 2
Mean Performance Measures for Experiment 2

Measure	Representation Condition: Internal	Representation Condition: External
Trials with any pattern (max = 4)	3.13	3.65
*At least one good pattern	1.95	2.75
*No patterns	.83	.35
*Patterns/trial	1.56	2.15
*Good patterns/trial	.68	1.06
p(Good patterns/all patterns)	.44	.52
Correspondence rating (max = 5)	3.56	3.71
Transformation complexity (max = 13)	2.98	3.33
*Creative patterns/trial	.16	.33
p(Creative patterns/all patterns)	.09	.16
No. subjects producing at least one creative pattern (max = 20)	9	15

*A significant difference at the .05 level or beyond.

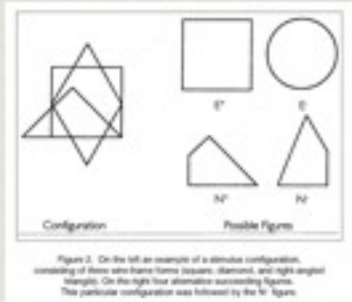
Explaining the Difference: Combining vs. Restructuring - 1

- Verstijnen et al. (2000) propose that the difference in the results may turn on whether subjects were only required to combine components or also restructure them

Figure 1. On the left (a) a pattern used by Reed and Johnson (1975). If the parts (e.g., hourglasses) do not form part of the perceptually predominant structure (e.g., overlapping triangles), discovery of these parts is difficult in mental imagery. On the right (b) Jastrow's duck/rabbit (Jastrow, 1900).

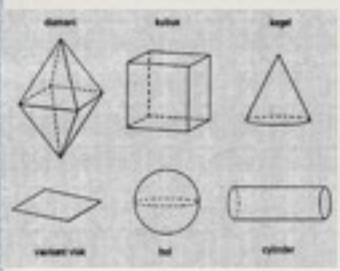
Explaining the Difference: Combining vs. Restructuring - 2

- In one task, Verstijnen et al. had subjects first learn a number of component forms (E)
  - They then saw a composite configuration
- They were then tested on possible included forms (components [E] or novel forms [N]) and asked to judge whether they were present in the configuration
- Novice and expert sketchers did equally well, whether they could sketch or not, on the component forms (E)
- For experts, but not novices, sketching made a significant difference on novel forms (N)



Explaining the Difference: Combining vs. Restructuring - 3

- Verstijnen et al., 1998, used shapes and showed that
  - Expert and novice sketchers were alike with regard to combining
  - Expert sketchers showed more restructuring



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Duncker's Radiation Problem

- Gick and Holyoak (1983) explored role of text and diagrams in analogical problem solving
- Problem: Suppose you are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed the patient will die. There is a kind of ray that can be used to destroy the tumor. If the rays reach it all at once at a sufficiently high intensity, the tumor will be destroyed. Unfortunately, at this intensity the healthy tissue that the rays pass through on the way to the tumor will also be destroyed. At lower intensities the rays are harmless to healthy tissue, but they will not affect the tumor either. What type of procedure might be used to destroy the tumor with the rays, and at the same time avoid destroying the healthy tissue?

Verbal Analogy: Red Adair

- For some subjects, the Radiation Problem was preceded by a story
- An oil well in Saudi Arabia exploded and caught fire. The result was a blazing inferno that consumed an enormous quantity of oil each day. After initial efforts to extinguish it failed, famed firefighter Red Adair was called in. Red knew that the fire could be putout if a huge amount of fire retardant foam could be dumped on the base of the well. There was enough foam available at the site to do the job. However, there was no hose large enough to put all the foam on the fire fast enough. The small hoses that were available could not shoot the foam quickly enough to do any good. It looked like there would have to be costly delay before a serious attempt could be made.
  However, Red Adair knew just what to do. He stationed men in a circle all around the fire, with all of the available small hoses. When everyone was ready all of the hoses were opened up and foam was directed at the fire from all directions. In this way a huge amount of foam quickly struck the source of the fire. The blaze was extinguished, and the Saudis were satisfied that Red had earned his three million dollar fee.

Verbal Analogy vs. Diagram

- Only 10% of those not presented the Red Adair story solved the radiation problem
- Of those who were presented the Red Adair story, 40% solved the radiation problem without a hint
  - After a hint to consider the story, an additional 36% solved the problem
- Other subjects saw this figure in a pattern recognition problem prior to attempting to solve the radiation problem

- The diagram did not help
  - Of those who saw the diagram, only 7% solved the problem without a hint
  - With a hint, 60% more solved the problem
- Combination of story plus diagram was less effective than the story analogue alone: only 23% solved the problem before the hint.

Does Quality of Diagram Matter?

- Beveridge and Parkins (1987) suggested the flaw was with the diagram Gick and Holyoak employed—it did not encode the solution.
- Alternative diagram and physical prop (hinged set of transparent blue strips) resulted in significantly better performance both with children and adults

Table 1
Number and Percentage of Correct Solutions to the Problem for Each Analogue Type in Experiments 1 and 2

Analogue Type	Correct Solutions Number	Correct Solutions Percentage
Experiment 1 (Children)		
Control	0/29	0
Red Adair	10/71	14
Colored Strips	38/118	32
Experiment 2 (Adults)		
Control	23/40	57
Red Adair	30/40	75
Gick and Holyoak (1983)		
Diagram	26/40	65
Summative Intensity	60/73	82
Colored Strips	38/40	95

Information Processing Analysis: Representations and Operations

- Major lesson from development of information processing models
  - Whether a representation is useful or easier to use depends on how it is coupled with the operations that are to be applied to it
- Operations for Larkin and Simon:
  - Search—finding items in the data structure that satisfy productions
  - Recognition—matching data set items to productions
  - Inference—executing actions specified in productions
- Representations for Larkin and Simon:
  - Sentential: Data structures in which elements appear in a single sequence
  - Diagrammatic: Data structures in which elements are indexed by a two-dimensional location

How do Diagrams Help?

- Larkin and Simon's pulley problem

1. The first weight is suspended from the left end of a rope over Pulley 'A. The right end of this rope is attached to, and partially supports, the second weight.

2. Pulley A is suspended from the left end of a rope that runs over Pulley B, and under Pulley C. Pulley B is suspended from the ceiling. The right end of the rope that runs under Pulley C is attached to the ceiling.

3. Pulley C is attached to the second weight, supporting it jointly with the right end of the first rope.

Task: Find the ratio of the second to the first weight if the system is in equilibrium

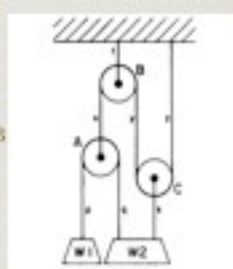


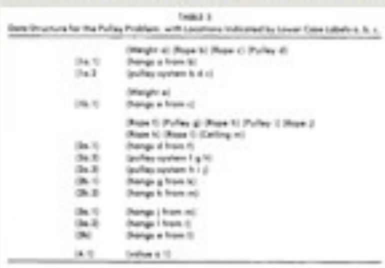
Figure 1. Diagram of the pulley problem.

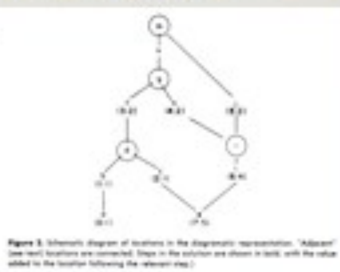
Solving the Pulley Problem Through Symbolic Manipulation

- Solution reached by applying production rules to propositional representations: 7 steps
- Major challenge: searching for the data elements that satisfy productions at each step

Solving the Pulley Problem Through Operations On Diagrams

- Information is linked to a locality (a, b, etc.).
  - All information at a location is available when attention is directed there
  - Attention shifts to new locations when they are mentioned in elements introduced by the application of production rules: again, 7 steps





The Superiority of Diagrams

- In the pulley problem, diagrammatic representation greatly shortened search time
  - In other problems, diagrammatic representations also shortened recognition time
- Diagrams can group together all information that is used together, thus avoiding large amounts of search for the elements needed to make a problem-solving inference.
- Diagrams typically use location to group information about a single element, avoiding the need to match symbolic labels.
- Diagrams automatically support a large number of perceptual inferences, which are extremely easy for humans

Diagrams in Discovery

- Scientific discovery was a key interest of Simon's: With collaborators he developed computer programs designed to "discover" a number of scientific theories from the data that were available to the scientists who made the discoveries
- Cheng and Simon (1995) investigated diagrams in discoveries about inclined planes. Example:
  - From the mean proportional theorem tDC / tDG = √(dDC.dDG) / dDG
  - Discover Galileo's theorem: equal time is required to travel any chord of a circle
    - Apply it to Quickest Descent Problem to show descent on AE is fastest


Figure 4. Galileo's Theorem


Figure 1. Quickest Descent Problem : Proposition 30

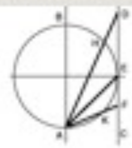


Figure 3. Solution to Quickest Descent Problem

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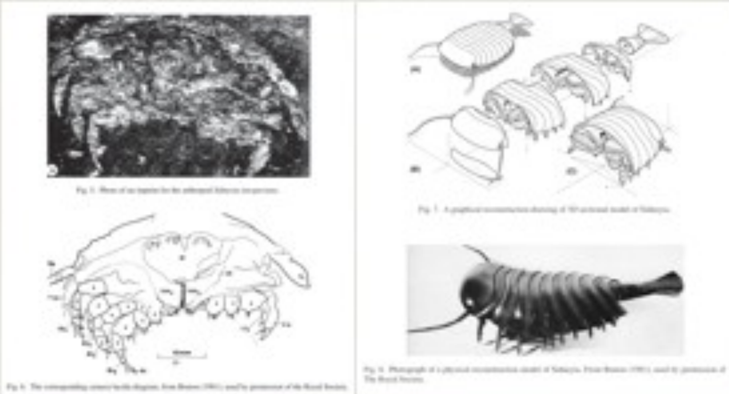
Explanatory Vehicles: From Laws to Mechanisms

- Simon's work, like most philosophy of science in the mid-20th century, focused on laws as the chief explanatory vehicle
- In biology, however, one seldom encounters distinctively biological laws
  - Although laws from physics and chemistry are frequently employed
    - Which might suggest that biological explanation is simply derivative from explanations in physics and chemistry
- Attention to biology, however, reveals something else
  - When producing explanations biologists commonly refer to seeking the mechanism responsible for the phenomena
  - A mechanistic explanation requires
    - Identifying the working parts of the mechanism
    - Identifying the operations within the mechanism
    - Localizing operations in working parts
    - Determining how the parts are organized and the operations orchestrated so as to generate the phenomenon

Gooding: Transforming Images to Identify Parts



Gooding: Transforming Images to Identify Parts - 2

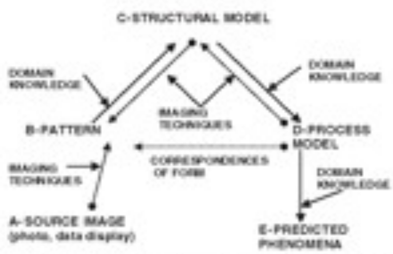
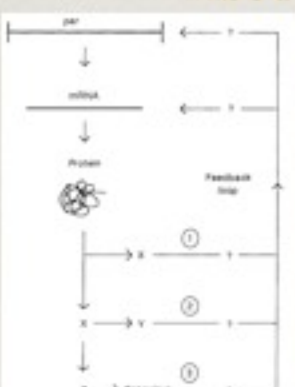
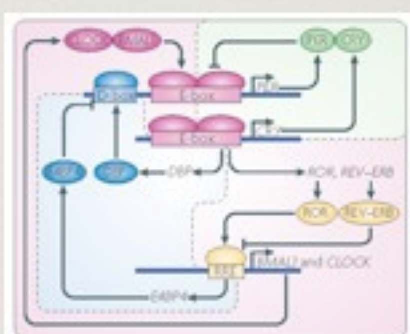


Fig. 10. Diagram of visual inference showing application of technologies and domain knowledge to produce a structural model (arc B → C) and its expansion into a process model (arc C → D). Models at C and D are validated by deriving known phenomenology (arcs C → B, D → B) and by predicting new phenomena or features (D → E).

Representing and Reasoning About Operations



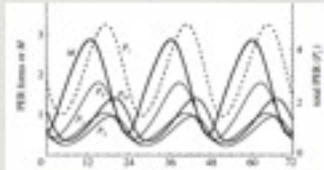
Hardin et al., 1990

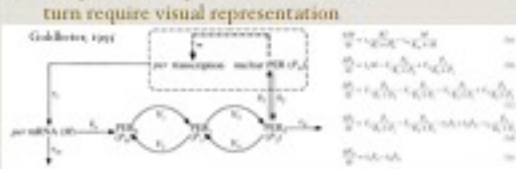


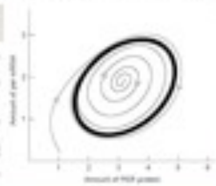
Zhang and Kay 2010

Using Computational Models to Reason about Mechanisms

- With some relatively simple mechanisms it is possible to simulate their behavior mentally
- But with feedback loops and other complex modes of organization computational modeling is required
- Diagrams of mechanisms often guide construction of models
- Outputs of computational models in turn require visual representation







Learning to Use and Construct Diagrams

- By taking advantage of our visual processing capacities, diagrams often seem easy to understand
- But don't be deceived
  - Once one has learned the conventions used in a diagram, they seem transparent
  - But learning to use them is often a challenge
    - One strategy for understanding the cognitive processes that go into processing diagrams is to study what students must learn in order to use them
    - Others?

Conclusions

- Diagrams serve to represent
  - Phenomena
  - Research strategies
  - Proposed mechanisms
  - Variables and parameters in a computational model
- Diagrams can often be imaged mentally, but for some tasks external diagrams seem to be crucial
- Provided the right mental operations, diagrams support problem solving, including scientific discovery
- Diagrams figure in discovery of mechanisms
  - Discovery of structures
  - Discovery of operations and organization
  - Determining how a mechanism will behave

Fellow WORGODS

Adele
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CRL, UCSD

Daniel
Burnston
UCSD

Benjamin
Sheredos
UCSD

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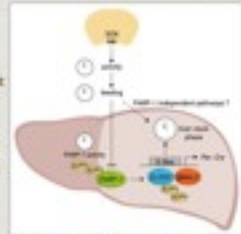
A Recent Practice: Graphical Abstracts - 2



- Asher, G., Reinke, H., Altmeyer, M., Gutierrez-Arcelus, M., Hottiger, M. O., & Schibler, U. (2010). Poly(ADP-Ribose) Polymerase 1 Participates in the Phase Entrainment of Circadian Clocks to Feeding. Cell, 142, 943-953.
- Summary: Circadian clocks in peripheral organs are tightly coupled to cellular metabolism and are readily entrained by feeding-fasting cycles. However, the molecular mechanisms involved are largely unknown. Here we show that in liver the activity of PARP-1, an NAD+-dependent ADP-ribosyltransferase, oscillates in a daily manner and is regulated by feeding. We provide biochemical evidence that PARP-1 binds and poly (ADP-ribosyl)ates CLOCK at the beginning of the light phase. The loss of PARP-1 enhances the binding of CLOCK-BMAL1 to DNA and leads to a phase-shift of the interaction of CLOCK-BMAL1 with PER and CRY repressor proteins. As a consequence, CLOCK-BMAL1-dependent gene expression is altered in PARP-1-deficient mice, in particular in response to changes in feeding times. Our results show that Parp-1 knockout mice exhibit impaired food entrainment of peripheral circadian clocks and support a role for PARP-1 in connecting feeding with the mammalian timing system.

A Recent Practice: Graphical Abstracts - 4

- Depetris-Chauvin, A., Berni, J., Aranovich, E. J., Muraro, N. I., Beckwith, E. J., & Ceriani, M. a. F. (2011). Adult-Specific Electrical Silencing of Pacemaker Neurons Uncouples Molecular Clock from Circadian Outputs. Current Biology, 21, 1783-1793.
- Summary
- Background: Circadian rhythms regulate physiology and behavior through transcriptional feedback loops of clock genes running within specific pacemaker cells. In Drosophila, molecular oscillations in the small ventral lateral neurons (sLNvs) command rhythmic behavior under free-running conditions releasing the neuropeptide PIGMENT DISPERSING FACTOR (PDF) in a circadian fashion. Electrical activity in the sLNvs is also required for behavioral rhythmicity. Yet, how temporal information is transduced into behavior remains unclear.
- Results: Here we developed a new tool for temporal control of gene expression to obtain adult-restricted electrical silencing of the PDF circuit, which led to reversible behavioral arrhythmicity. Remarkably, PERIOD (PER) oscillations during the silenced phase remained unaltered, indicating that arrhythmicity is a direct consequence of the silenced activity. Accordingly, circadian axonal remodeling and PDF accumulation were severely affected during the silenced phase.
- Conclusions: Although electrical activity of the sLNvs is not a clock component, it coordinates circuit outputs leading to rhythmic behavior.