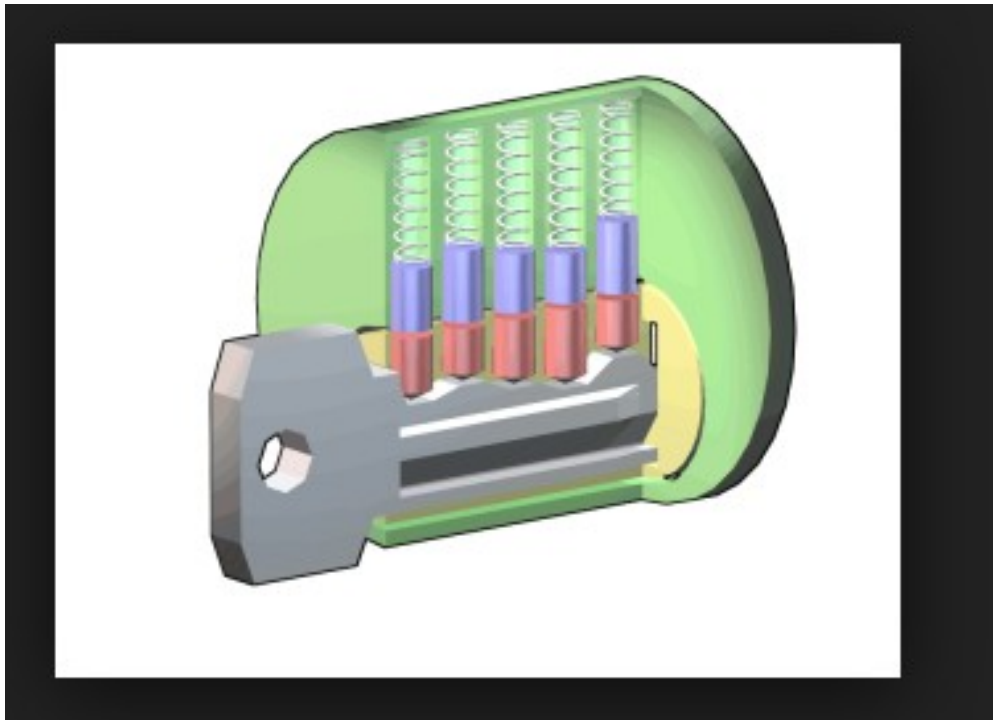
What are Cognitively Plausible Goals of Science Education?

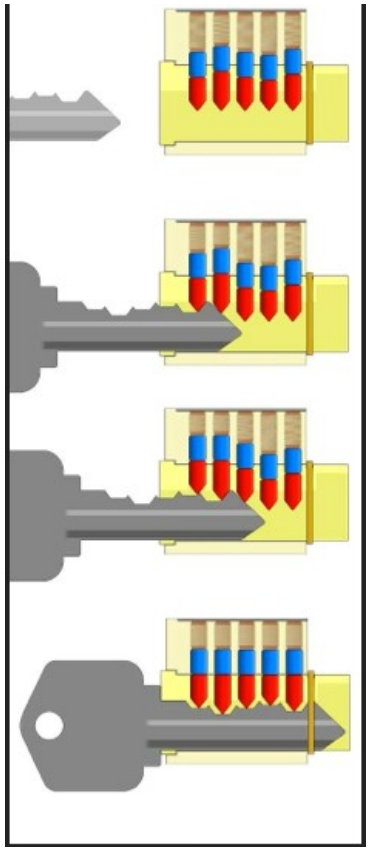
Frank Keil

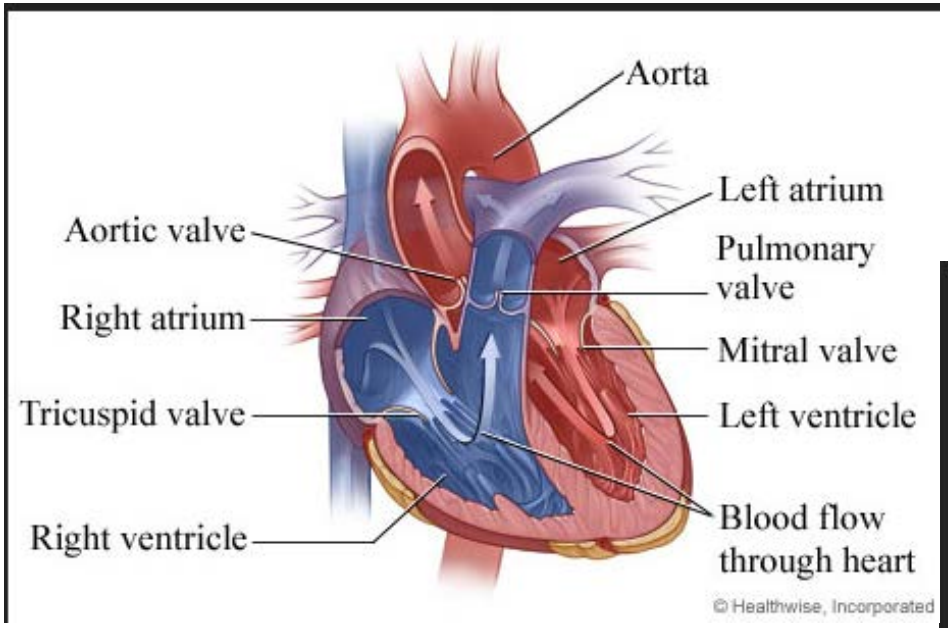
NIH Science Education Conversations Series 2013

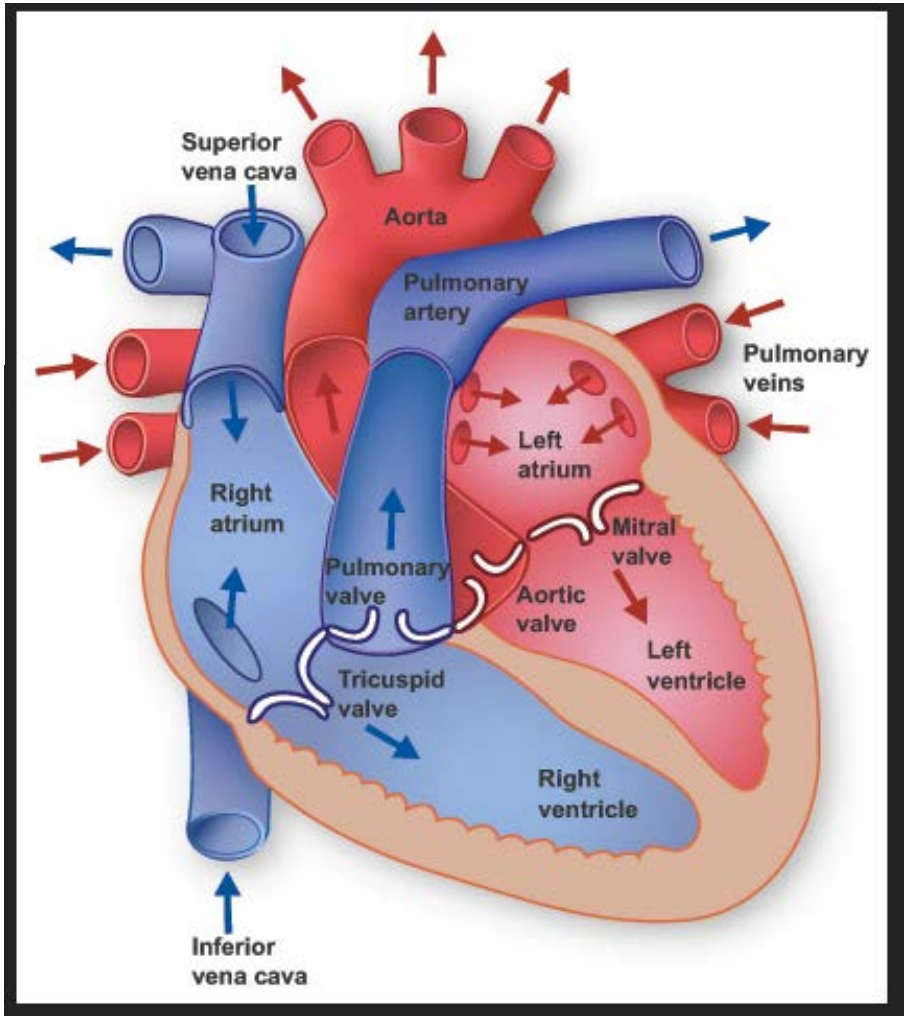
Mechanistic understanding?

- The “obvious” goal of science education??






Aorta
Left atrium
Aortic valve
Pulmonary valve
Right atrium
Mitral valve
Tricuspid valve
Left ventricle
Blood flow through heart
Right ventricle
© Healthwise, Incorporated


Superior vena cava
Aorta
Pulmonary artery
Pulmonary veins
Left atrium
Right atrium
Mitral valve
Pulmonary valve
Aortic valve
Left ventricle
Tricuspid valve
Right ventricle
Inferior vena cava

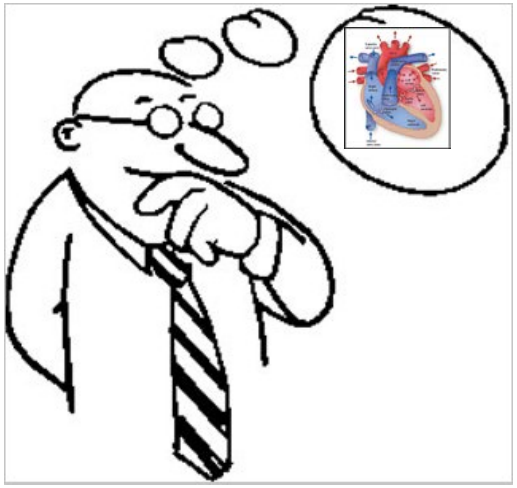
An insatiable quest for mechanism?

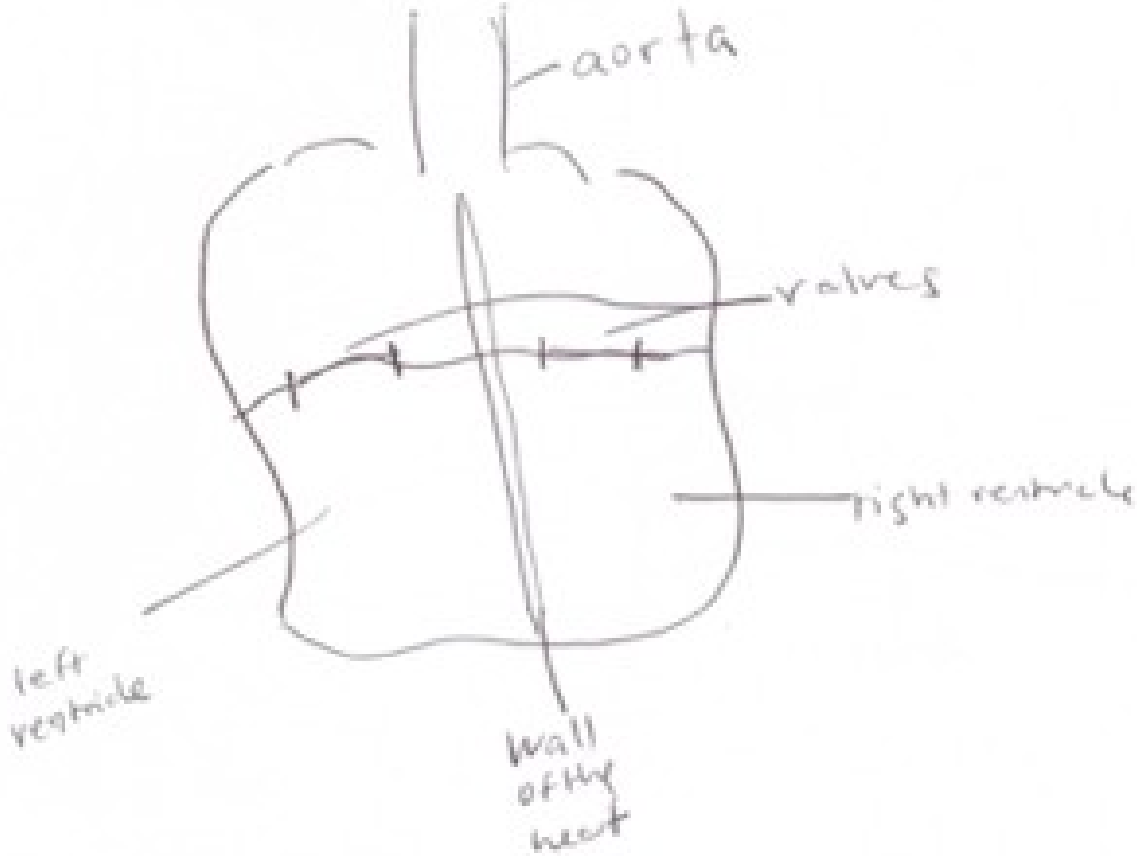
- Preschoolers - driven to uncover mechanism

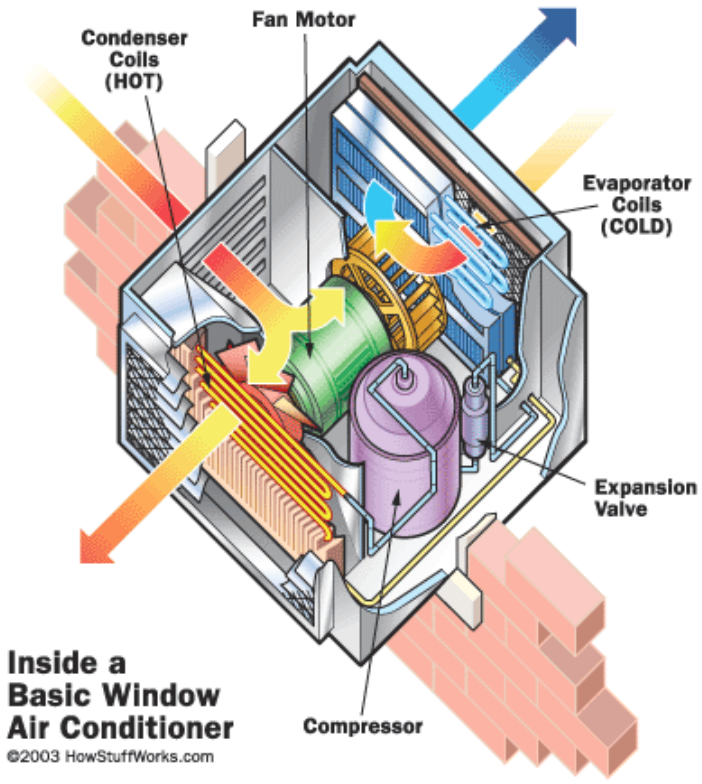
  - unsatisfied if don't get mechanistic answers (Callanan & Oakes, 1992; Chouinard, 2007; Frazier, Gelman & Wellman, 2009)
- Adults- mechanism information normally easily overpowers statistical (Ahn & Kalish, 2000).
- Causal explanations w/o mechanism seem empty

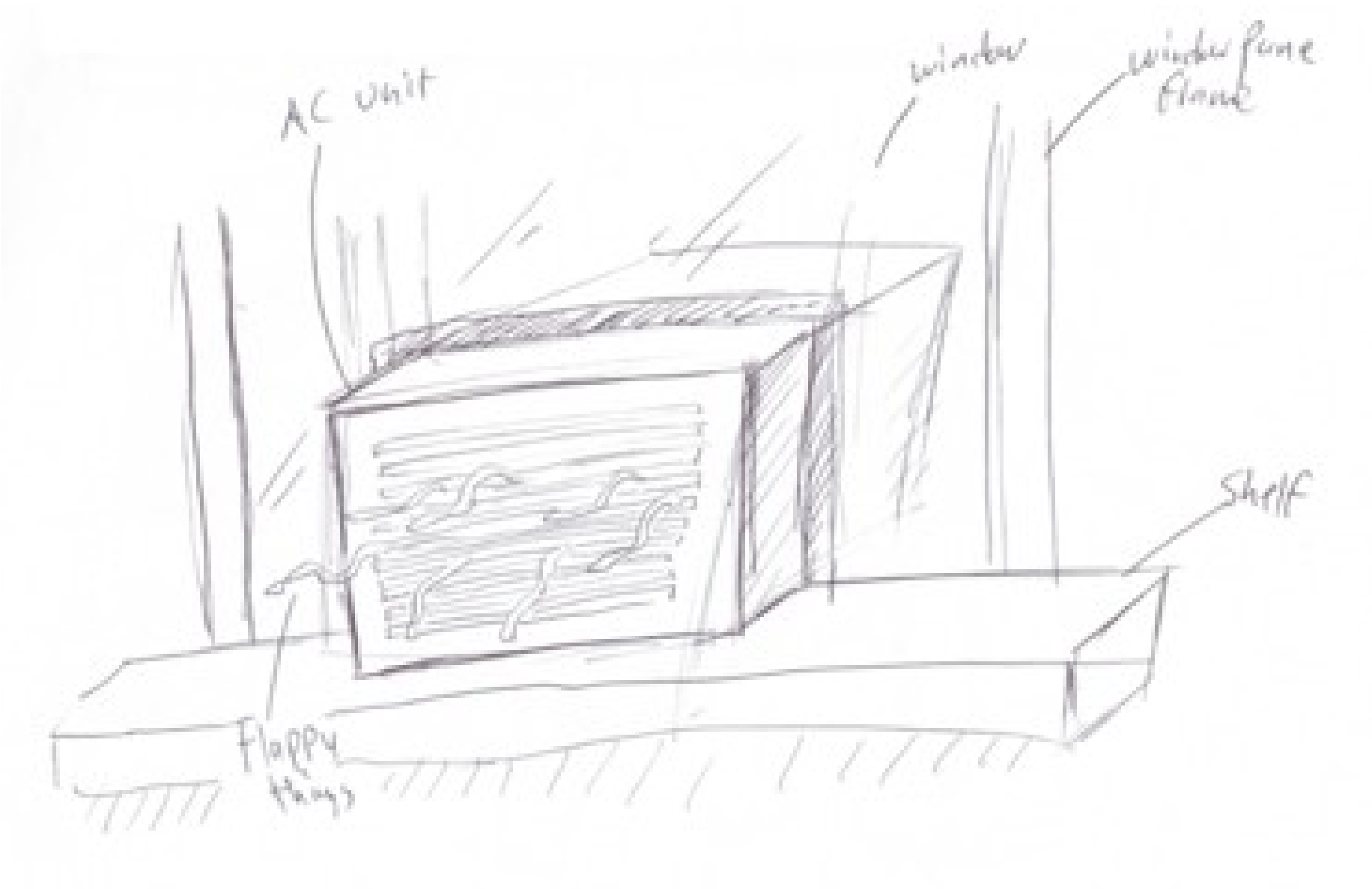
Yet- we can’t retain mechanism

- For artifacts, biological systems, and non-living natural systems…the same story
- Even when there is mastery, it decays rapidly
- Arguably decays much more rapidly than memory for places, narratives, etc.



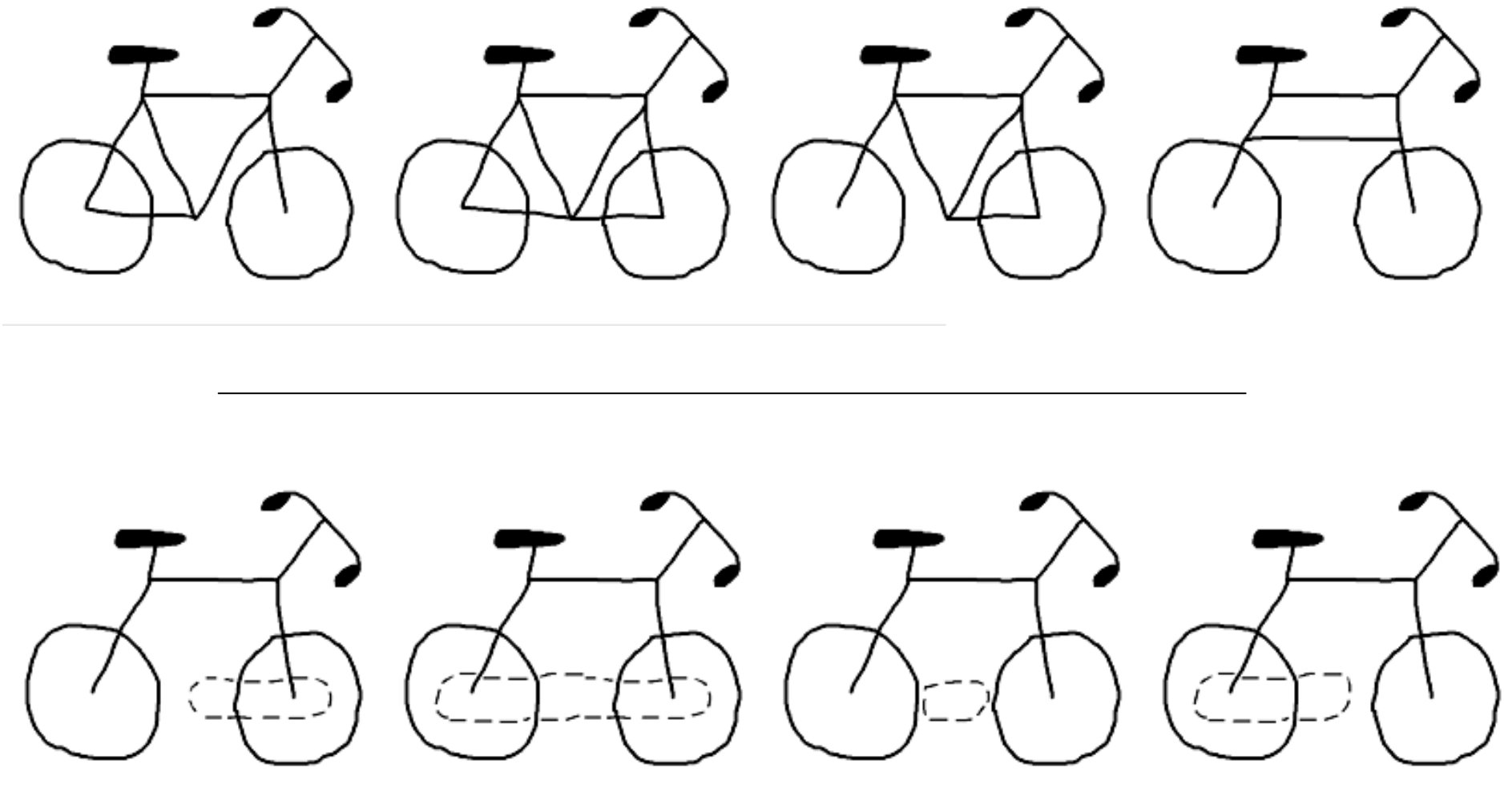

aorta
valves
right ventricle
left ventricle
wall of the heart


Condenser Coils (HOT)
Fan Motor
Evaporator Coils (COLD)
Expansion Valve
Compressor
Inside a Basic Window Air Conditioner
©2003 HowStuffWorks.com


AC unit
window
window pane frame
Shelf
Floppy things

Not just in production

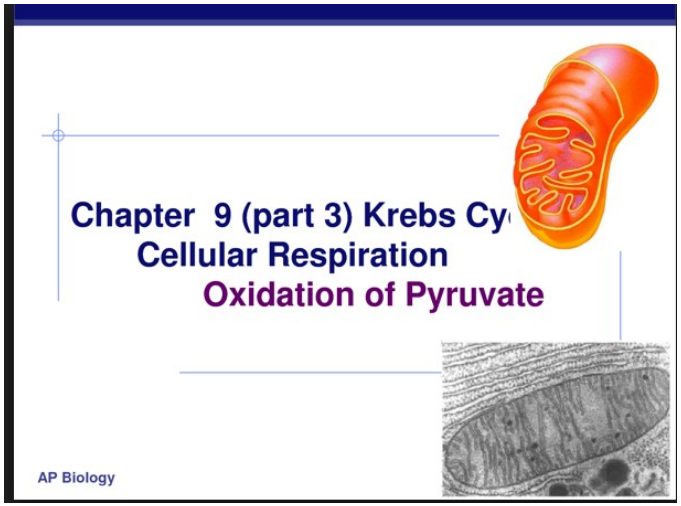
- Recognition as well
- Simple bicycles
  - Mostly exposed parts
  - Lots of experience

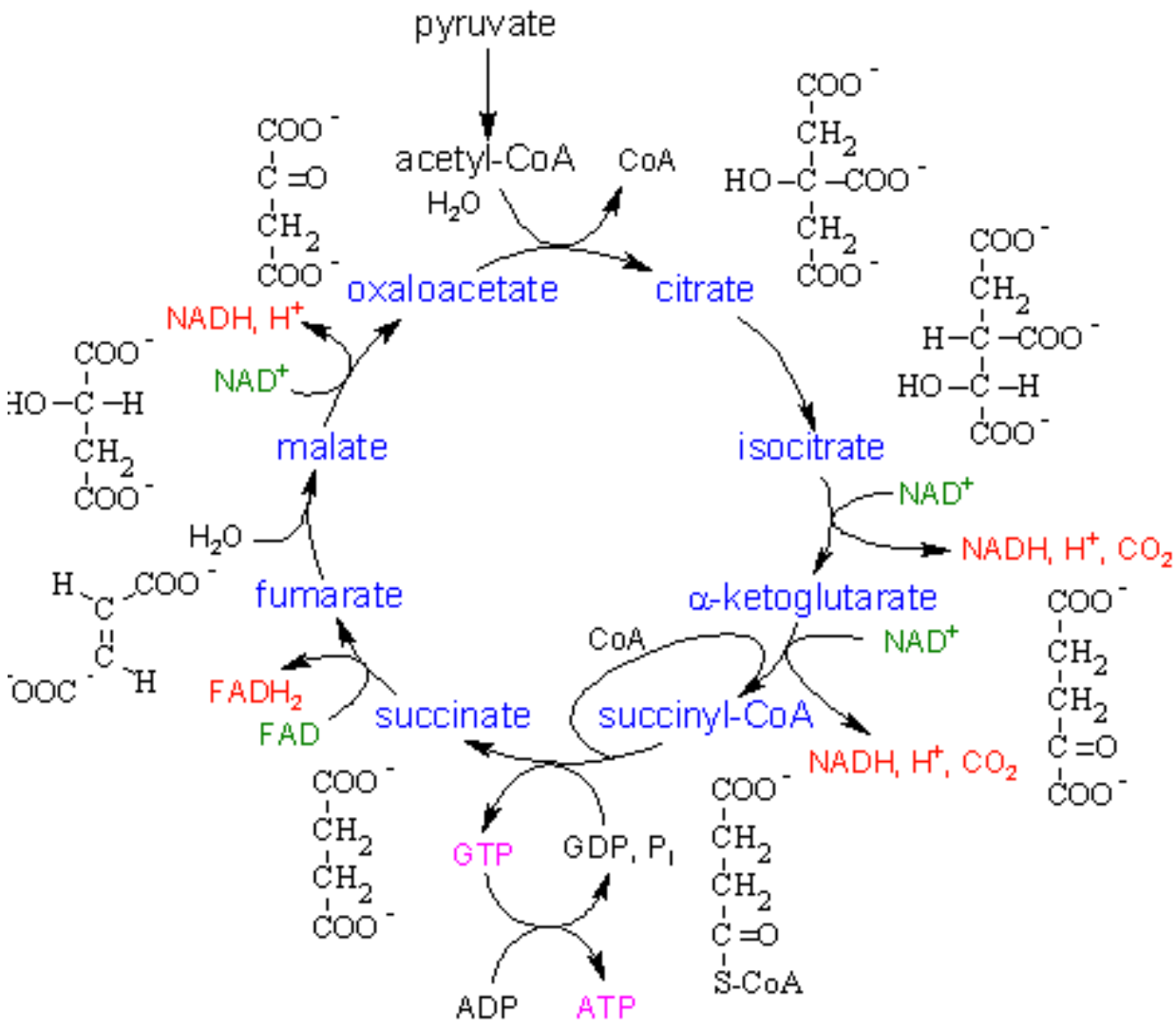


Lawson (2006)

Even when they once knew it well

- The Krebs cycle (citric acid cycle)
- Core part of AP Bio curriculum
  - Major part of several standardized tests
- What about “superb” learners?
  - What do they retain a year or two later?
- Take those with very high SAT II and AP scores




pyruvate
acetyl-CoA
H_2O
CoA
oxaloacetate
citrate
isocitrate
NAD^+
$NADH, H^+, CO_2$
α-ketoglutarate
NAD^+
$NADH, H^+, CO_2$
CoA
succinyl-CoA
succinate
GTP
GDP, P_i
ADP
ATP
FAD
$FADH_2$
fumarate
H_2O
malate
NAD^+
$NADH, H^+$

citric acid cycle

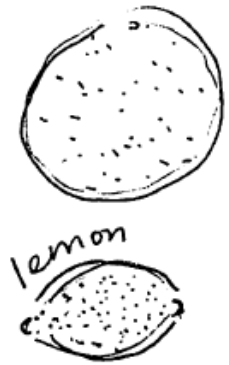
no idea

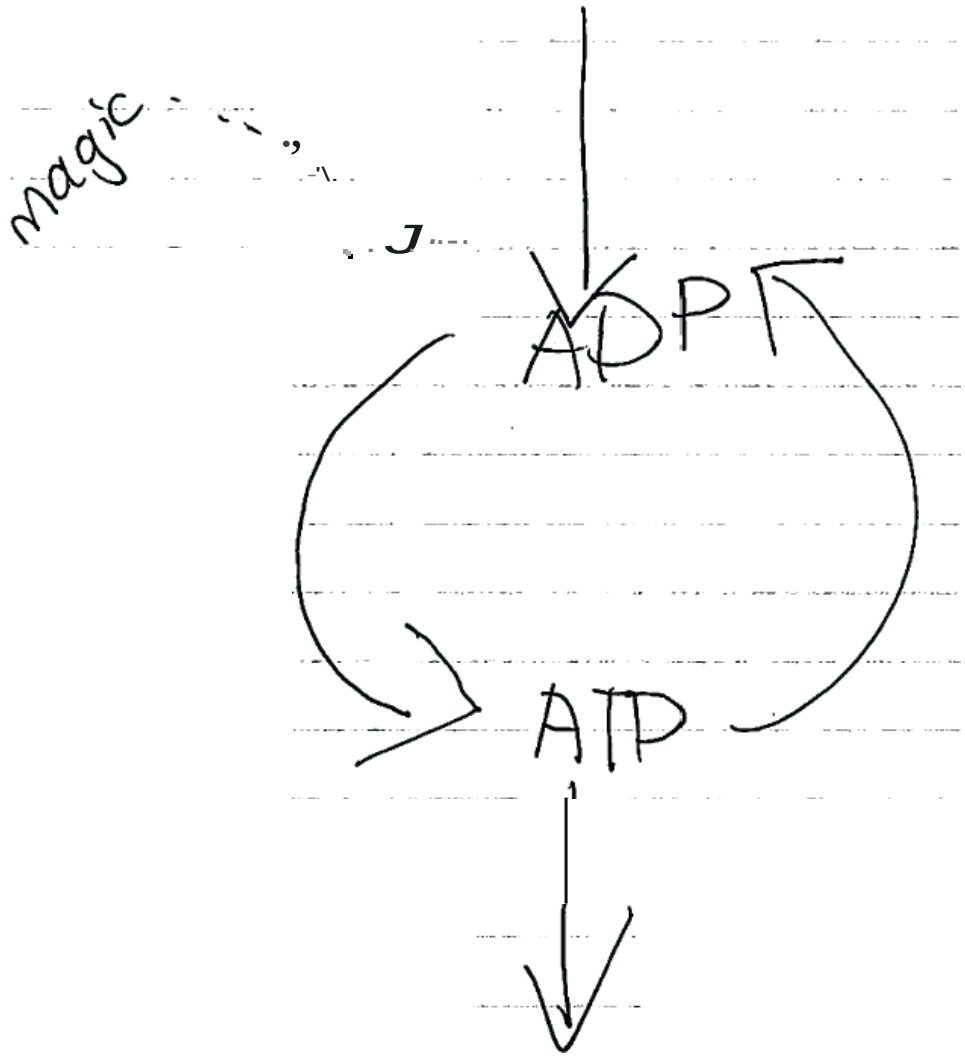
citric acid comes into system

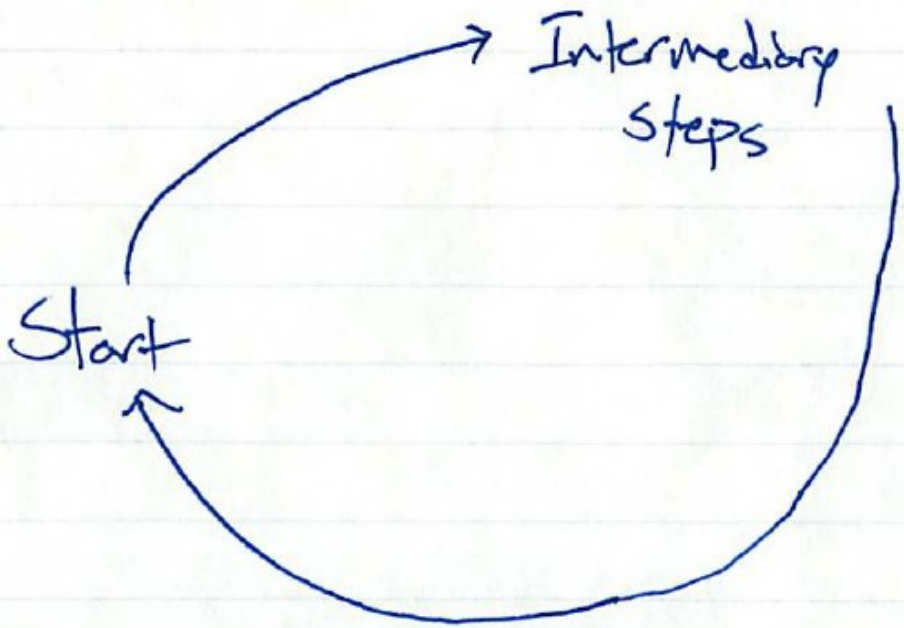
something happens

something is broken down

something is different

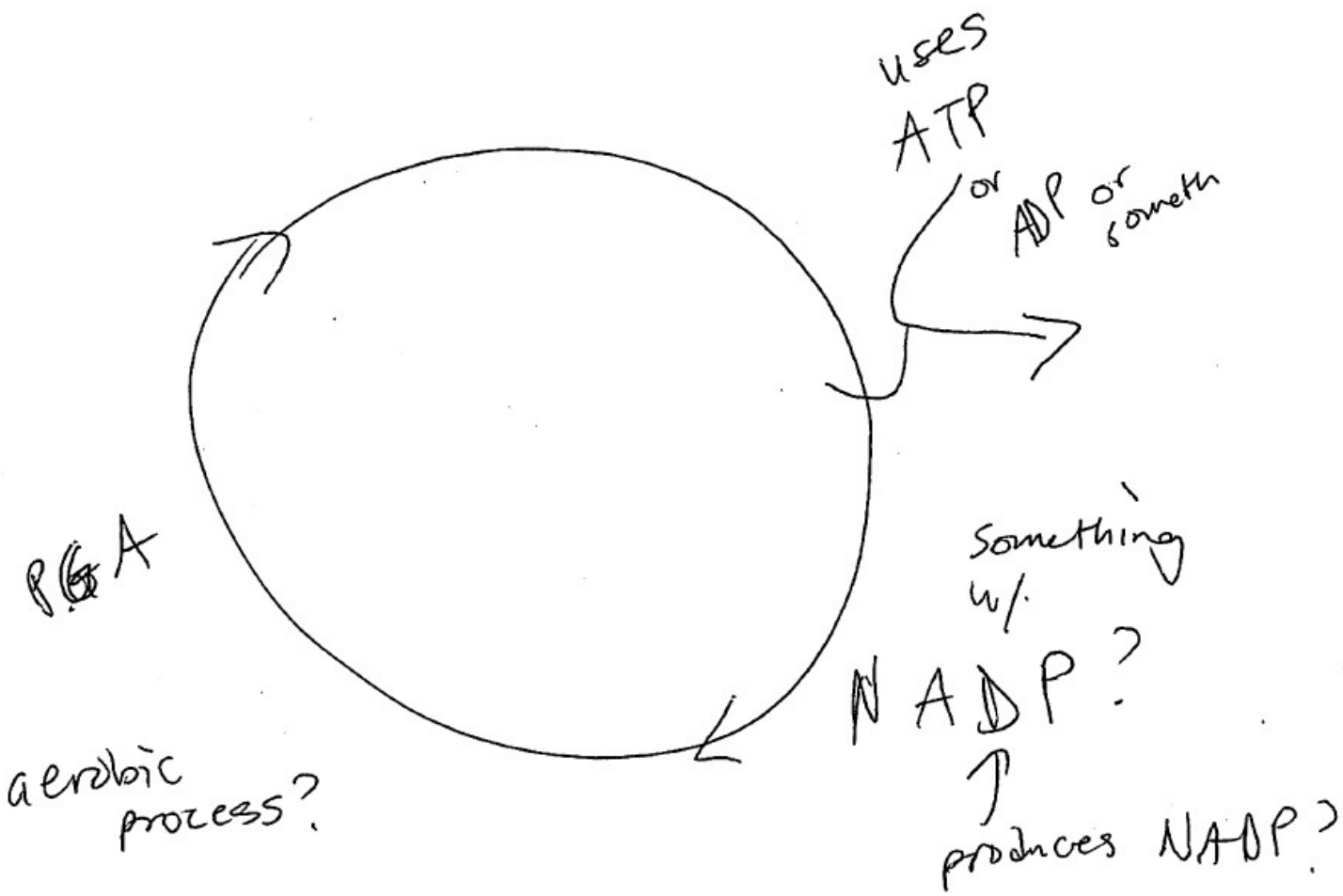



magic
ADP
ATP



Aka "I don't know"

KREBS CYCLE


uses ATP or ADP or someth
PGA
something w/ NADP?
aerobic process?
produces NADP?

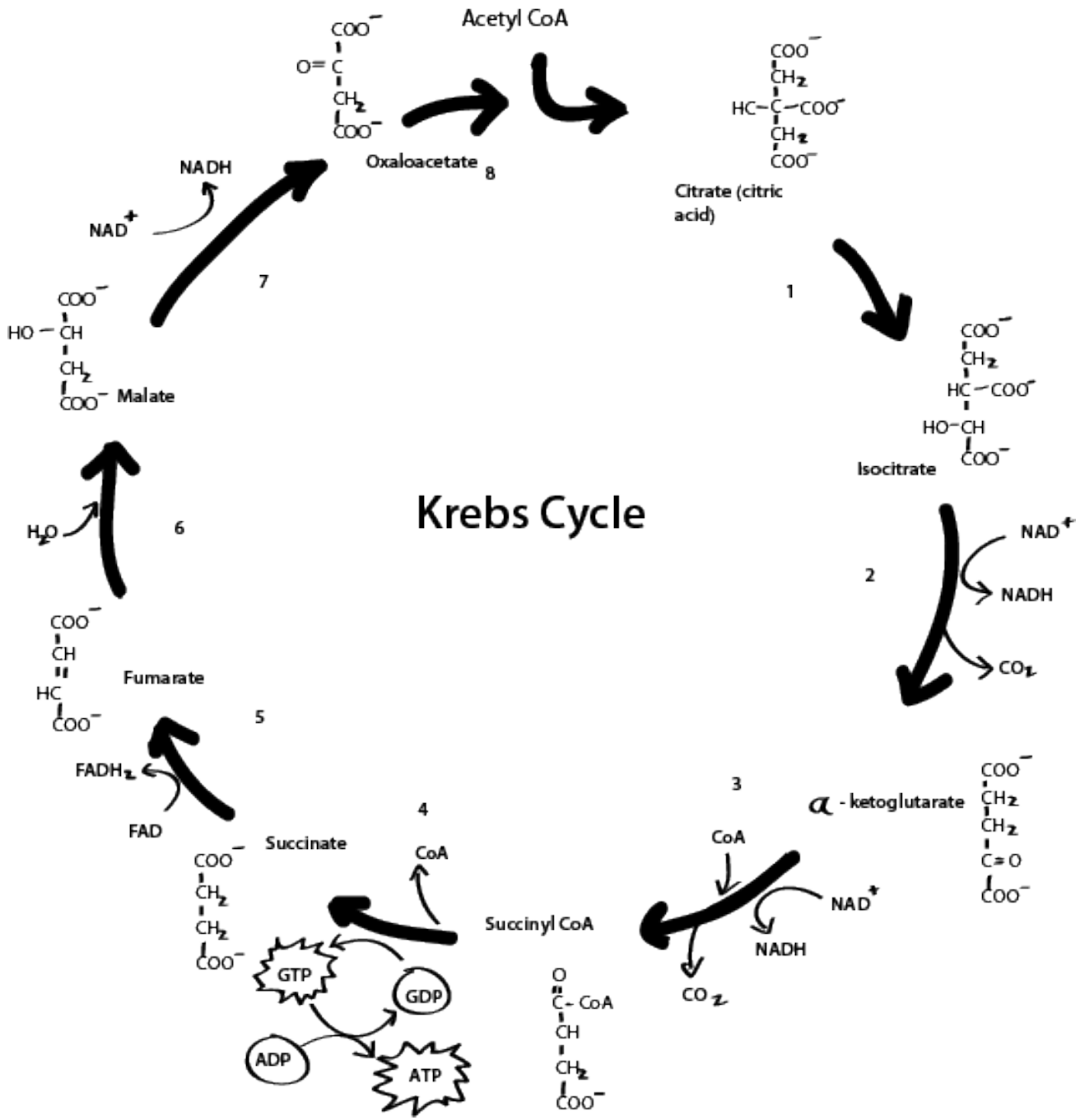
Kreb's Cycle (I remember how to spell it...)

ATP

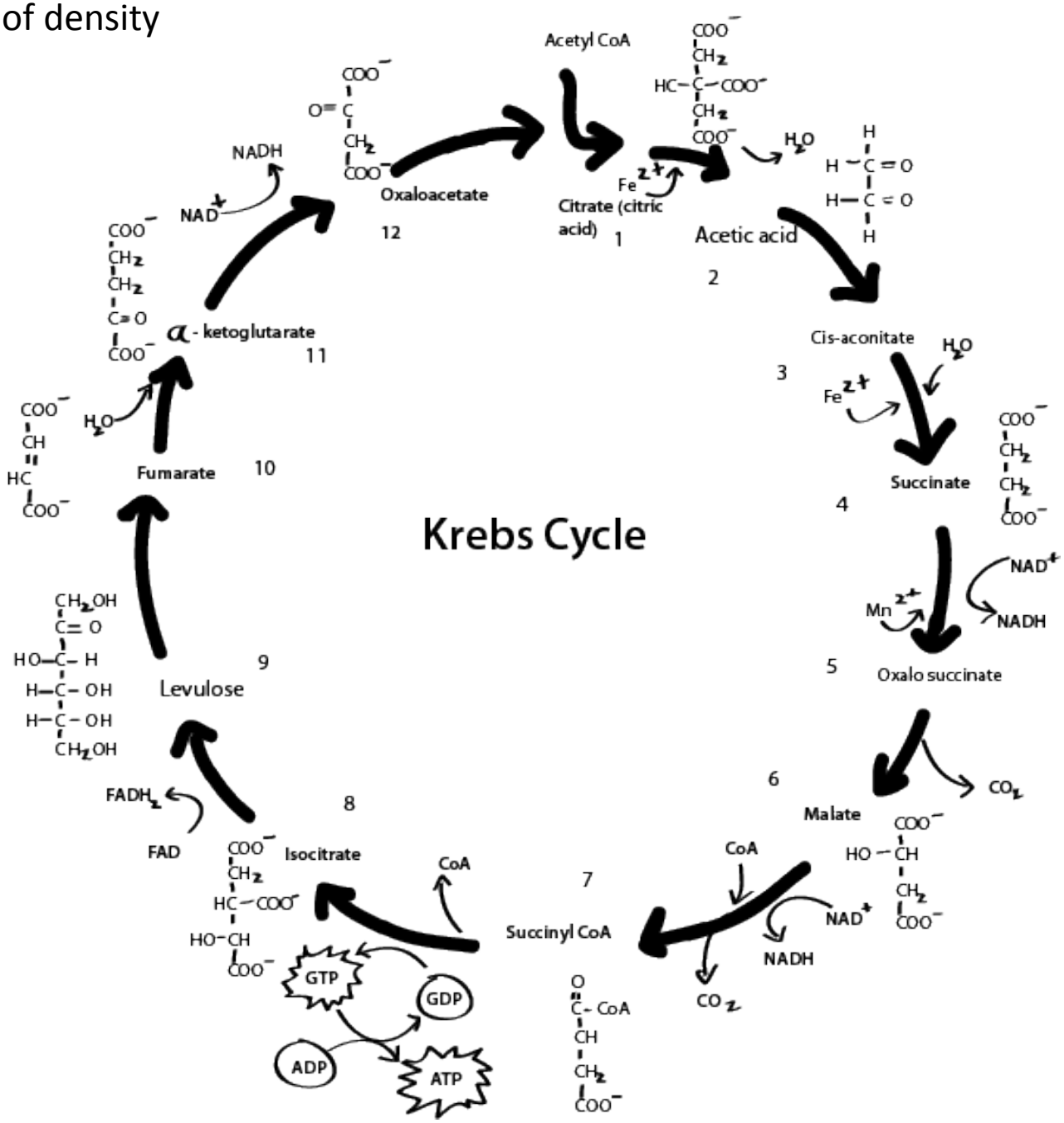
That's it...

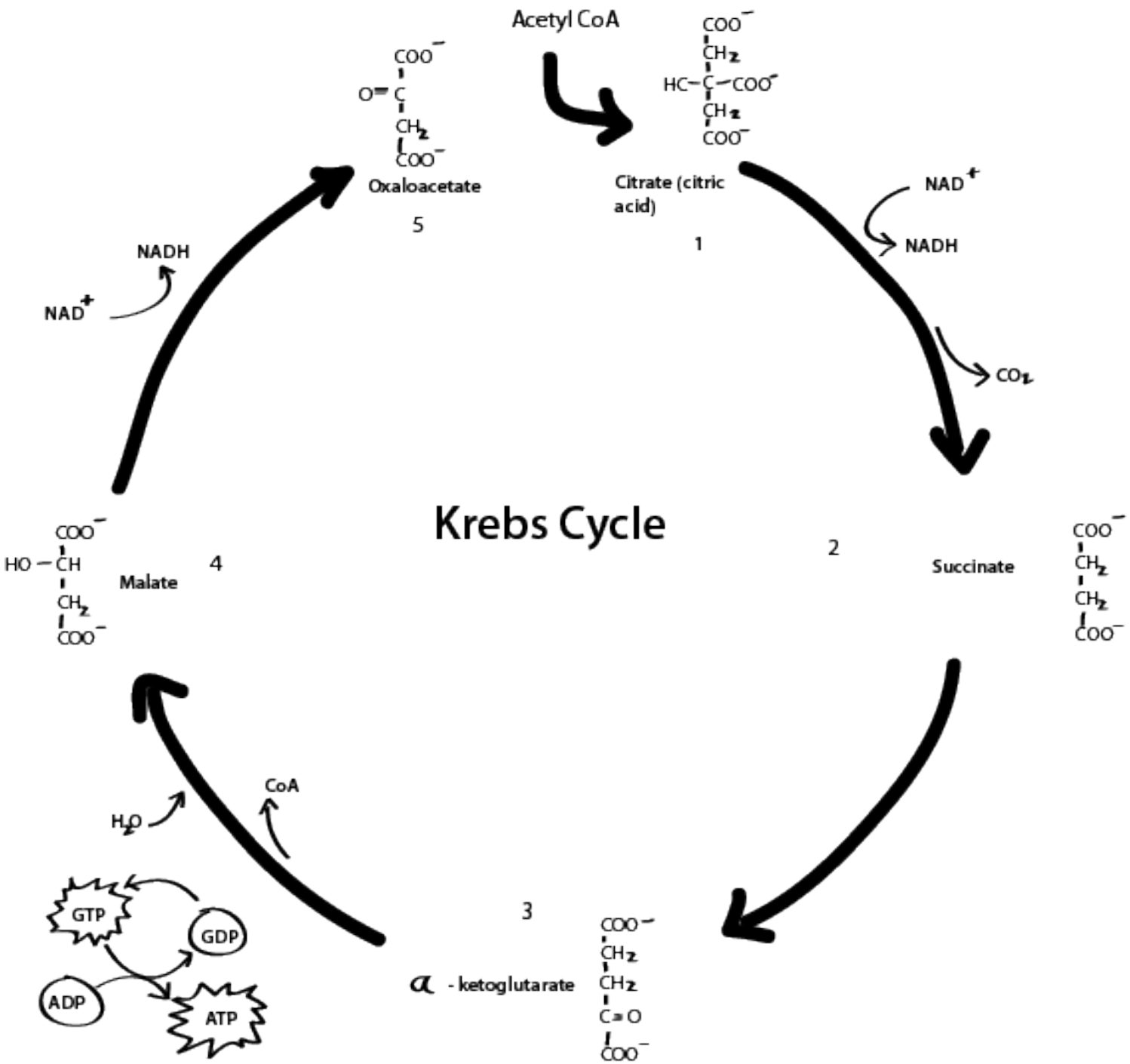
AP Bio (2007-2008 school year)

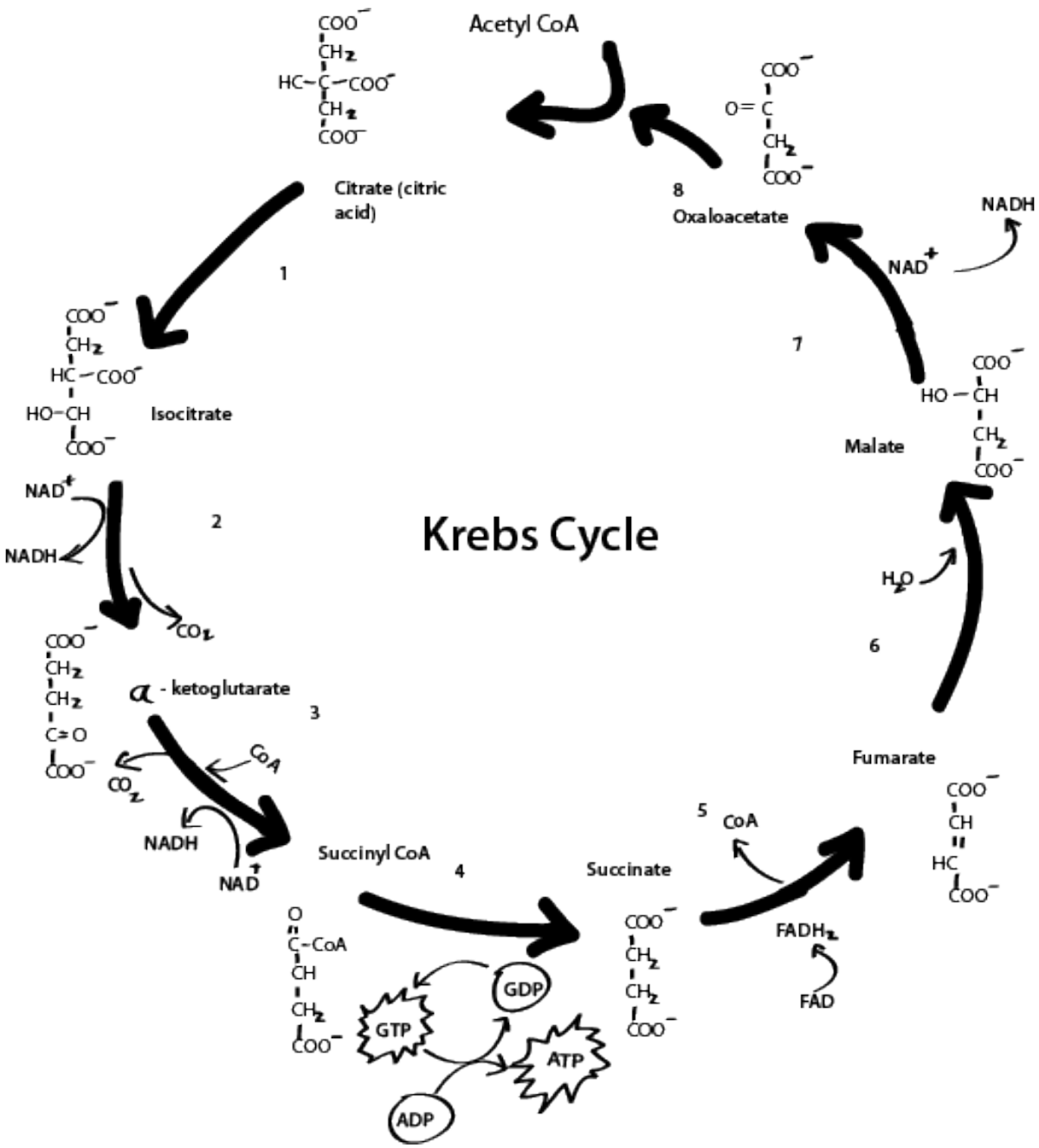
Score: 5


Krebs Cycle
Acetyl CoA
Oxaloacetate
8
Citrate (citric acid)
1
Isocitrate
NAD+
NADH
2
CO2
3
α - ketoglutarate
CoA
NAD+
NADH
CO2
Succinyl CoA
4
CoA
Succinate
GTP
GDP
ADP
ATP
FAD
FADH2
5
Fumarate
6
H2O
7
Malate
NAD+
NADH

Some sense of density




Krebs Cycle
Acetyl CoA
Citrate (citric acid)
1
NAD+
NADH
CO2
2
Succinate
3
α - ketoglutarate
CoA
4
Malate
H2O
5
Oxaloacetate
NAD+
NADH
GTP
GDP
ADP
ATP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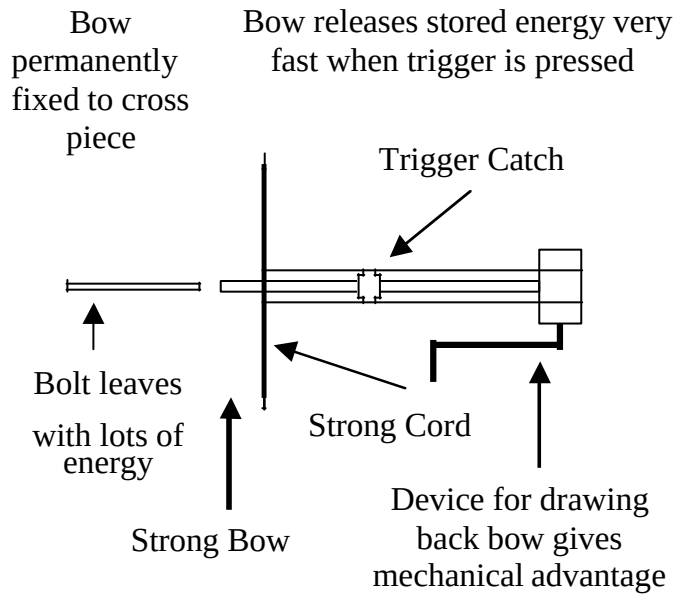
NADH
NAD+
Succinyl CoA
4
GTP
GDP
ATP
ADP
Succinate
5
CoA
FADH2
FAD
Fumarate
6
H2O
Malate
7
NAD+
NADH
8
Oxaloacetate

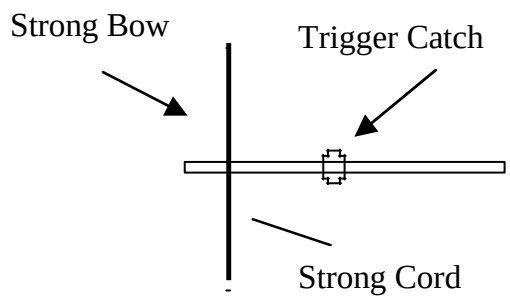
Compounded by illusions of understanding

- Not only don’t we know mechanism…
  - we aggravate the problem by illusions of knowing
- Thinking we have much more mechanistic knowledge than we really do
- The IOED



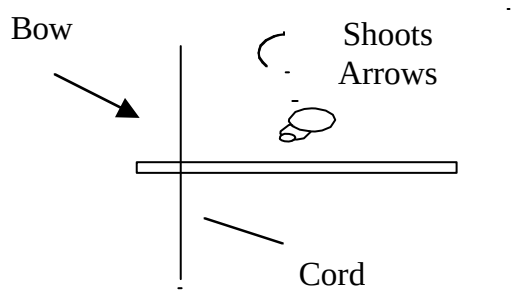
Level 7 Knowledge: diagram and text excerpt

[… that a crossbow] has a stiff, flexible piece of metal as a bow with a wire or strong line; that the bow is permanently mounted on a block of wood or metal; that the wire is pulled back by something that gives a mechanical advantage, either a lever, or small block and tackle, or by a crank wound around a spool that pulls a wire attached to the bow wire. The bow wire is then held back by a pin that is connected to a trigger, and an arrow is set in front of it. Often the pin is forked so the arrow can sit directly in the wire. The pin is directly connected to the trigger so that when you pull on the trigger, it causes it to pivot around a point such that the end that is the pin moves downwards and releases the bow wire. When the pin releases the string, the bow very quickly un-flexes, rapidly imparting all the energy stored in the flexed bow to the arrow.



Level 4 Knowledge: diagram and text excerpt

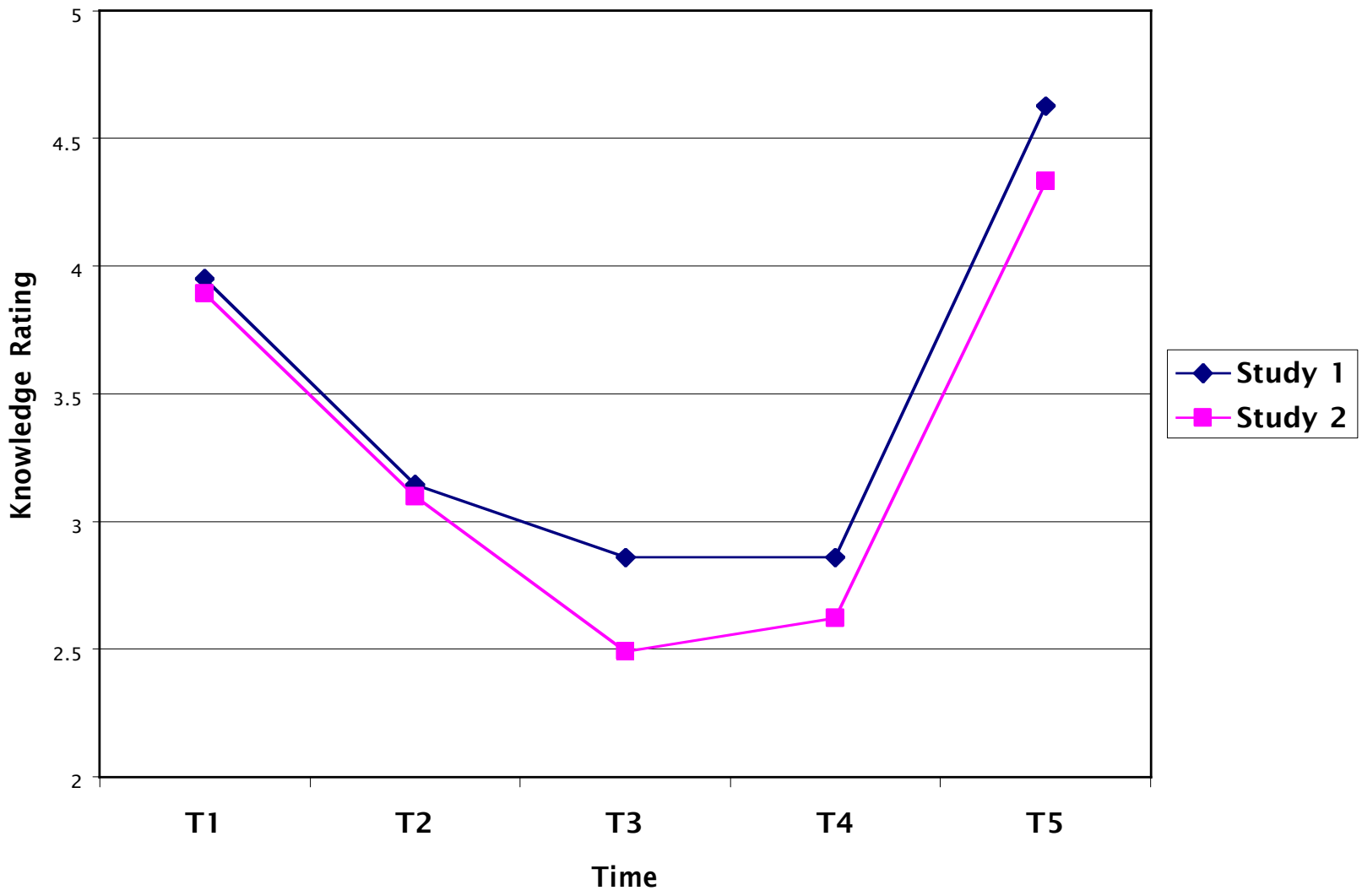
For example, someone might know only that the crossbow is a fixed bow and arrow arrangement; that it gets more power than a normal bow and arrow because it allows you to pull the string back extra hard and then trap it there rather than hold it, and that it is then released by a trigger. If this person were to draw a diagram of a crossbow it might look like this.



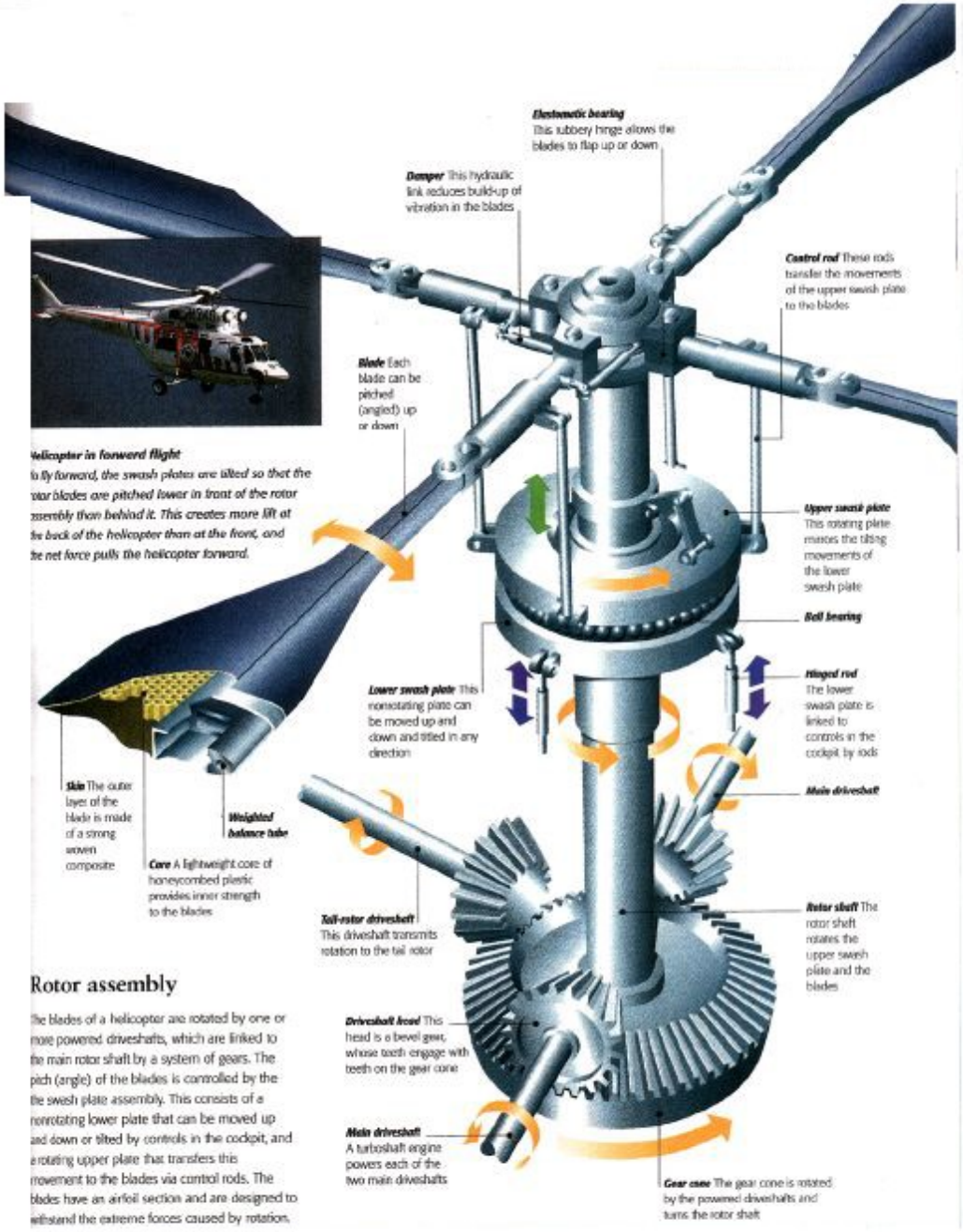
Level l Knowledge: diagram and text excerpt

someone might really only know what a crossbow looks like and what it does -- shoots arrows. That person's understanding might be best represented by the following diagram, where the lack of important parts and labels indicate they really

IOED Results

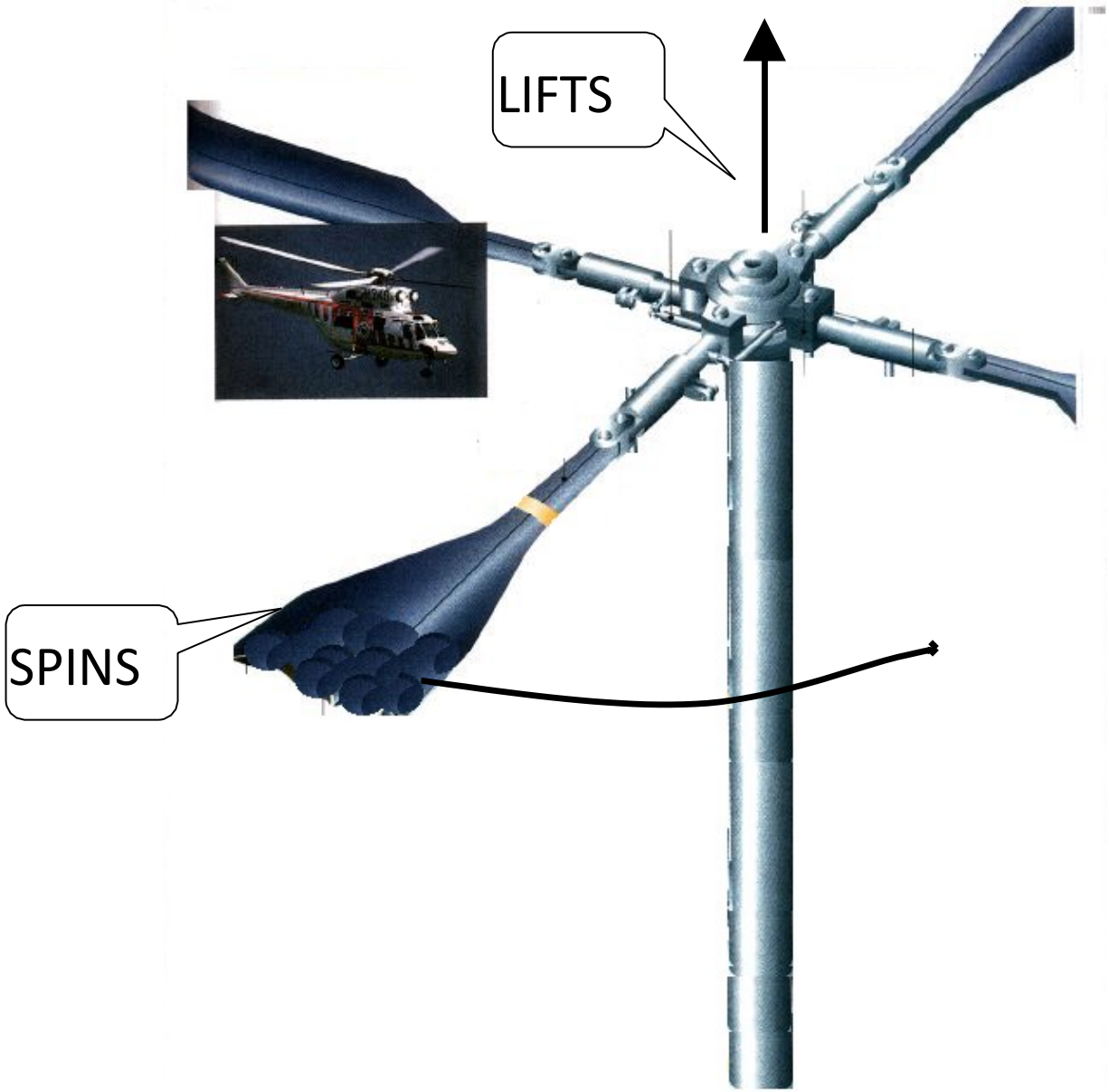


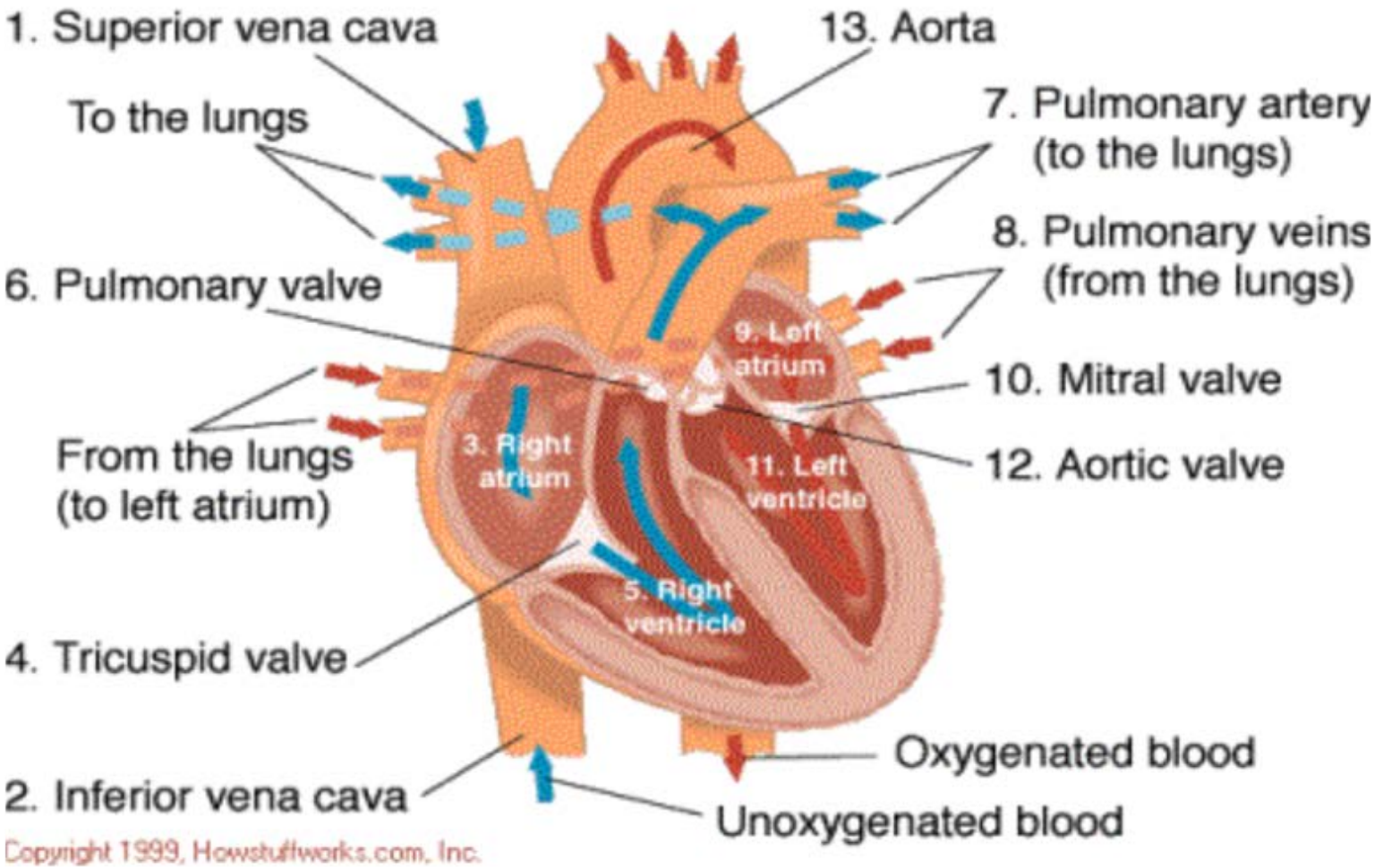
Keil & Rozenblit, 2002



Rotor assembly

The blades of a helicopter are rotated by one or more powered driveshafts, which are linked to the main rotor shaft by a system of gears. The pitch (angle) of the blades is controlled by the the swash plate assembly. This consists of a nonrotating lower plate that can be moved up and down or tilted by controls in the cockpit, and a rotating upper plate that transfers this movement to the blades via control rods. The blades have an airfoil section and are designed to withstand the extreme forces caused by rotation.


LIFTS
SPINS


1. Superior vena cava
To the lungs
13. Aorta
7. Pulmonary artery
(to the lungs)
8. Pulmonary veins
(from the lungs)
6. Pulmonary valve
9. Left
atrium
10. Mitral valve
From the lungs
(to left atrium)
3. Right
atrium
11. Left
ventricle
12. Aortic valve
5. Right
ventricle
4. Tricuspid valve
Oxygenated blood
2. Inferior vena cava
Unoxygenated blood
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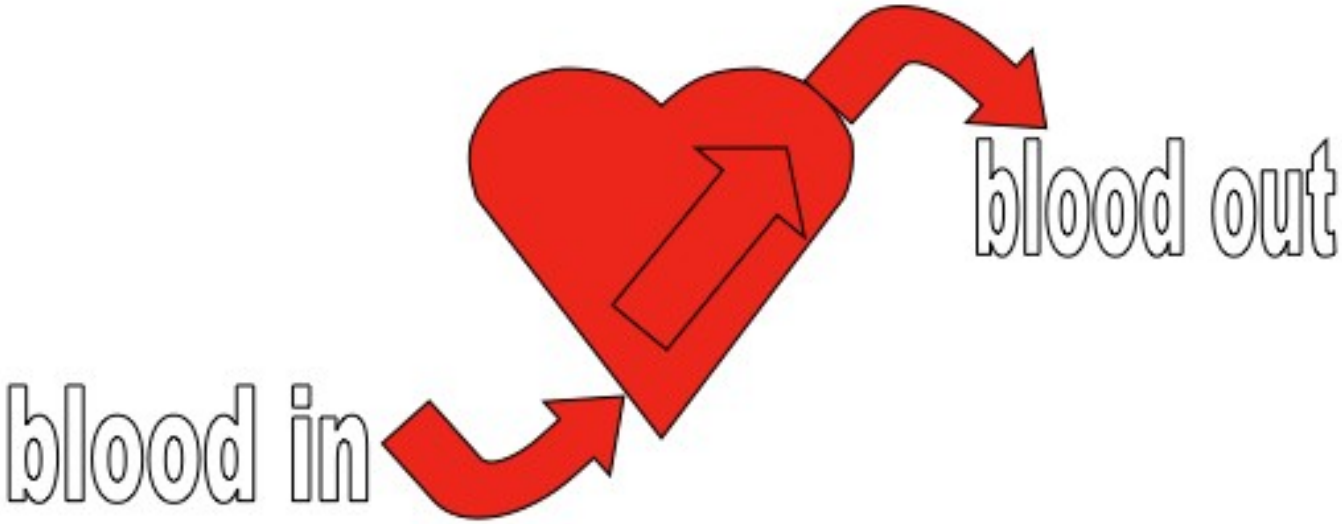

blood in
blood out

Illusion of detail

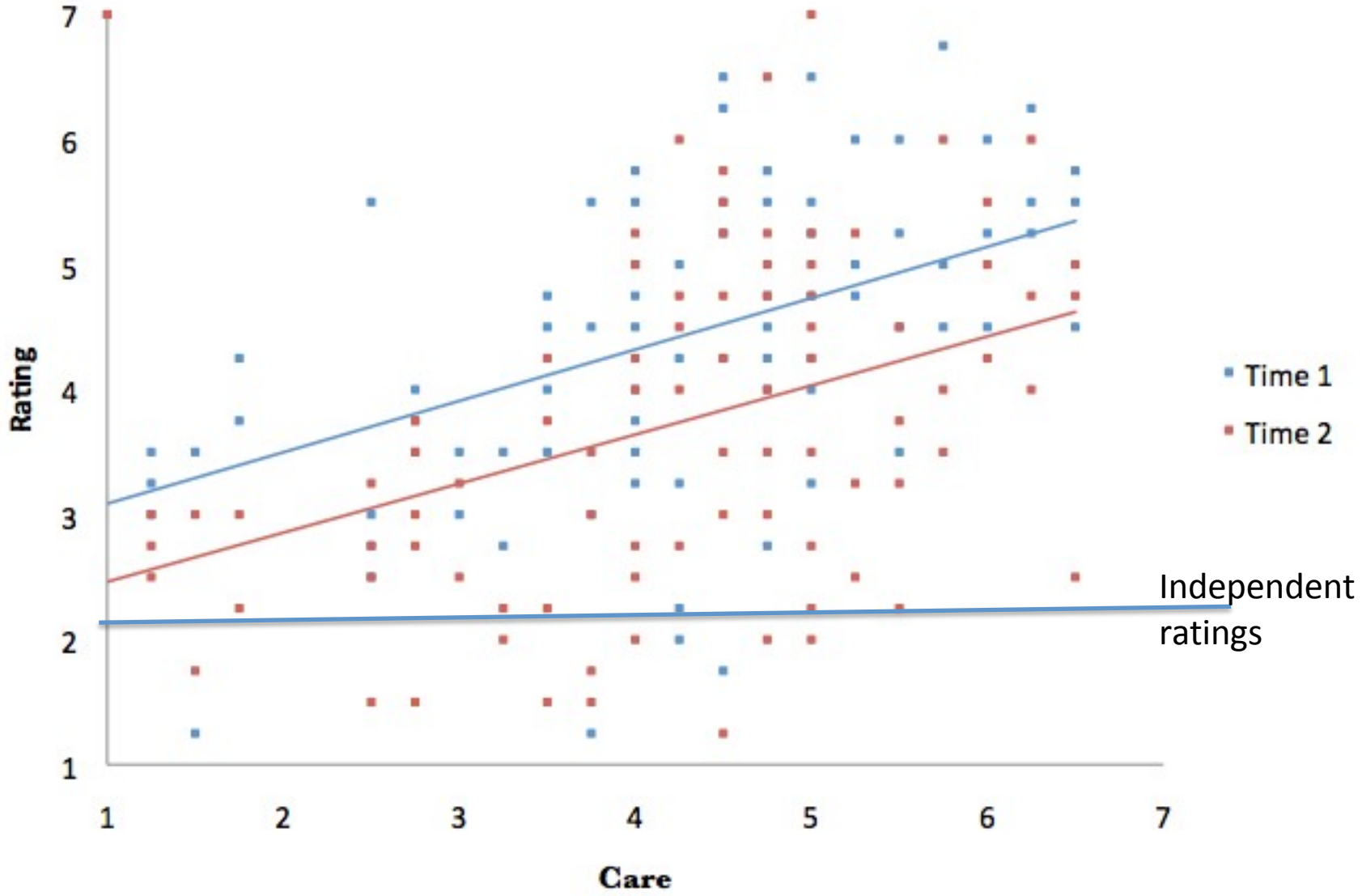
- In visual cognition…but may draw on processes that are also part of IOED
- We often feel that we have fully processed, and represented objects in a scene…and yet (Wolfe, Reinecke, Brawn, 2006)
- Please look carefully at the following objects….one will change into another

Links to illusions of understanding

- We think we represent the world in terms of "how things work" diagrams
- We encounter exposed mechanism or idealized representations in instruction
  - And assume we have stored them
- a "blueprints bias"
- Extends to beliefs about justifying arguments

Illusion of argument justification

- How well can you justify your view of:
- Human activity and global warming
- Cell phone leading to cancer
- Stem cell research
- (teach scale of good vs. weak arguments)
  - Similar to cross bow case
- Also ask: *how much do you care about this issue?*



Fisher & Keil, in press (JEP:G)

Illusion of argument justification

- The more you care, the worse the illusion
- Investment, exposure, and time spent do not necessarily translate into good calibration
- Even being in an argument doesn’t necessarily reduce illusion...depends on kind of argument
    - Argue to win vs. argue to learn

It gets worse

- IOED compounded by Illusions of Insight
- We think we have gained insight, when we haven't
- The blinding "light" of many neuroimaging results
  - Lose ability to tell good from bad explanations when add salient but irrelevant neuroimaging reports

Weisberg, Keil, Goodstein, Rawson& Gray, 2008 -JCN.

Why the illusions?

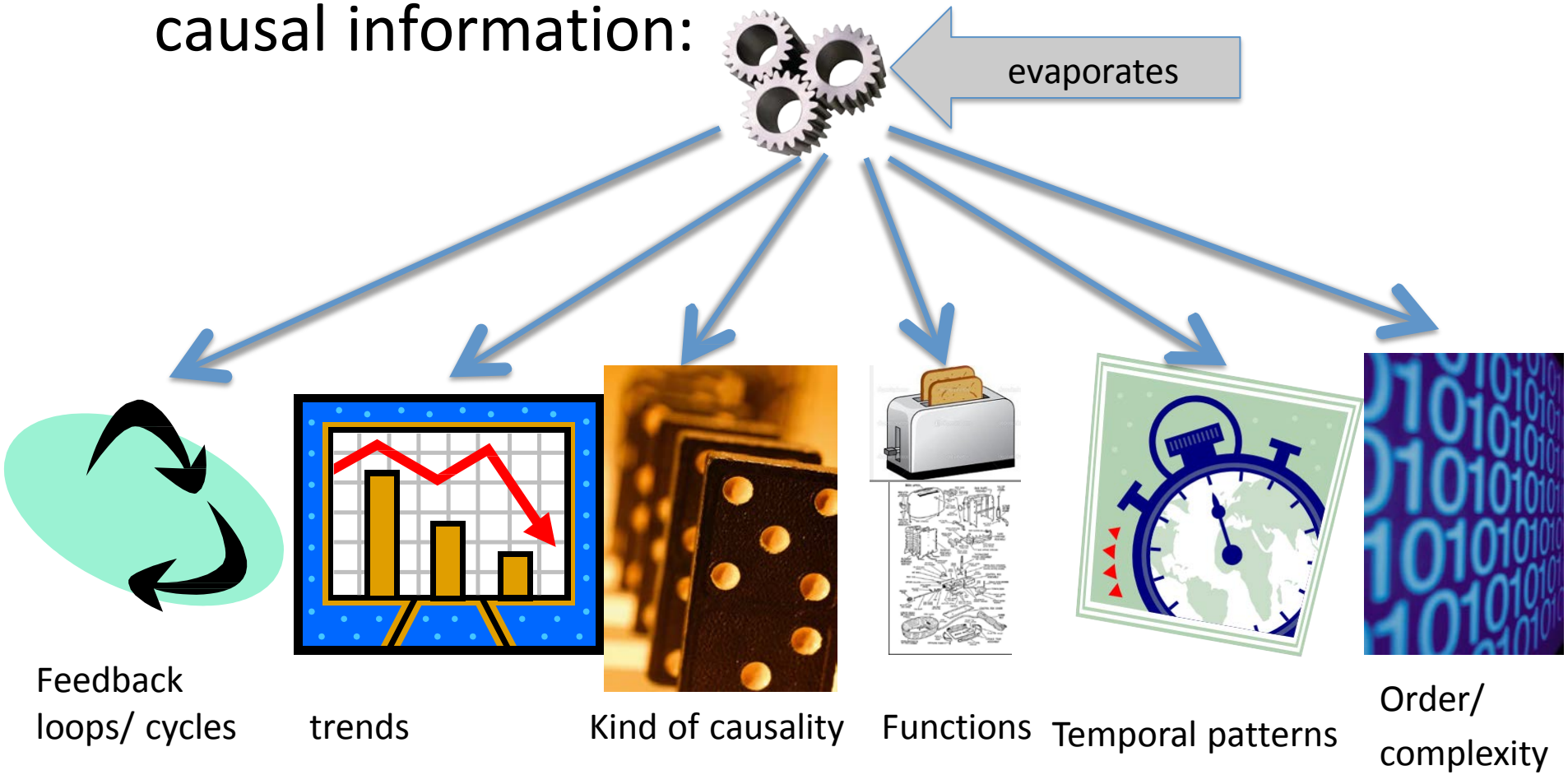
- May be adaptive (Lockhart et. al., 2002)
  - Perhaps a <u>developmental legacy</u>
    - Value of an illusion early on
      - Irrational optimism motivates learning
- Confusions across levels
  - Function for mechanism— misleading insights
- "reverse engineering" with objects at hand is confused with stored knowledge
- Knowledge "misplaced"
  - not "missing"
  - More on this

Is Nothing Learned?

- Without mechanism, what else is there?
- Is the quest for mechanism an exercise in futility?

Why seek mechanism?

- As a conduit to other more abstract levels of causal information:

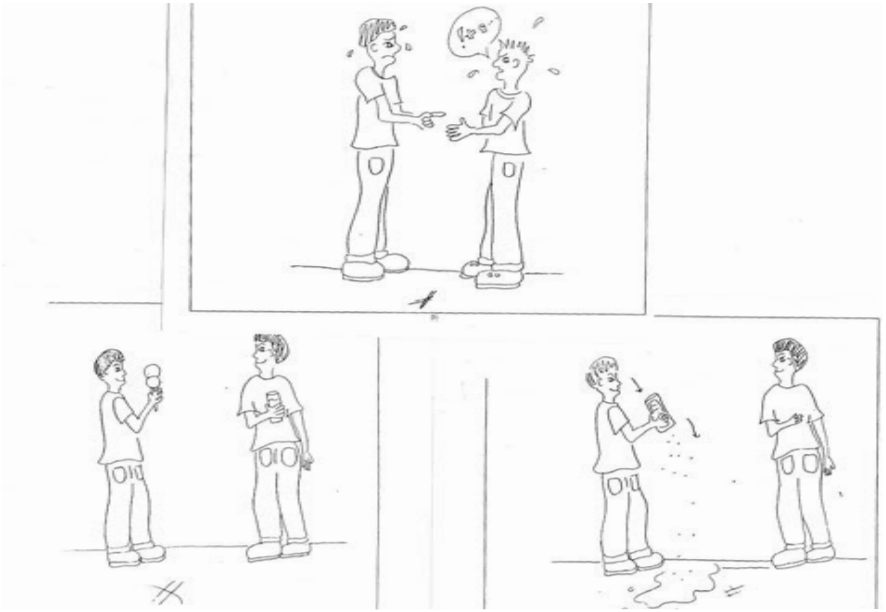


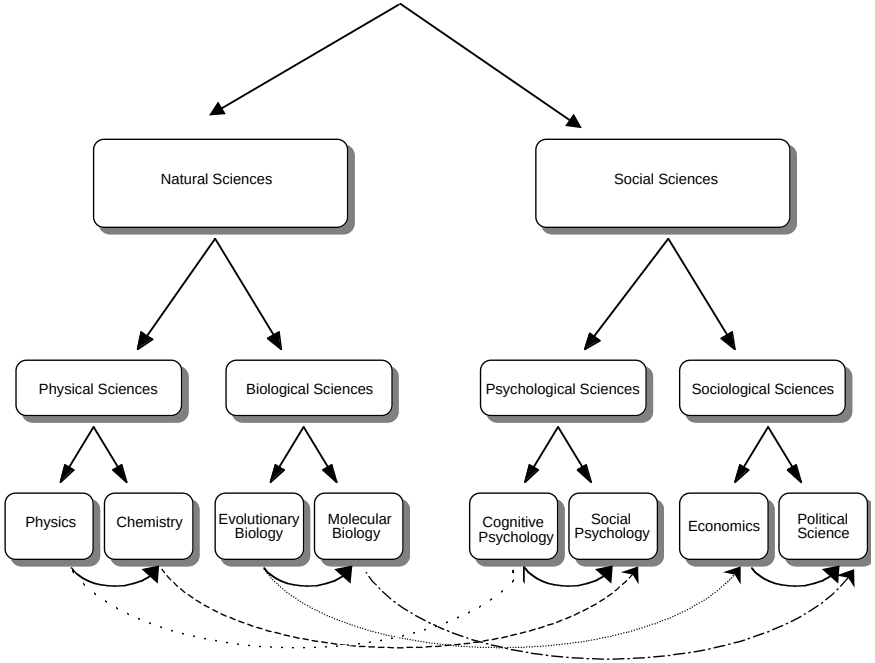
Developmental Insights

- Children reveal the most cognitively natural building blocks of intuitive science…
  - Tell us what is most used/retained, even in adults
- Children are worst at retaining mechanism
  - Compensate by using abstract causal patterns to
    - Locate experts and areas of expertise
    - Defer selectively
    - Evaluate explanations
  - Illustrate how scientific understanding is feasible

Using causal patterns to infer division of cognitive labor

- Even kindergartners can discern disciplines





Keil, Stein, Webb, Billings, & Rozenblit,. 2008

Using causal density to infer plausible domains of expertise

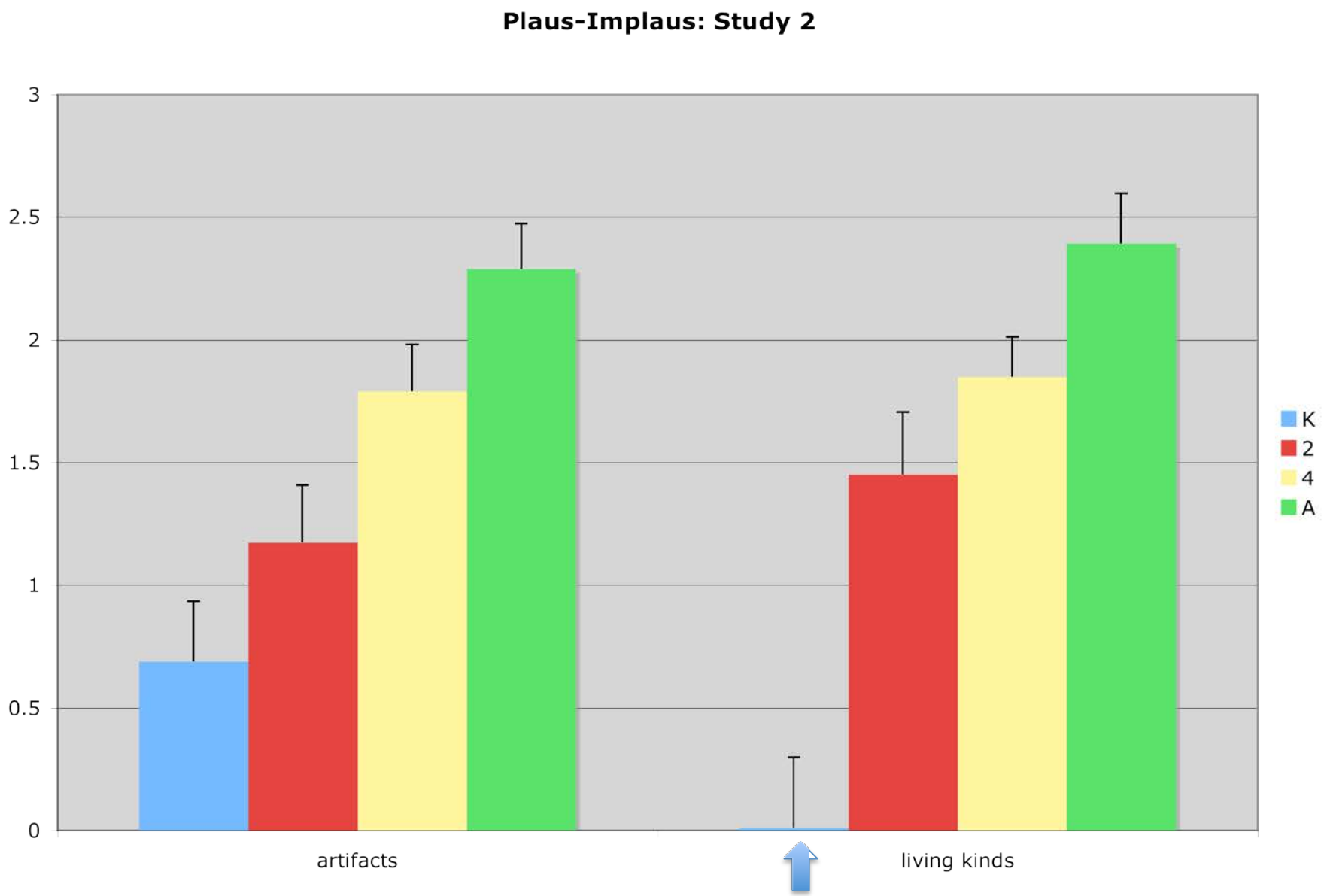
- No experts needed if no internal causal structure
- Use as guide to learning/allocation of resources

Causally rich vs. lean

- Artifact: Cars that drive on rough roads vs. Cars that have dirty windshields

Biological kind: Dogs that are good at hunting vs. Dogs with red collars

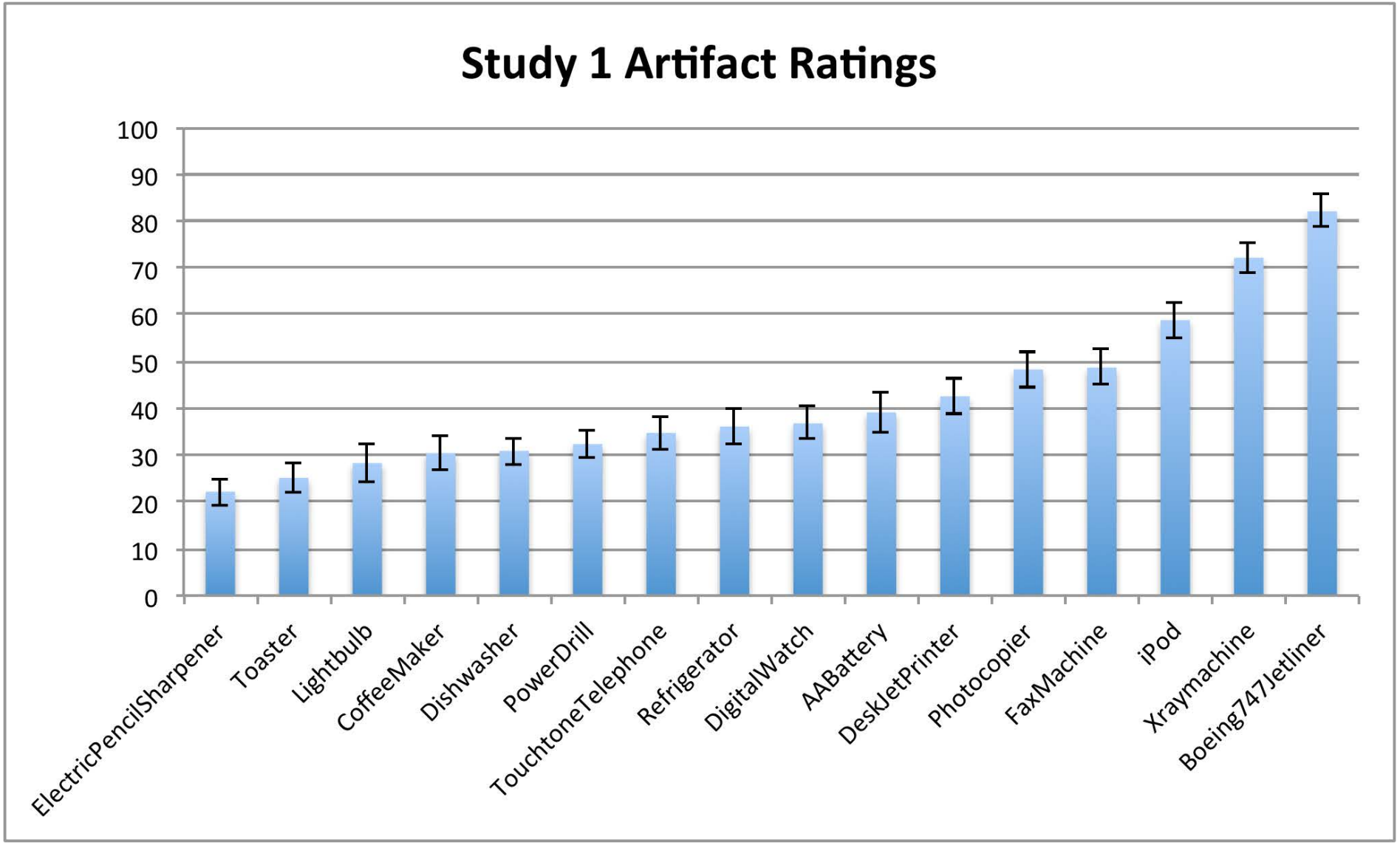
- Non-living natural kind: Clouds that you see just before thunderstorms vs. Clouds that you see just before baseball games


Plaus-Implaus: Study 2
3
2.5
2
1.5
1
0.5
0
artifacts
living kinds
K
2
4
A

Keil, 2010

Relative complexity

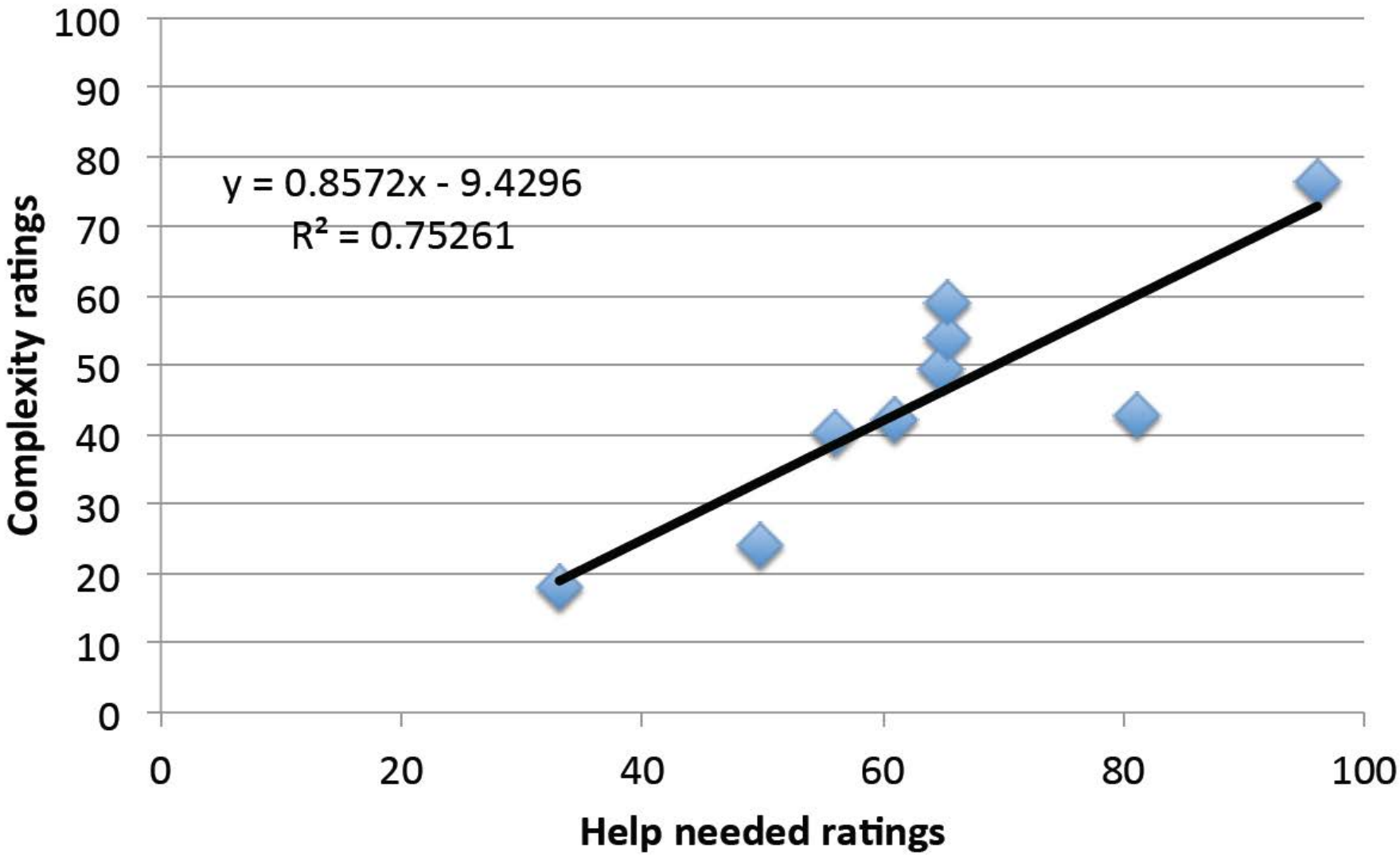
- Can we sense relative complexity w/o mech?
- List of 16 artifacts, 16 biological parts
  - Great range: e.g. toaster to 747 jet
- Rate on 1-100 scale on how hard to fully understand + explain
  - Wide range of ratings
  - Cronbach's alphas >> high consensus



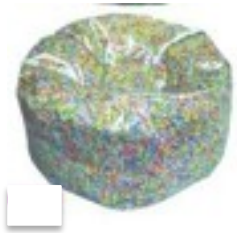
Adults repeatedly yield Cronbach alphas above .90… much lower before age 10

Kominsky & Keil, in prep

Complexity drives deference



The complexity of causal complexity



- Complex heuristics
  - Go far beyond part counts
    - No one “suckered” by beanbag chairs
- What is early and what develops?
  - Early: random vs. ordered, part diversity
    - Even infants sensitive to order and randomness (Newman, Keil et. al., 2010; Xu et. al., 2012).
  - Late: embedded complexity, hierarchical structure
  - Growth in school years

Domain X Complexity Biases

- Reductionistic biases (Keil, Lockhart, et al., 2008)
- Physics>biology>neuroscience>psychology>economics
- Strongest in young children but residual remains in adults
- Complexity guides deference but we can fail to defer because of these biases
  - Extraordinary examples in the legal system when psychological complexity is discounted as "self-evident"
  - Psych experts are not allowed to testify because claimed to be common sense…never happens in "harder" sciences

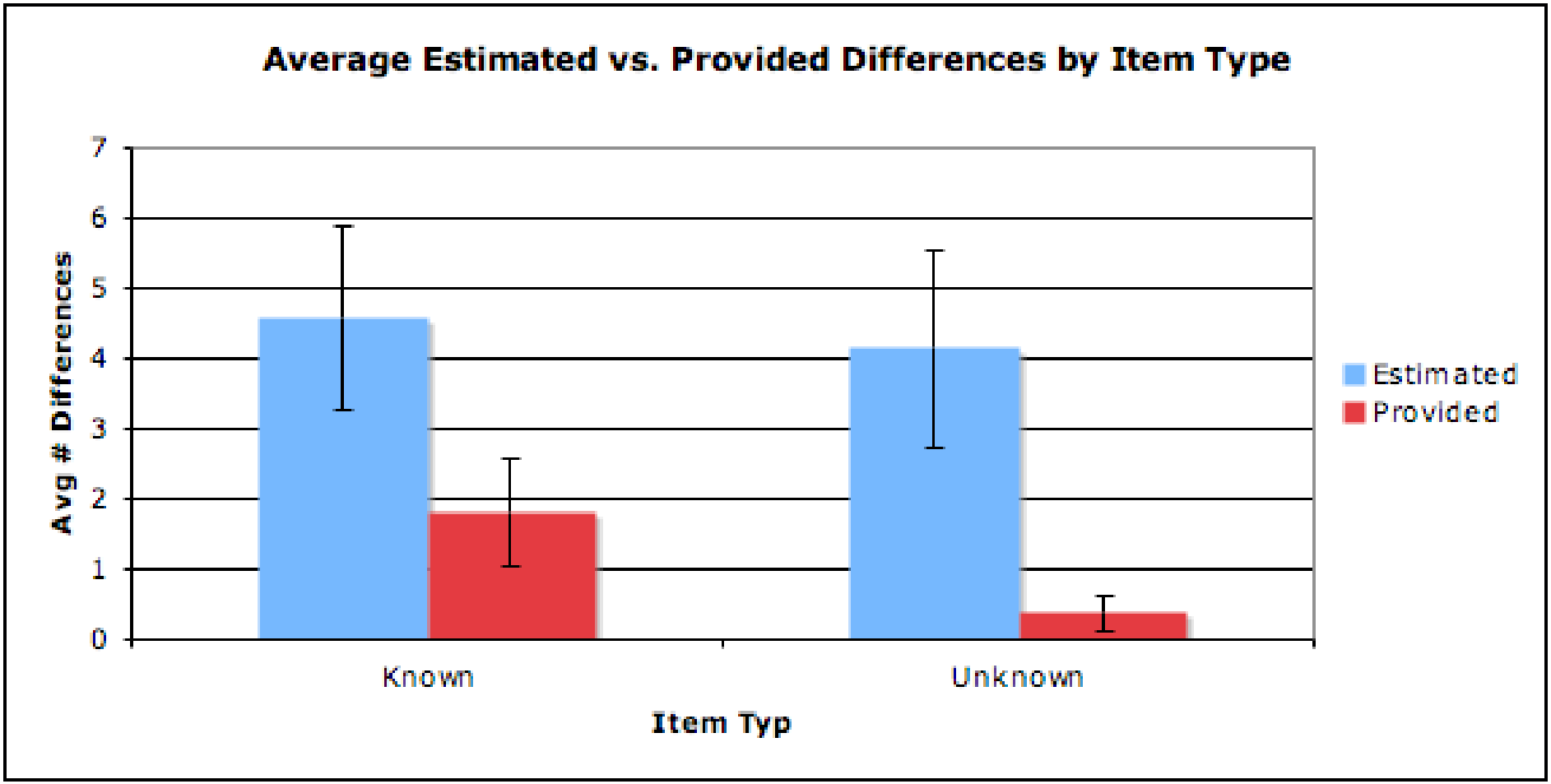
Deferring but not Knowing

- We massively "outsource" knowledge, but underestimate: an "individualism bias" (Gelfert, 2011)
  - Confuse deferred with owned knowledge
- Even preschoolers use causal patterns to solve division of cognitive labor problems (Keil et. al., 2008)
  - But early and automatic use may lead to confusion of where knowledge is actually located
  - Helps explain IOED and "knowing" w/o knowing
- An example with word meanings

Misplaced meanings

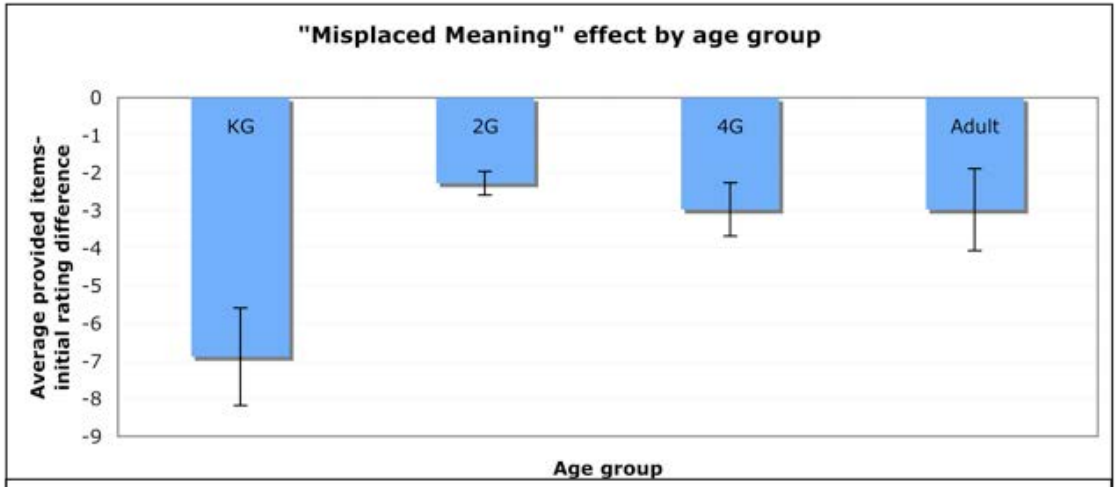
- Automatic locking on to domains and experts leads to:
  - Knowing yet not-knowing – ("individualism bias")
- Studies with adults and children
- Three kinds of pairs: known similars, unknown similars, pure synonyms
  - wolf-dog, rowboat-canoe, seal-walrus
  - ferret-weasel, pine-fir, blackbird-starling
  - sofa-couch, car-automobile, baby-infant

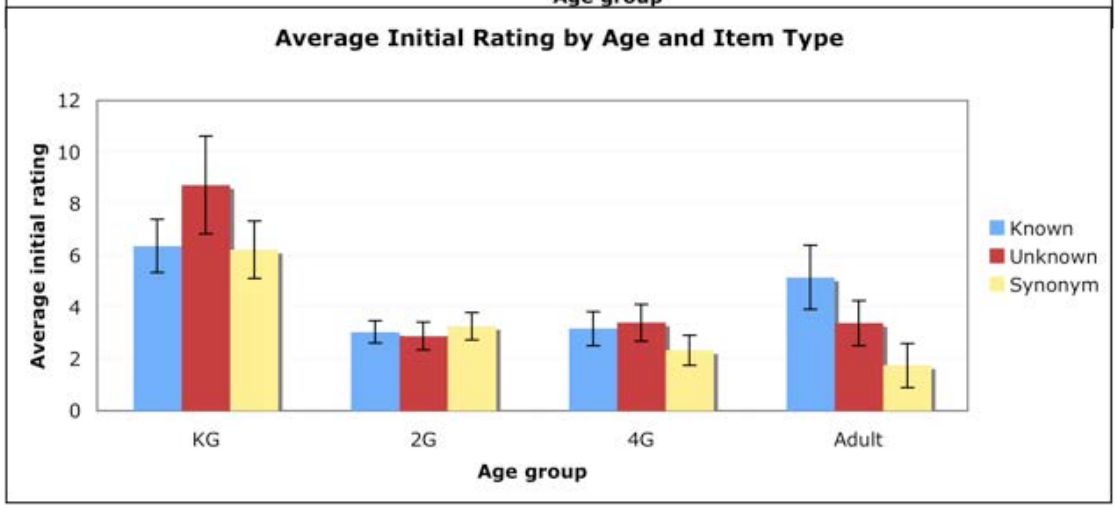
- How many features do you know that can tell pairs apart?
- Do quickly (no self test) for long list, then test

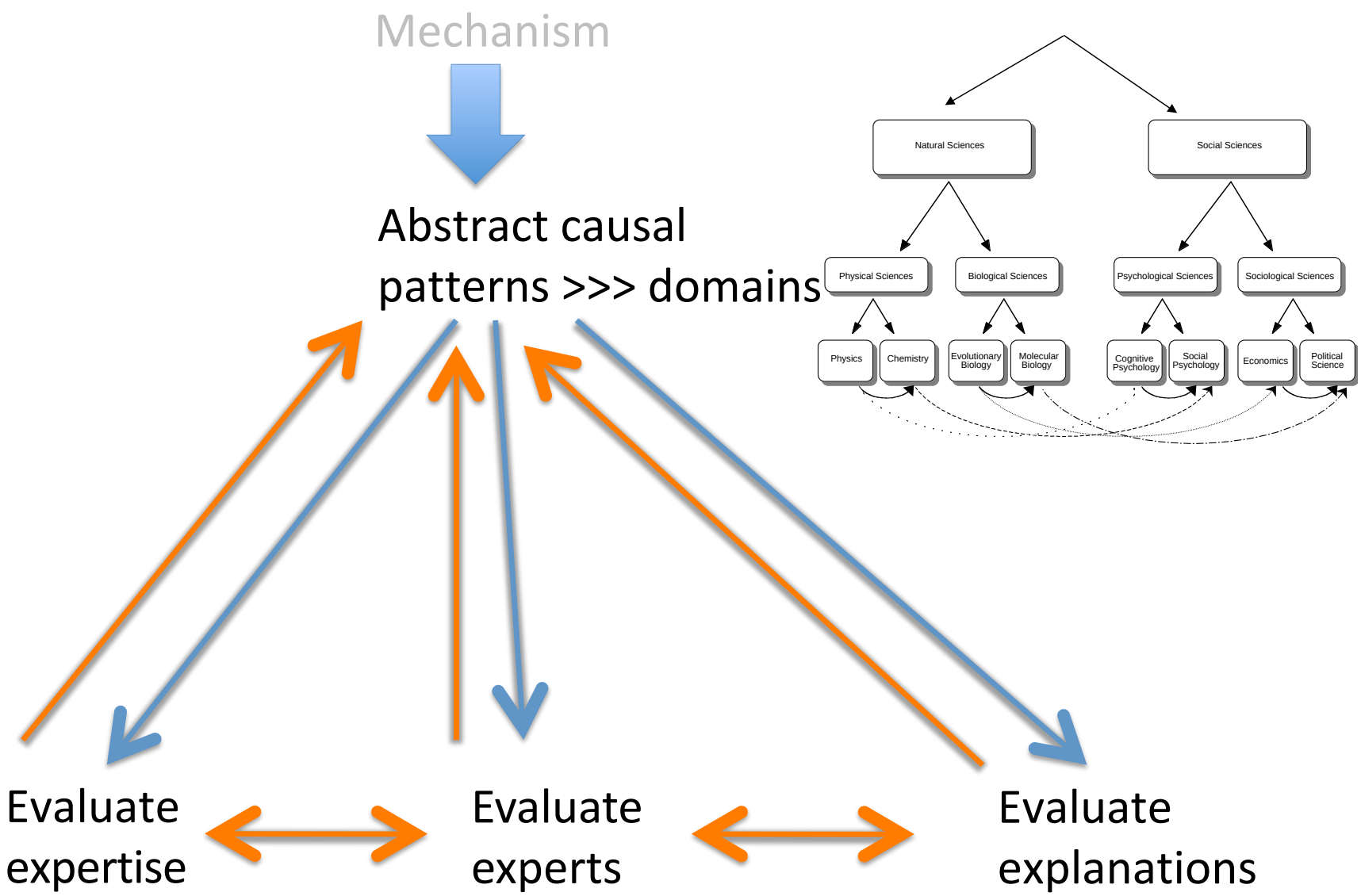


(Kominsky & Keil, under review)

Misplaced meanings-children






Mechanism
Abstract causal patterns >>> domains
Natural Sciences
Social Sciences
Physical Sciences
Biological Sciences
Psychological Sciences
Sociological Sciences
Physics
Chemistry
Evolutionary Biology
Molecular Biology
Cognitive Psychology
Social Psychology
Economics
Political Science
Evaluate expertise
Evaluate experts
Evaluate explanations

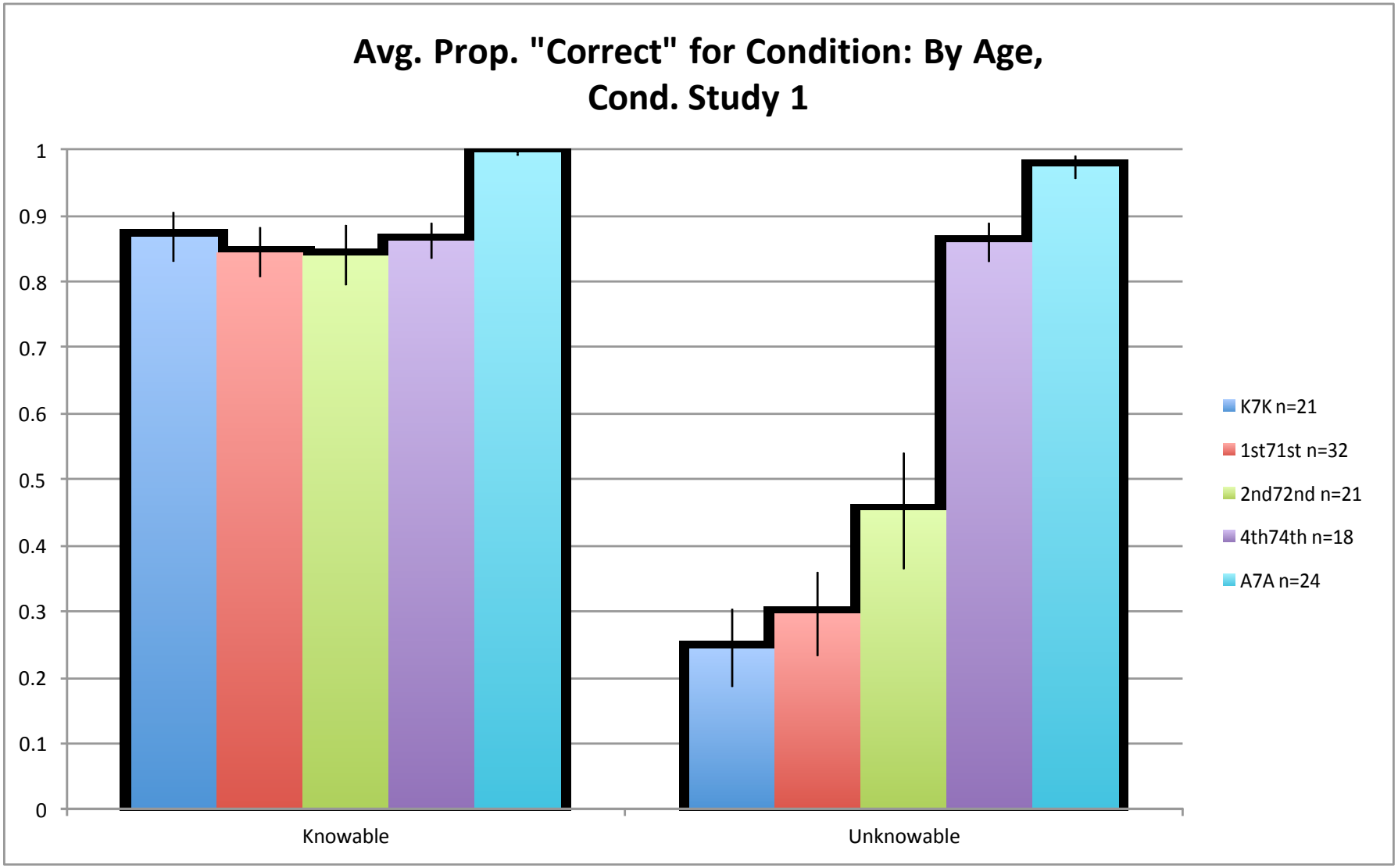
Evaluating Experts

- When should an expert say “I don’t know” and when is “I know ….” a sign of ignorance?
- Certainty/precision: rough heuristic for expertise
  - But tempered by real world knowledge
    - Must be plausible links between knowledge and causal structure of the world
    - Sense of randomness, uncertainty, scale, plausibility

Misleading numerical certainty

- If you count all the bones that are normally in a rabbit, how many will you get?
  - There are exactly 206 bones in a rabbit's body
  - I don't know because it is not possible to answer that question precisely.
- If you count all the leaves on all trees in the entire world, how many will you get?
  - There are exactly 809,343,573,353,235 leaves on all trees in the world vs.
  - I don't know because it is not possible to answer that question precisely

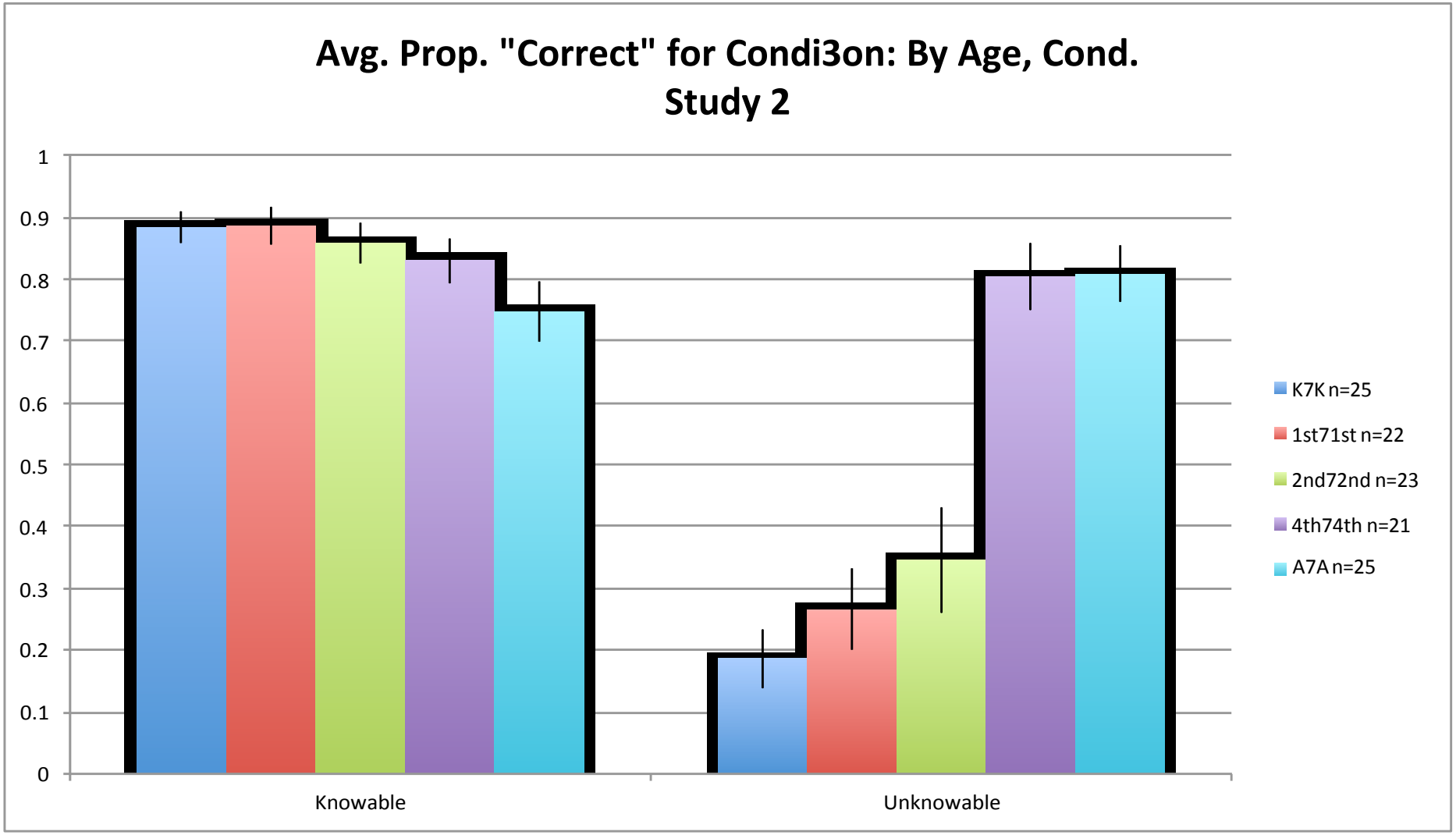
Numerical Certainty



Keil & Langthorne, in prep

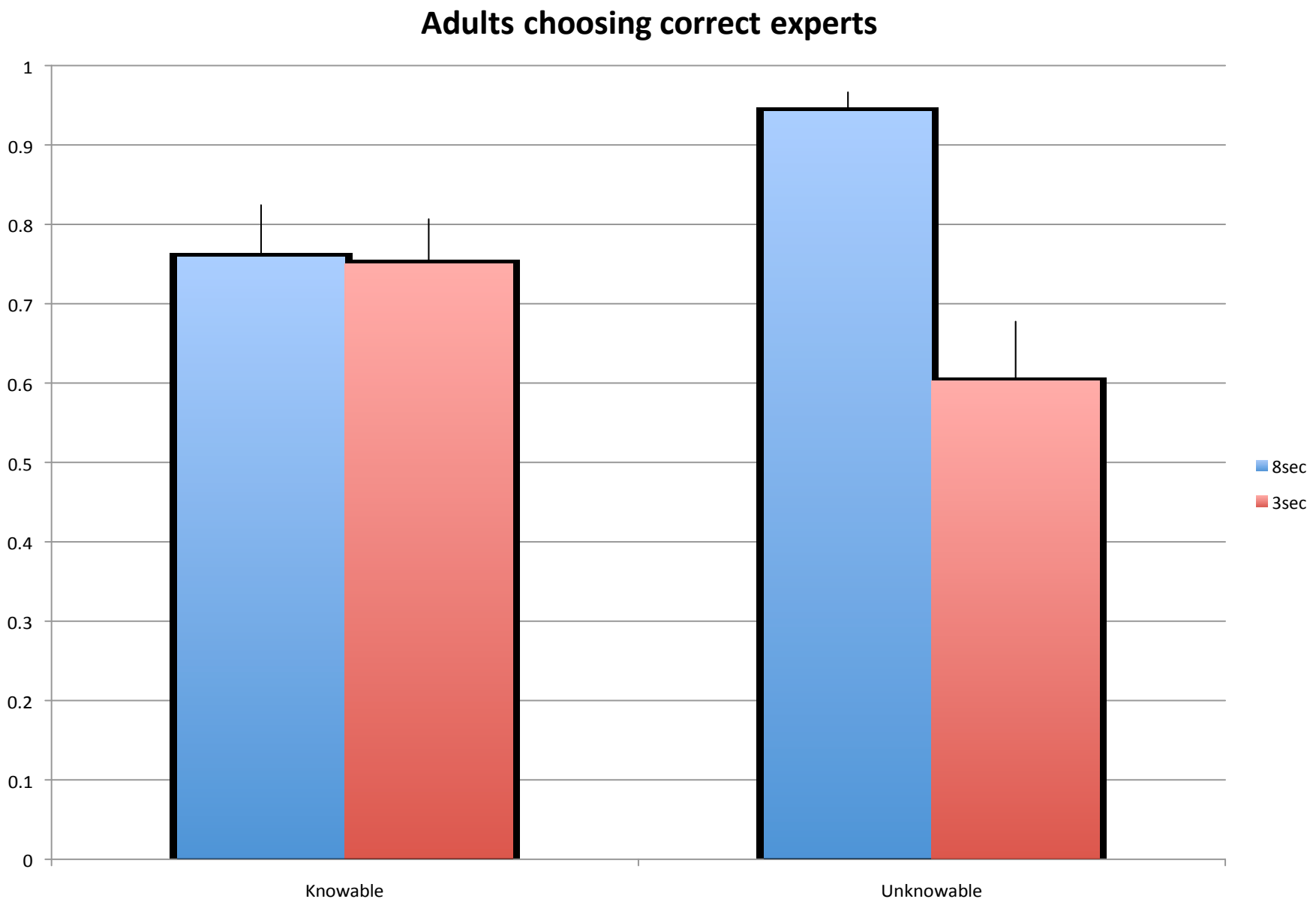
Misleading predictive certainty

- What colors will a rainbow have on April 4, 2721?
  - A rainbow will definitely have the colors red, orange, yellow, green, blue, indigo, and violet on April 4, 2721. (vs. IDK)
- How long will the president's spouse's hair be, in inches, on February 17, 2033?
  - The president's spouse's hair will definitely be 15 inches long on February 17, 2033.
- Sensing stable vs. transient causal patterns


Avg. Prop. "Correct" for Condi3on: By Age, Cond.
Study 2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Knowable
Unknowable
K7K n=25
1st71st n=22
2nd72nd n=23
4th74th n=21
A7A n=25

Developmental legacy

- Adults more like children if under cognitive load
- Do certainty studies under time pressure
- Adults embrace far more false certainty claims

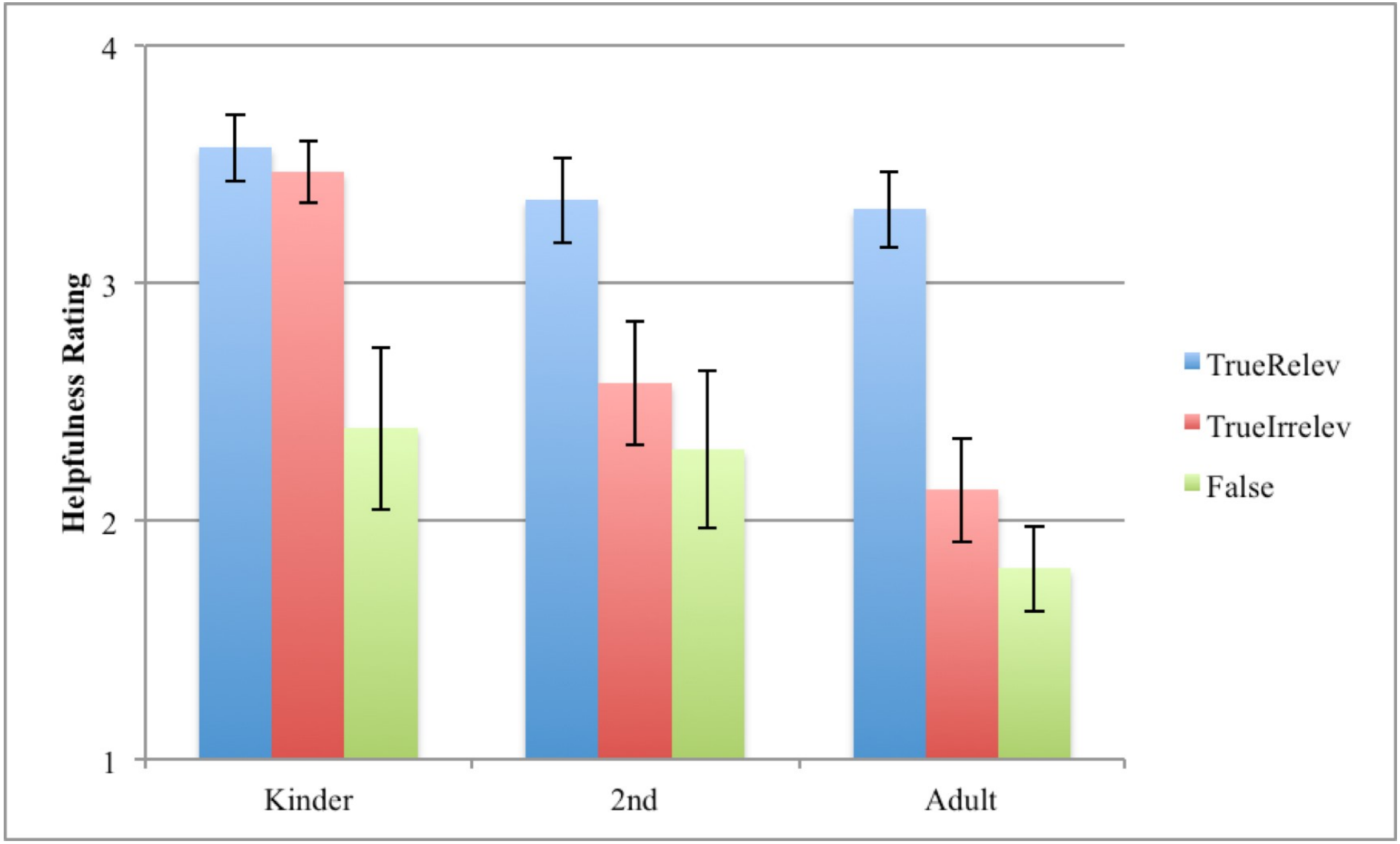

Adults choosing correct experts
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Knowable
Unknowable
8sec
3sec

Evaluating Explanations

- What makes an explanation compelling beyond plausibility of real world patterns?
- Relevant? Appropriate gist of information
- Right level?

Relevance and “gisting”

- …which things are most helpful for understanding *what makes cars go?*
- *Cars have brakes that stop the wheels*
- *Cars have radios that play music*
- *Cars have engines that turn gasoline into power*
- *Cars have windshield wipers that clean the windows*
- *Cars have batteries that start the motor*
- *Cars have headlights that light up the road*
- *Cars have steering wheels that turn the tires*
- *Cars have trunks that hold extra bags*
- *And false items (e.g., Cars hold 20 people).*



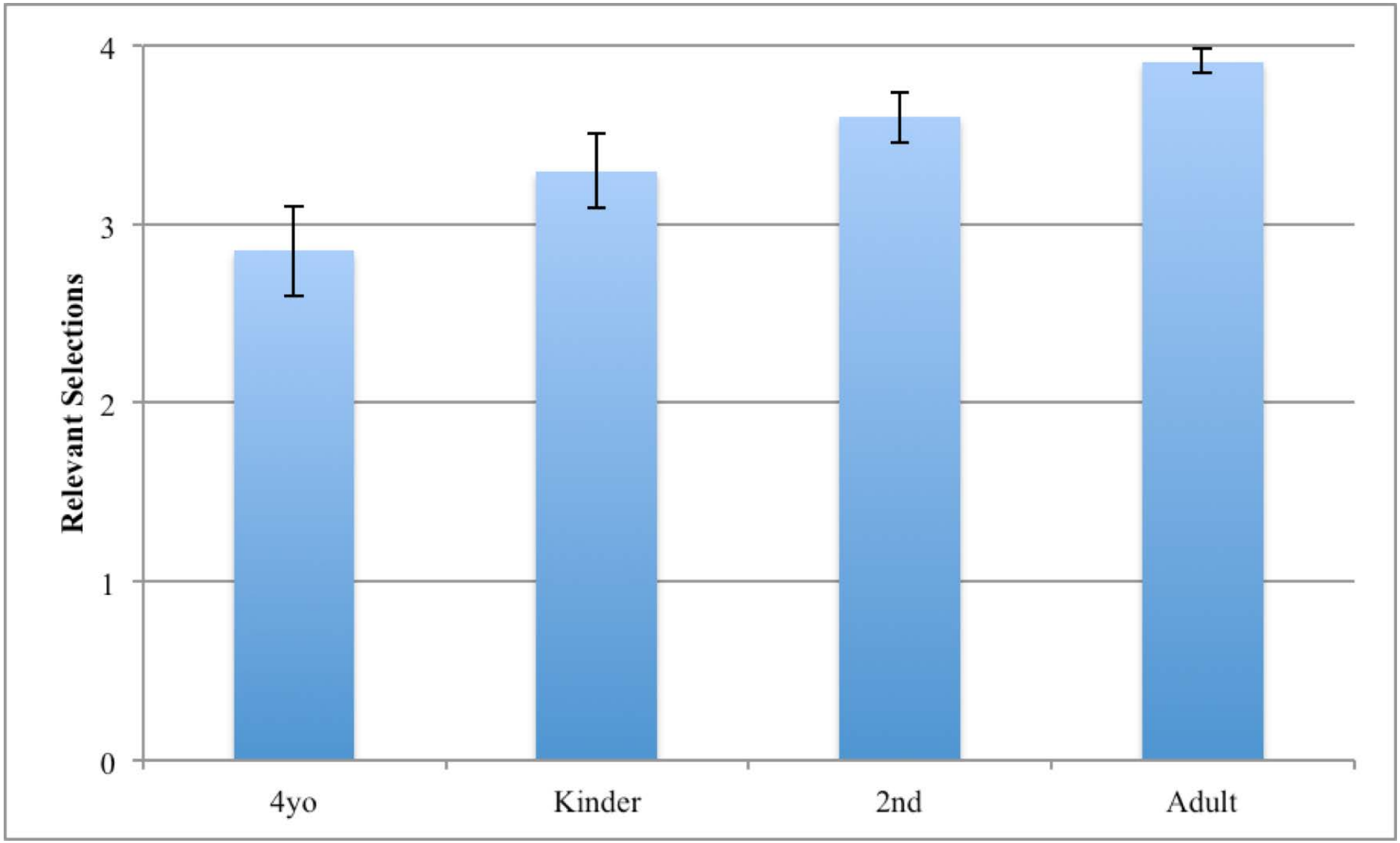
Johnston & Keil, in prep

Huge developmental shift

- Can easily tell true from false
- Can’t tell true/irrelevant from true relevant
- But are younger children strictly unable?
- Perhaps more fragile competency can be revealed with appropriate cognitive support
- Making salient the contrast

Relevance w/ contrasts

- *<u>which one is</u> most helpful for understanding what makes cars go?*
- *Cars have brakes that stop the wheels*
  - *Cars have radios that play music*
- *Cars have engines that turn gasoline into power*
  - *Cars have windshield wipers that clean the windows*
- *Cars have batteries that start the motor*
  - *Cars have headlights that light up the road*
- *Cars have steering wheels that turn the tires*
  - *Cars have trunks that hold extra bags*


Relevant Selections
4
3
2
1
0
4yo
Kinder
2nd
Adult

The contrast effect

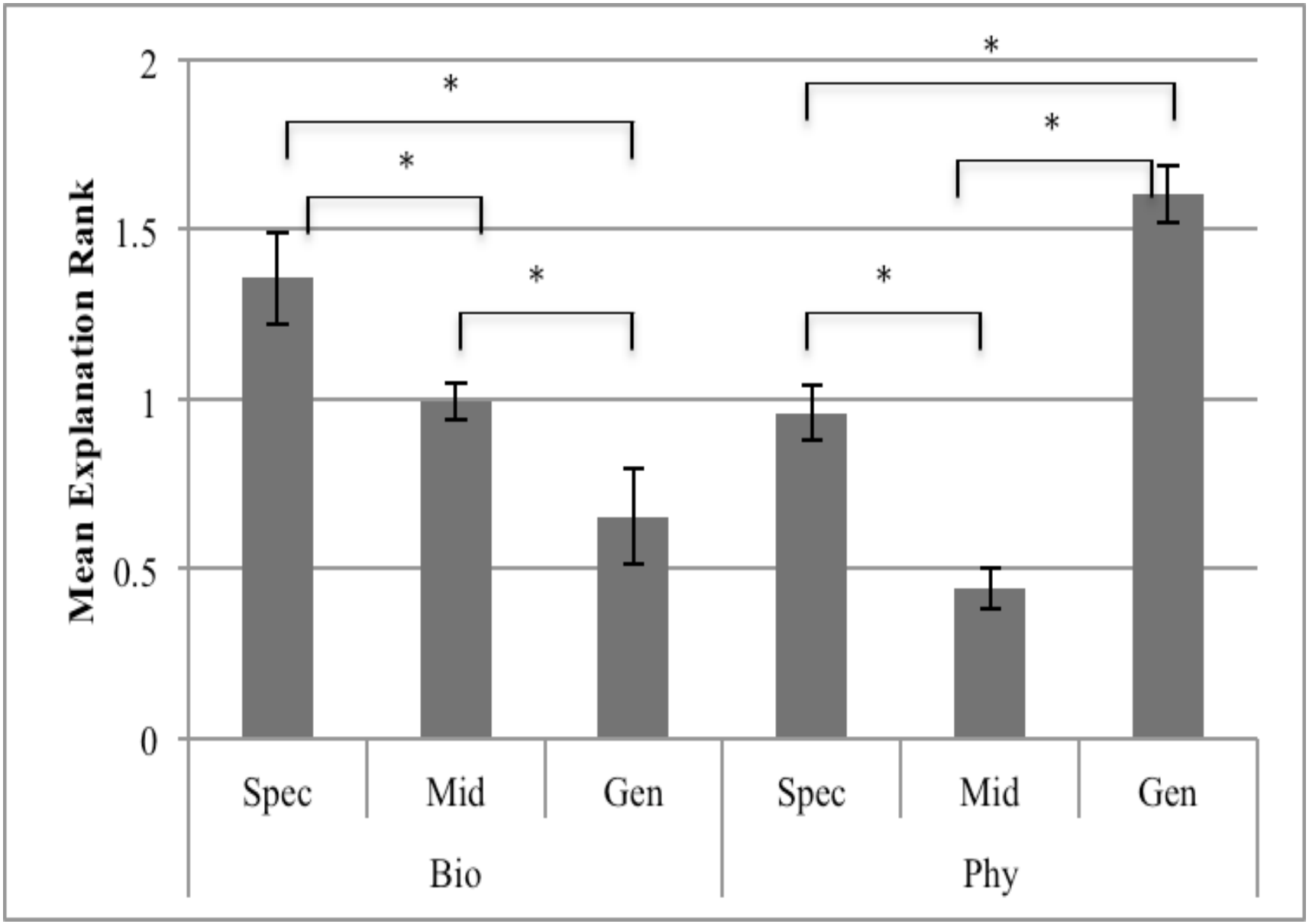
- Early on, causal relevance is hard to judge as an absolute
- But…relative relevance is much easier
- Pedagogical implications……
  - Even though contrasts present more info at once, may be much more effective at fostering insight
  - Most presentations don’t do this

Detecting and preferring levels

- Tradeoffs between high and low generality (Strevens, 2009).
  - Power vs. details
- Adults have strong preferences that vary across domains
- Would seem to be a late emerging, highly abstract domain by level interaction…but
  - w/ sensitive measures….very early

Physics vs. Biology- 3 levels

- How can the puffer fish hear?
  - Puffers > fish > animals have a drum like thing in their ears that rumbles when there is a sound
- How come the hat fell to the ground?
  - Hats > clothing > things are pulled down by the hugeness of the earth
- What level is the best explanation?



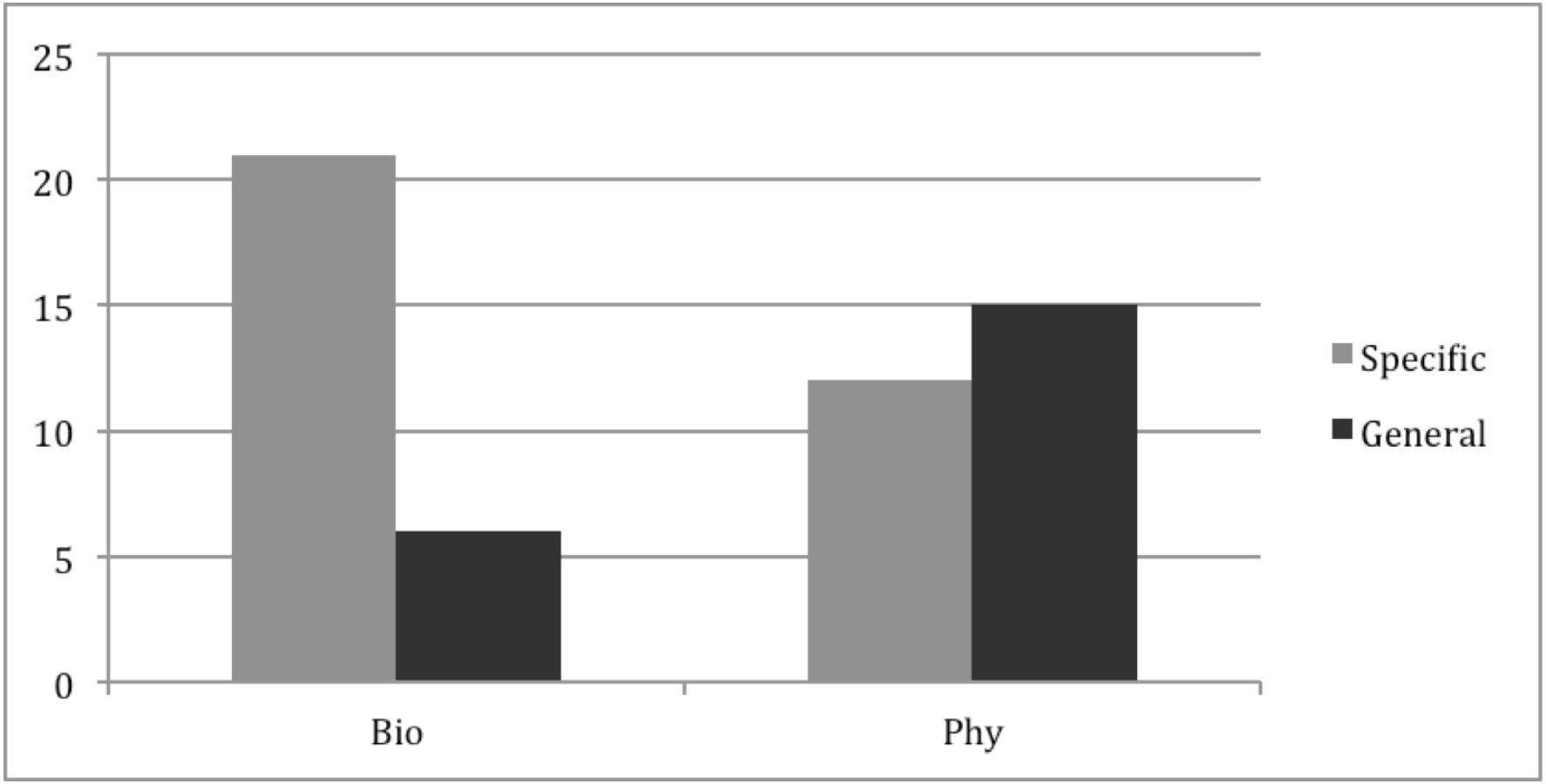
Adults

Sheskin, Johnston & Keil, in prep

Is it just applicability?

- Applicability check : how applicable each explanation was to “all animals” (biology) or “all things” (physics).
  - applicability of bio items higher than physics items (p = .020) - opposite of direction of effect
- More subtle intuitions
  - even if applies to more animals, each instantiation is more causally distinct than for physics
  - Requires tracking of local causal patterns

Five year olds



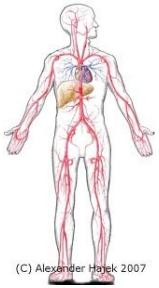
A second trend of overall increasing generality preference with age

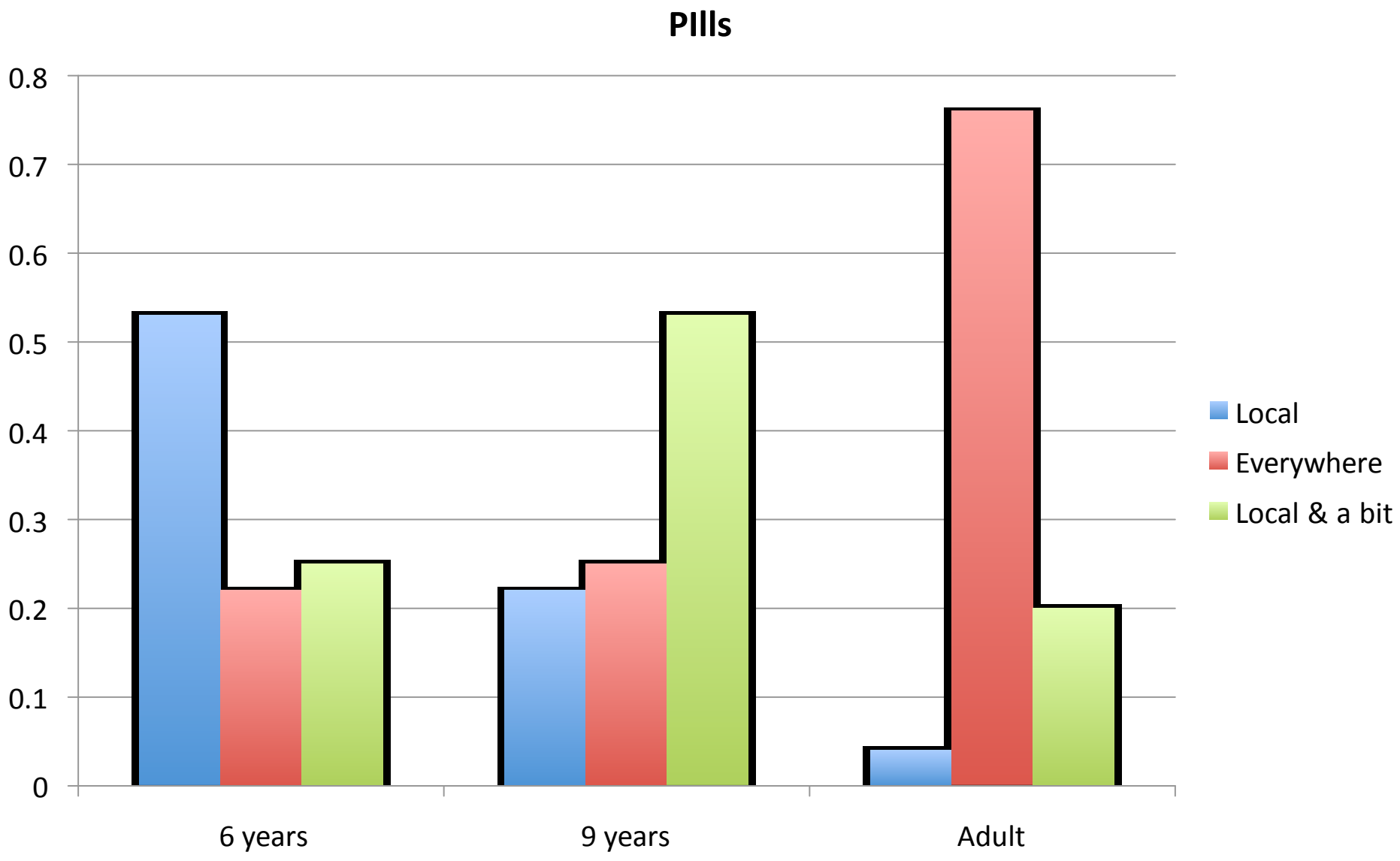
Abstractions don’t always map smoothly

- Concepts of medicine actions (Lockhart & Keil, in prep)
- Always seem to have causal hunches
  - Built off real patterns… but mapping is imperfect
- Two contrasting developmental patterns
  - Initial schemas are misapplied and get better
  - Tracking actually gets worse w/age: schema overpowers

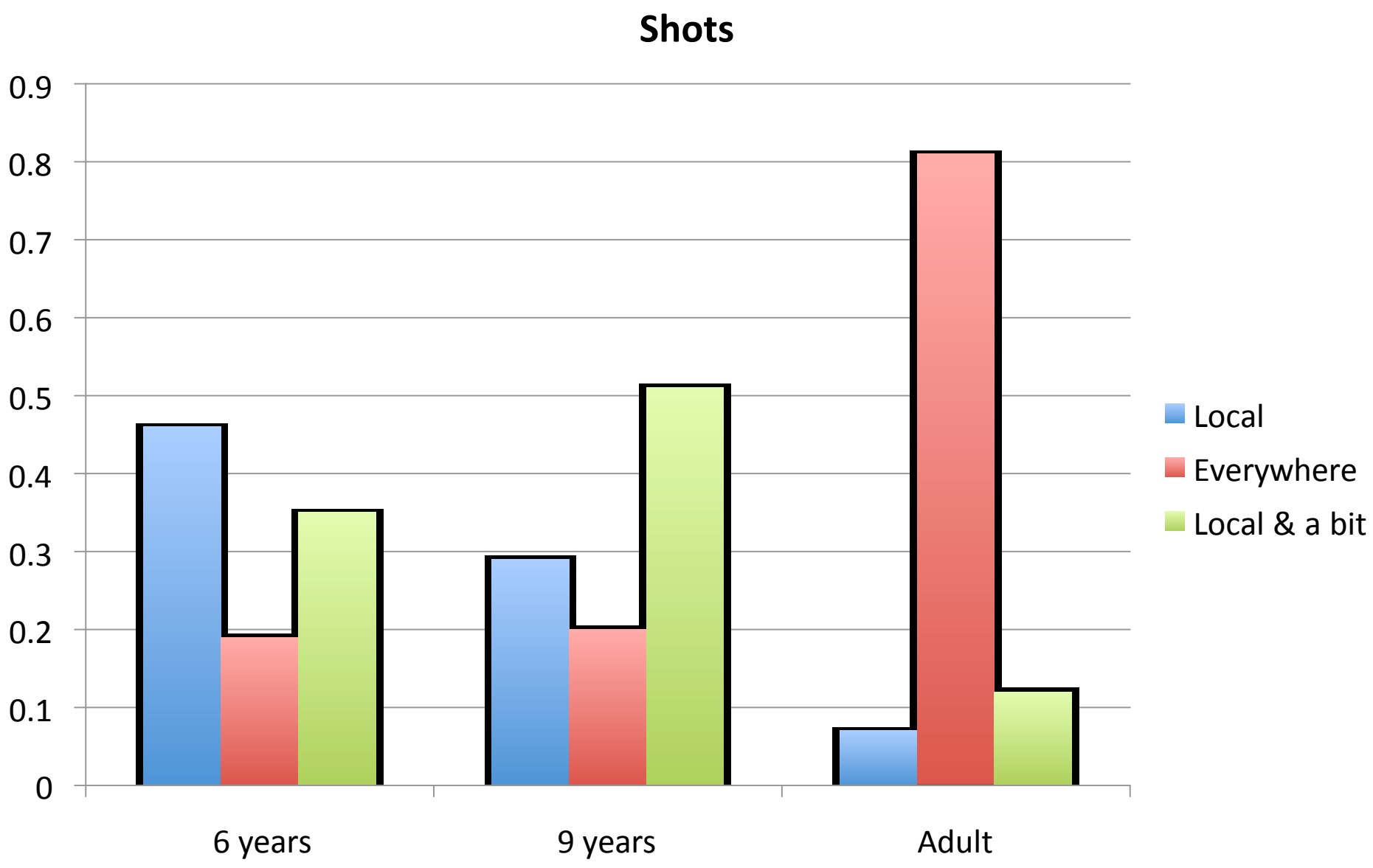
Where does medicine go?

- Consider localized afflictions
- Where would pill or shot go??
- Local, hybrid, or global?





Lockhart & Keil, in prep

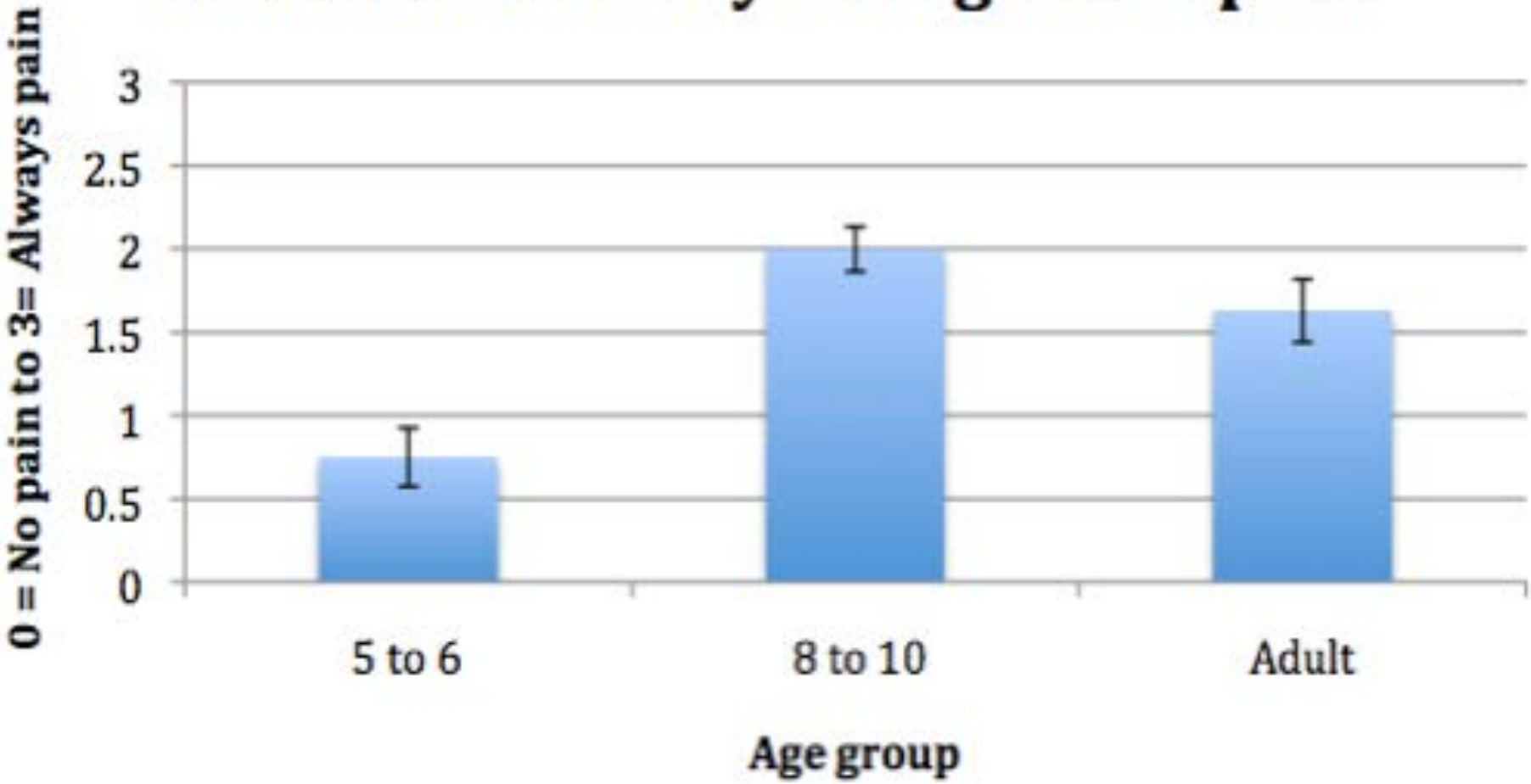


Lockhart & Keil, in prep

Side effects and Efficacy

- What has more efficacy…a drug with painful side effects or one with minimal side effects?
- The emergence of a no-pain no-gain model?
- In some ways younger are more correct

Figure 4 Endorsement of greater treatment efficacy with greater pain



Lockhart & Keil, in prep

Causal schemas for medicines

- Highly abstract schematic expectations
- All have some threads of truth
  - Capture real world patterns
- But can be misapplied
- Sometimes get more misapplied with age
- Don't think of as misconceptions or deficits, but rather interpretative tools, used imperfectly
- Good teaching may often involve showing how to map schemas to phenomena
  - By sharpening schemas
  - By illustrating contradictions

What to teach?

- Surprisingly..,.mechanism
  - But not with goal of retaining mechanism
  - Rather as vehicle for more enduring types of causal memories
    - Surprisingly abstract & diverse
    - Development often from abstract to concrete
- Connect mechanism to other levels
  - Functional, relational, causal powers, complexity etc.
- Teach how to use causal patterns to locate and evaluate experts and explanations
  - Very young children already do this automatically
    - Build on their tendencies, highlight cause

How to teach?

- Have a feasible goal of retained knowledge
  - A hugely neglected research topic – Krebs case
  - Reconsider what science literacy means
- Look for early competencies to build on, not deficits to erase
  - Work on refining mappings
- Narratives, historical embeddings
  - May help reduce the individualism bias & therefore IOED
    - Making clearer the social nexus supporting each person
- Active interventions to highlight causal patterns
- Provide contrasts that highlight relevant causal patterns vs. mere facts

Will it work for health literacy?

- Doctors and patients as partners in decision making?
  - What should be the common ground?
- What should a person know to be able to forage for and evaluate medical information?
  - How much about causal patterns, at what levels?
  - How much about evaluation skills?
  - What is feasible for most of the public?
- Huge remaining questions about grain and levels of causal understanding that should be retained…

A case study

- Patient X is diagnosed with prostate cancer
- Watchful waiting or surgery?
- How much biology, statistics is helpful?
  - The problem of individual cases vs. stats
    - Where biology/mechanism potentially enters in?
- How to evaluate competing experts?

End

- Thanks to NIH/ NICHD - R37 HD023922
- Thanks to Yale Cognition and Development Lab group
  - Kristi Lockhart
  - Matt Fisher, Angie Johnston, Jonathan Kominksy, Phil Langthorne, Mark Sheskin, Brent Strickland
  - Legions of undergraduate assistants