Updated 1/25/2022

Principles of Scalable Data Management: theory, algorithms and database systems

Be prepared to very succinctly state:

1. What do you hope to get out of this course ☺
2. What is your biggest fear for this course ☹
3. Something interesting/ surprising about you that is possibly related to this class

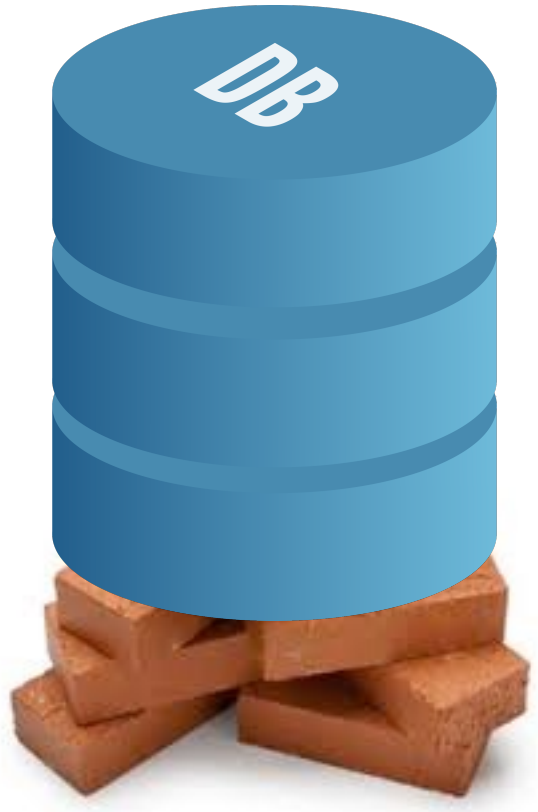
Wolfgang Gatterbauer

CS7240 Principles of scalable data management (sp22)

https://northeastern-datalab.github.io/cs7240/sp22/

1/18/2022

"Principles of Scalable Data Management"



Relational databases (and related technologies) are the core technology used for managing data at scale

Our intention it to build solid foundations and look at the algorithmic principles

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Background of instructors: Wolfgang Gatterbauer

Background

- PhD, Computer Science, Vienna University of Technology (2007)
- PostDoc, Database Group, University of Washington (2011)
- Assistant Professor, Tepper School of Business @ CMU
- At Khoury since 2017

Combining theory with database systems

What are the fundamental algebraic properties that allow algorithms to scale to large amounts of data? How to apply these principled to new data management problems?

- Inconsistencies & Trust
- Provenance & Explanations
- Uncertainty ("Probabilistic data")
- Graphs & Linear Algebra

Let's take turns

I call your name, please succinctly state:

1. What do you hope to get out of this course ☺
2. What is your biggest fear for this course ☹
3. Something interesting/ surprising about you that is possibly related to this class

This helps us get to know each other better / helps me understand your goals and expectations for the course

Foundations of relational databases

Some "birth-years". When was SQL born?

- 2004: Facebook

- 1998: Google
- 1995: Java, Ruby
- 1993: World Wide Web
- 1991: Python

?

- 1985: Windows

Some "birth-years". When was SQL born?

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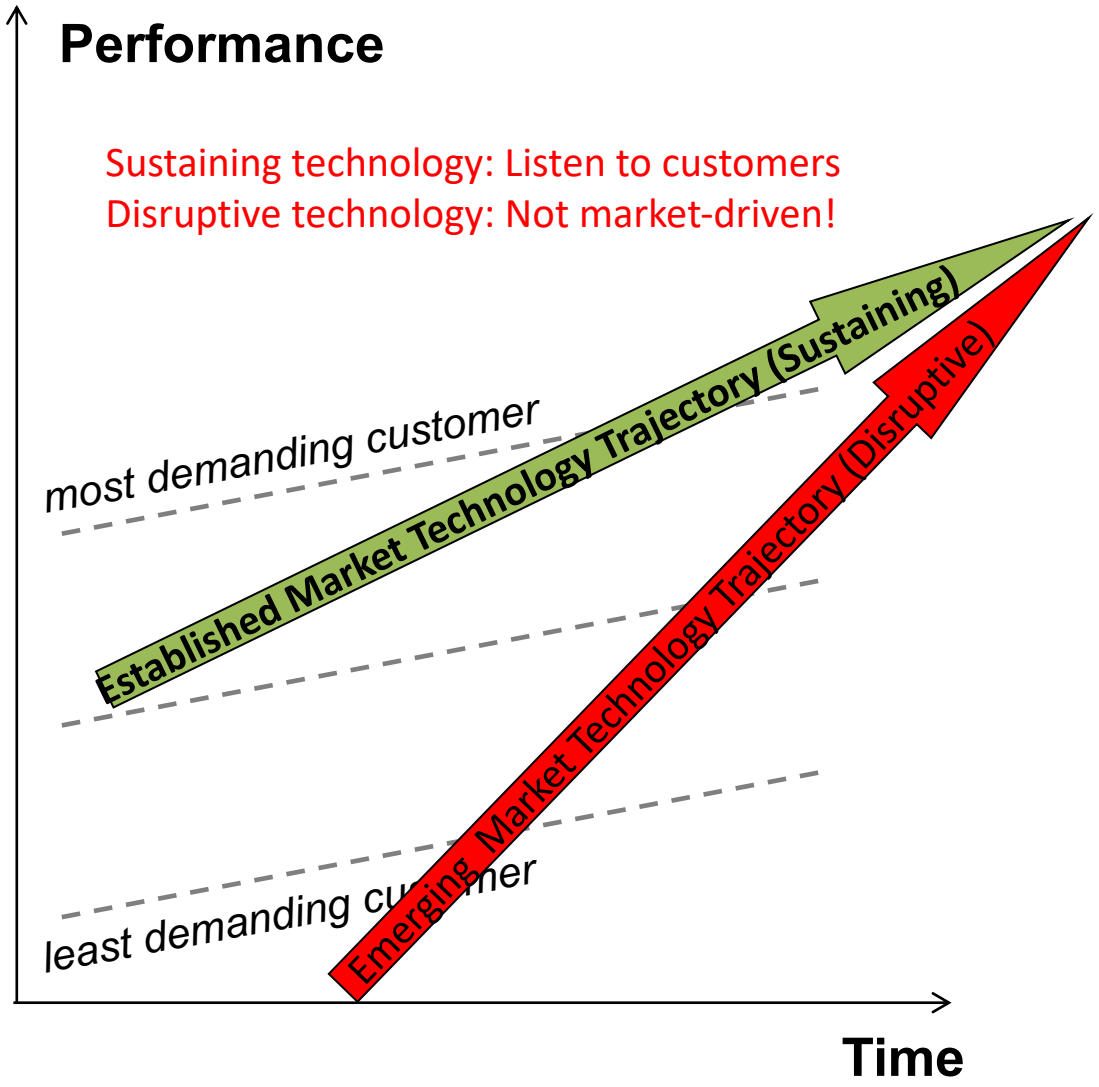
- 1985: Windows

- 1974: SQL

Disruptive Innovation



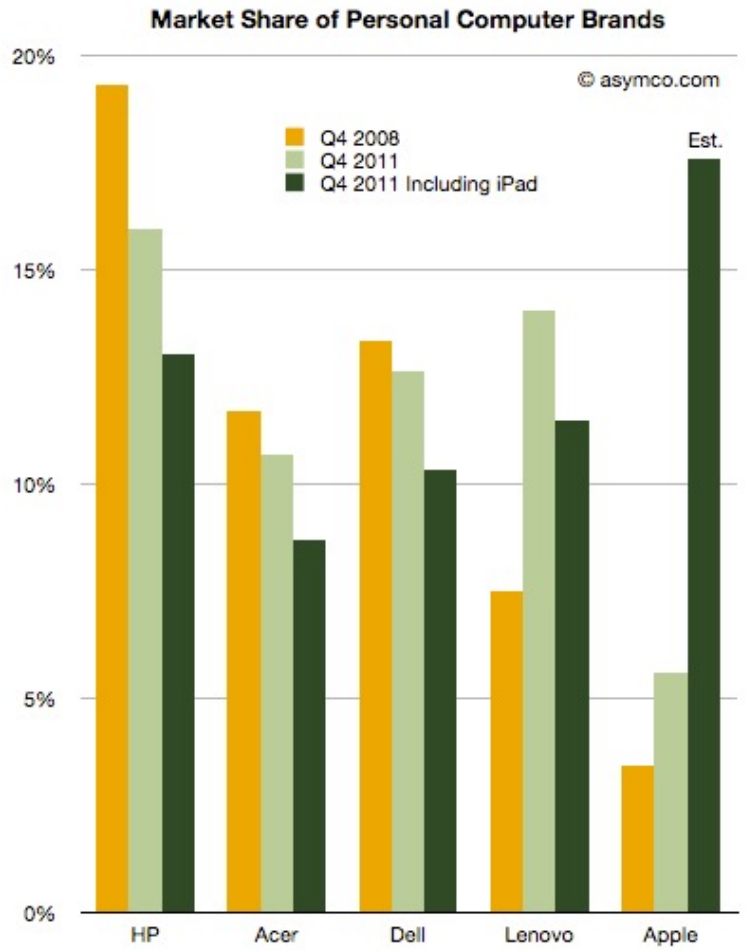
- Disruptive innovations are generally not acceptable for the mass market when they are introduced. Only the fringes of the market pick up the innovation in the first iteration
- It performs worse in one or more areas, but is typically simpler, more reliable, or more convenient than existing technologies.
- It is less profitable than existing technologies. Leading firms' most profitable customers generally can't use it and don't want it.
- As the innovator continues to refine their product the utility value to the market increases
- Its performance trajectory is steeper than that of existing technologies.
- Large organizations are fundamentally incapable of successfully bringing it to market.

Illustration and text compiled from "The Innovator's Dilemma" by Clayton Christensen, 1997. https://en.wikipedia.org/wiki/The_Innovator%27s_Dilemma
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

iPhone: Disruptive Innovation or not?

1: "Business Phones"
Microsoft in 2007

2: Laptops



Sources: http://www.youtube.com/watch?v=eywi0h_Y5_U, http://www.asymco.com/2012/01/16/apple-is-the-top-personal-computer-vendor/
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

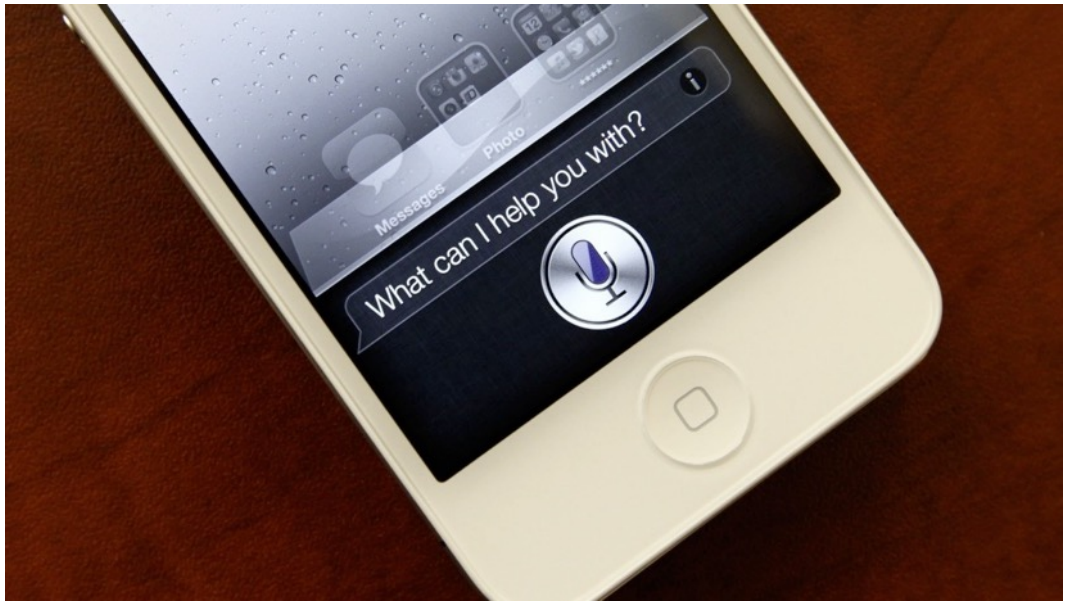
What keyboards without keys can do...

In Feb 2016, SwiftKey was purchased by Microsoft, for 250 M$

Sources: https://en.wikipedia.org/wiki/Swype, https://en.wikipedia.org/wiki/SwiftKey
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

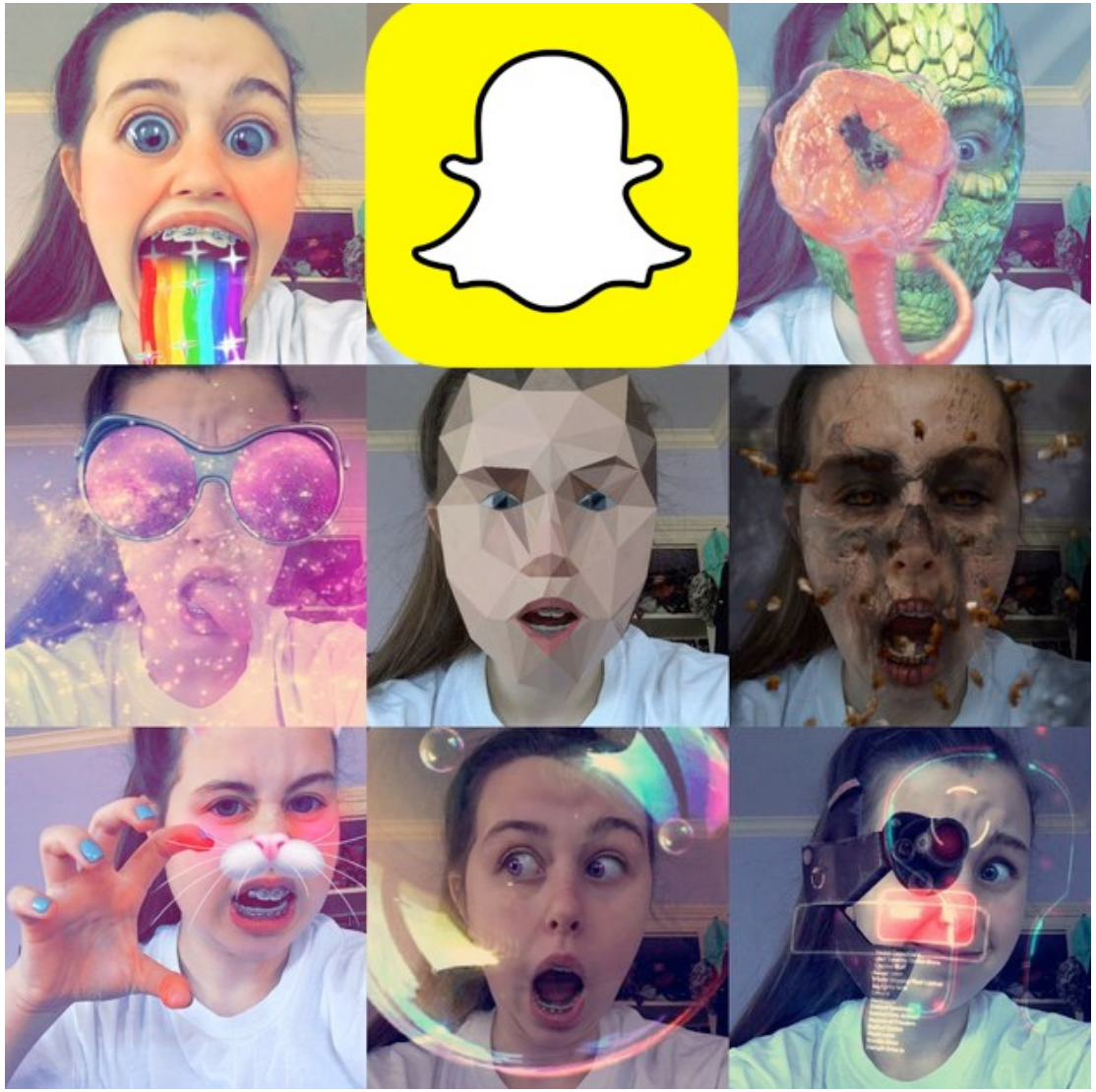
The keyboard of the future?

Source: http://www.wired.com/2014/06/siri_ai/


What can I help you with?
Messages
Photo


Eyes Free
MODE
MODE
engadget

Keyboards? Do we need text to communicate?



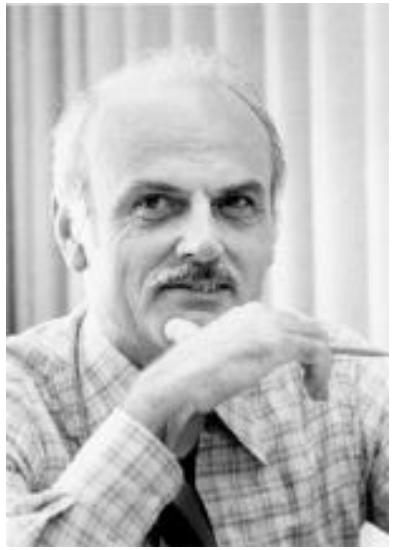
Source: http://www.buzzfeed.com/benrosen/how-to-snapchat-like-the-teens (2/2016)

What is this? (1975)

Source: http://pluggedin.kodak.com/pluggedin/post/?id=687843

SQL: some history

- Dr. Edgar Codd (IBM)
  - CACM June 1970: "A Relational Model of Data for Large Shared Data Banks" https://doi.org/10.1145/362384.362685
- Standardized
  - 1986 by ANSI: SQL1
  - 1992: Revised: SQL2
    - Approx 580 page document describing syntax and semantics
  - Revised: 1999, 2003, 2008, ...
- Players
  - Oracle (Relational Software), Microsoft, IBM, ….
- Every vendor has a slightly different version of SQL
- But the main commands are standardized



Codd's (disruptive ?) innovation

A Relational Model of Data for Large Shared Data Banks

E. F. Codd
IBM Research Laboratory, San Jose, California

Future users of large data banks must be protected from having to know how the data is organized in the machine (the internal representation). A prompting service which supplies such information is not a satisfactory solution. Activities of users at terminals and most application programs should remain unaffected when the internal representation of data is changed and even when some aspects of the external representation are changed. Changes in data representation will often be needed as a result of changes in query, update, and report traffic and natural growth in the types of stored information.

Existing noninferential, formatted data systems provide users with tree-structured files or slightly more general network models of the data. In Section 1, inadequacies of these models are discussed. A model based on *n*-ary relations, a normal form for data base relations, and the concept of a universal data sublanguage are introduced. In Section 2, certain operations on relations (other than logical inference) are discussed and applied to the problems of redundancy and consistency in the user's model.

KEY WORDS AND PHRASES: data bank, data base, data structure, data organization, hierarchies of data, networks of data, relations, derivability, redundancy, consistency, composition, join, retrieval language, predicate calculus, security, data integrity
CR CATEGORIES: 3.70, 3.73, 3.75, 4.20, 4.22, 4.29

1. Relational Model and Normal Form

1.1. Introduction

This paper is concerned with the application of elementary relation theory to systems which provide shared access to large banks of formatted data. Except for a paper by Childs [1], the principal application of relations to data systems has been to deductive question-answering systems. Levein and Maron [2] provide numerous references to work in this area.

In contrast, the problems treated here are those of *data independence*—the independence of application programs and terminal activities from growth in data types and changes in data representation—and certain kinds of *data inconsistency* which are expected to become troublesome even in nondeductive systems.

The relational view (or model) of data described in Section 1 appears to be superior in several respects to the graph or network model [3, 4] presently in vogue for noninferential systems. It provides a means of describing data with its natural structure only—that is, without superimposing any additional structure for machine representation purposes. Accordingly, it provides a basis for a high level data language which will yield maximal independence between programs on the one hand and machine representation and organization of data on the other.

A further advantage of the relational view is that it forms a sound basis for treating derivability, redundancy, and consistency of relations—these are discussed in Section 2. The network model, on the other hand, has spawned a number of confusions, not the least of which is mistaking the derivation of connections for the derivation of relations (see remarks in Section 2 on the "connection trap").

Finally, the relational view permits a clearer evaluation of the scope and logical limitations of present formatted data systems, and also the relative merits (from a logical standpoint) of competing representations of data within a single system. Examples of this clearer perspective are cited in various parts of this paper. Implementations of systems to support the relational model are not discussed.

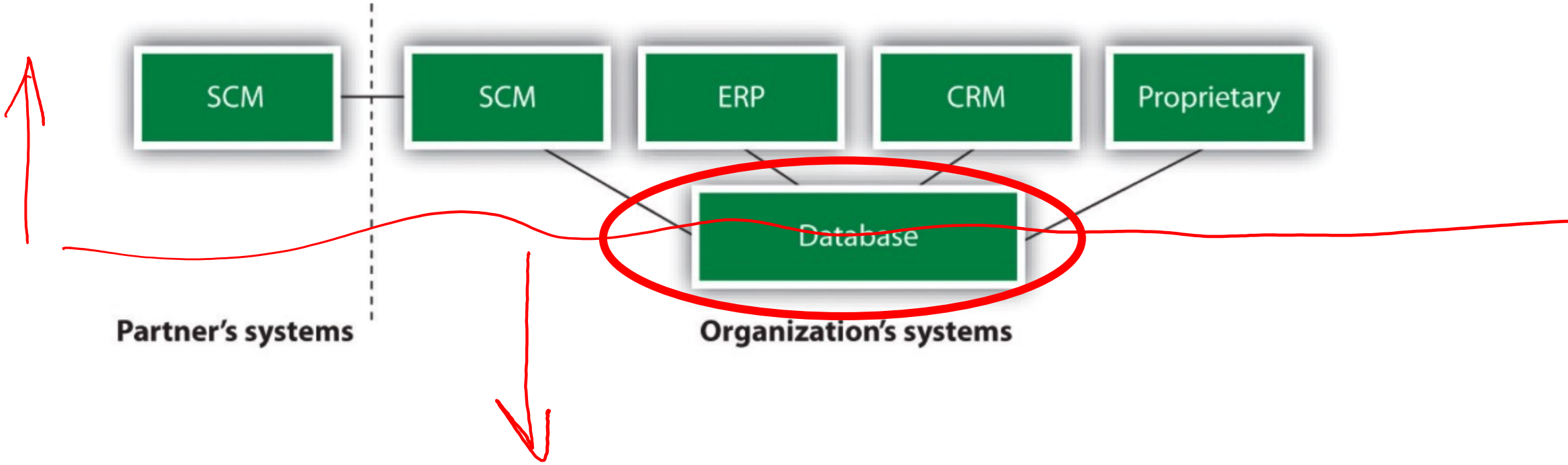
1.2. Data Dependencies in Present Systems

The provision of data description tables in recently developed information systems represents a major advance toward the goal of data independence [5, 6, 7]. Such tables facilitate changing certain characteristics of the data representation stored in a data bank. However, the variety of data representation characteristics which can be changed *without logically impairing some application programs* is still quite limited. Further, the model of data with which users interact is still cluttered with representational properties, particularly in regard to the representation of collections of data (as opposed to individual items). Three of the principal kinds of data dependencies which still need to be removed are: ordering dependence, indexing dependence, and access path dependence. In some systems these dependencies are not clearly separable from one another.

1.2.1. *Ordering Dependence.* Elements of data in a data bank may be stored in a variety of ways, some involving no concern for ordering, some permitting each element to participate in one ordering only, others permitting each element to participate in several orderings. Let us consider those existing systems which either require or permit data elements to be stored in at least one total ordering which is closely associated with the hardware-determined ordering of addresses. For example, the records of a file concerning parts might be stored in ascending order by part serial number. Such systems normally permit application programs to assume that the order of presentation of records from such a file is identical to (or is a subordering of) the

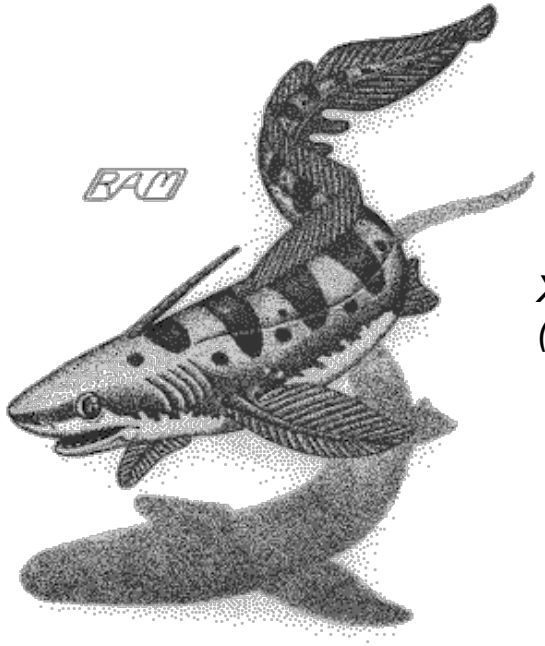
Source: Edgar F Codd. "A Relational Model of Data for Large Shared Data Banks ", CACM 1970. https://doi.org/10.1145/362384.362685
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

SQL and the relational model as standard

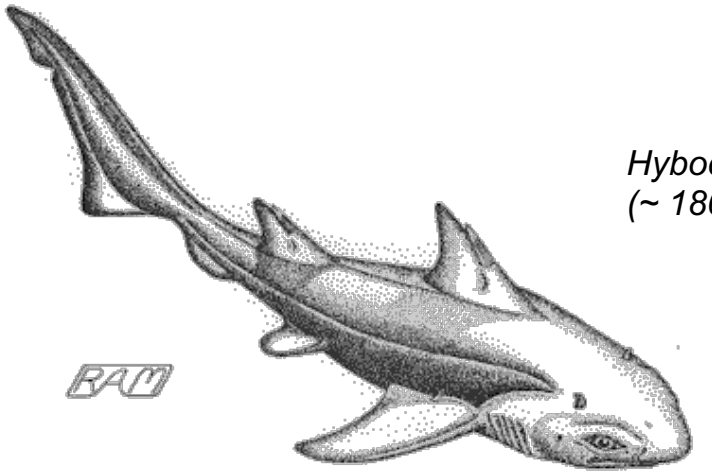


Source: "Information Systems: A Manager's Guide to Harnessing Technology (book v1.4)," p.185, Gallaugher, 2012. https://gallaugher.com/book/
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

Evolution of Sharks



Xenacanthus
(~ 280 million years ago)

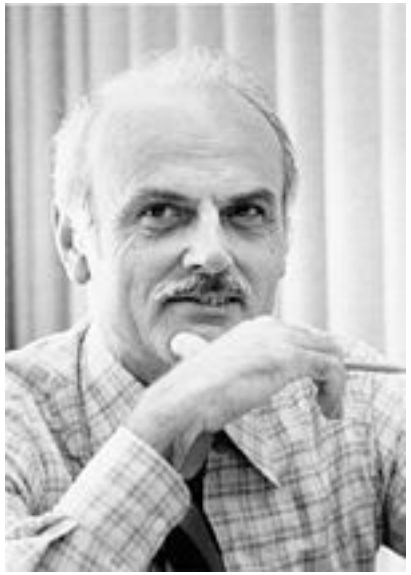


Hybodus sp.
(~ 180 million years ago)

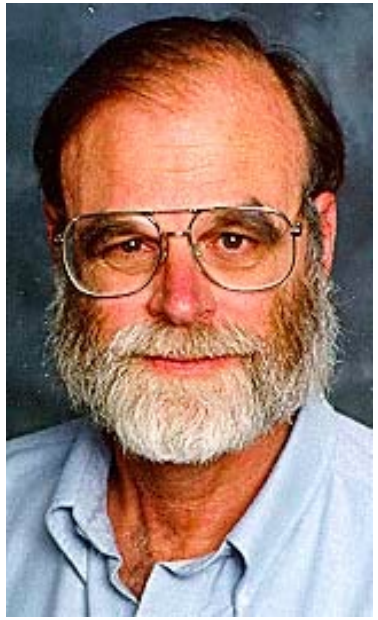
Source for picture on the right: http://themetapicture.com/evolution-it-makes-you-lose-friends/
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

Five Turing Award Winners

Charles Bachmann 1973



Edgar Codd 1981



Jim Gray 1998

Michael Stonebraker 2014

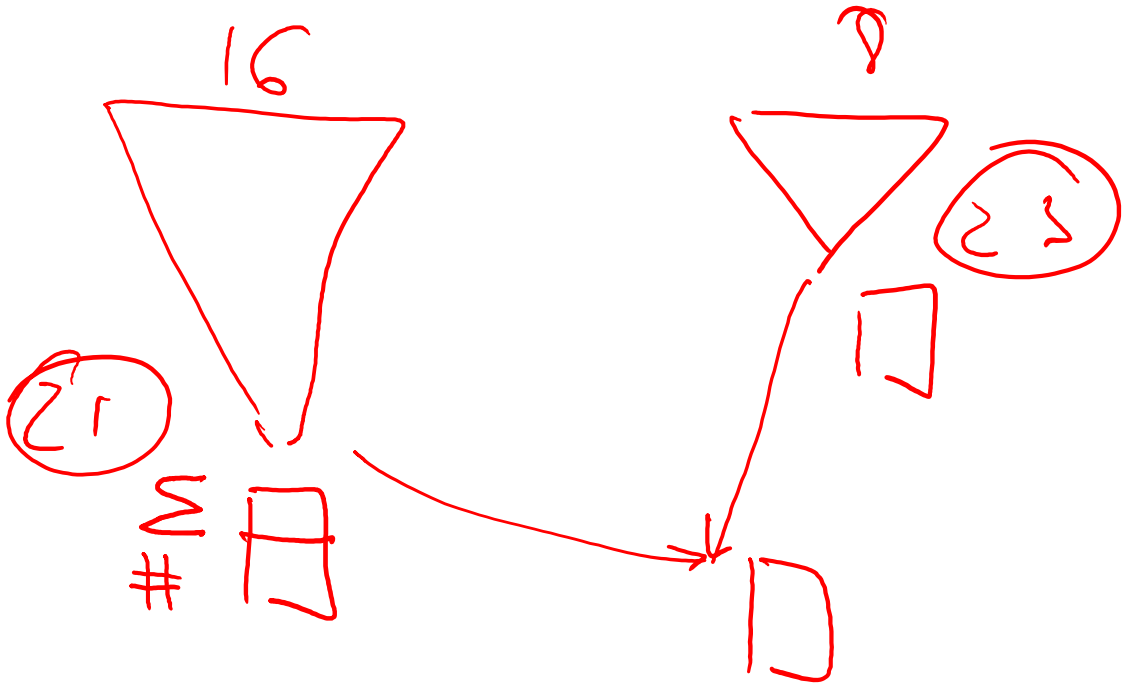
Jeffrey Ullman 2020

Compilers/PL/DB

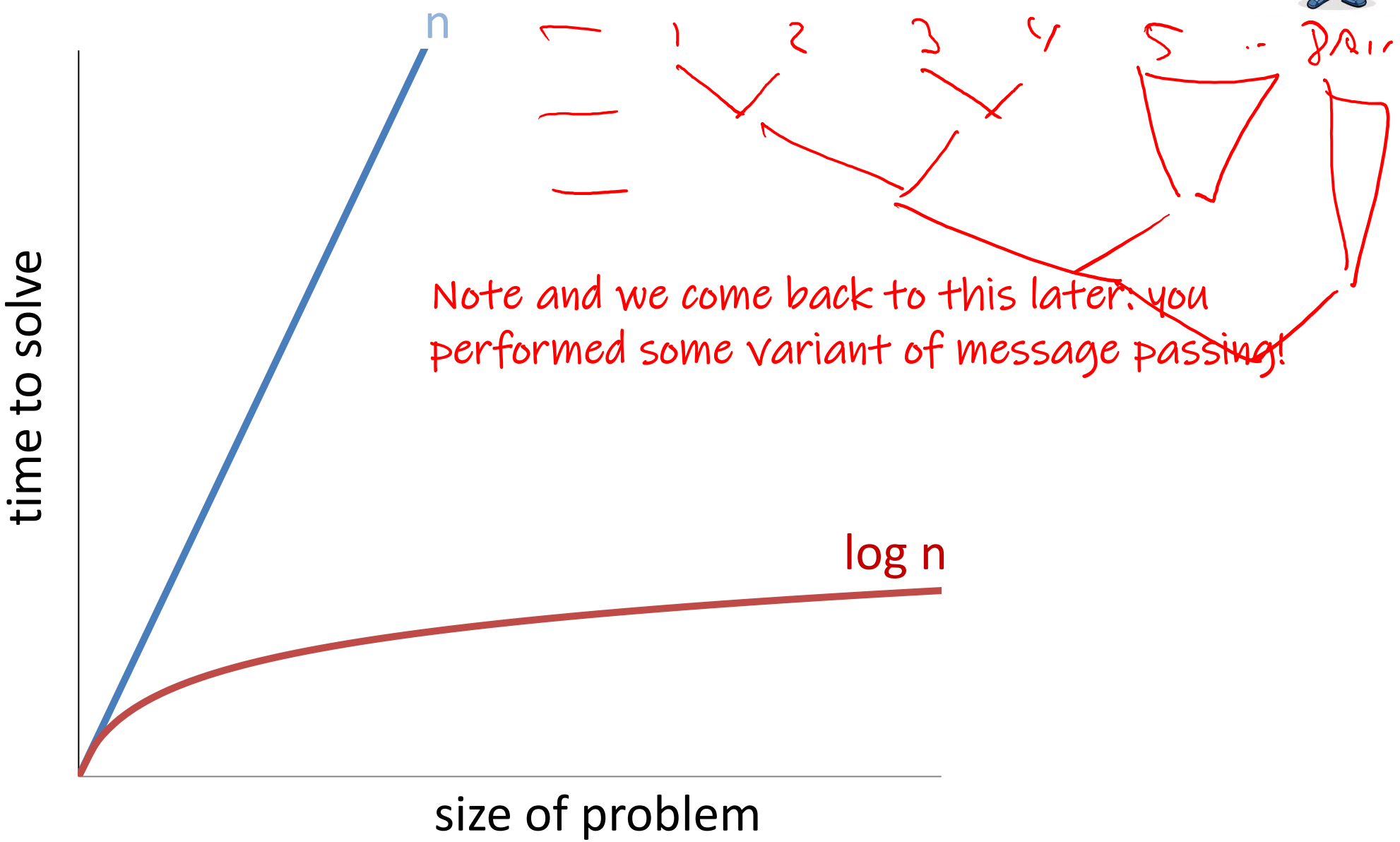
Three example for the intuition about this class' focus

1. Parallel query processing by example: An Algorithm

- Stand up and think of the number 1
- Pair off with someone standing, add your numbers together, and take the sum as your new number
- One of you should sit down; the other should go back to step 2



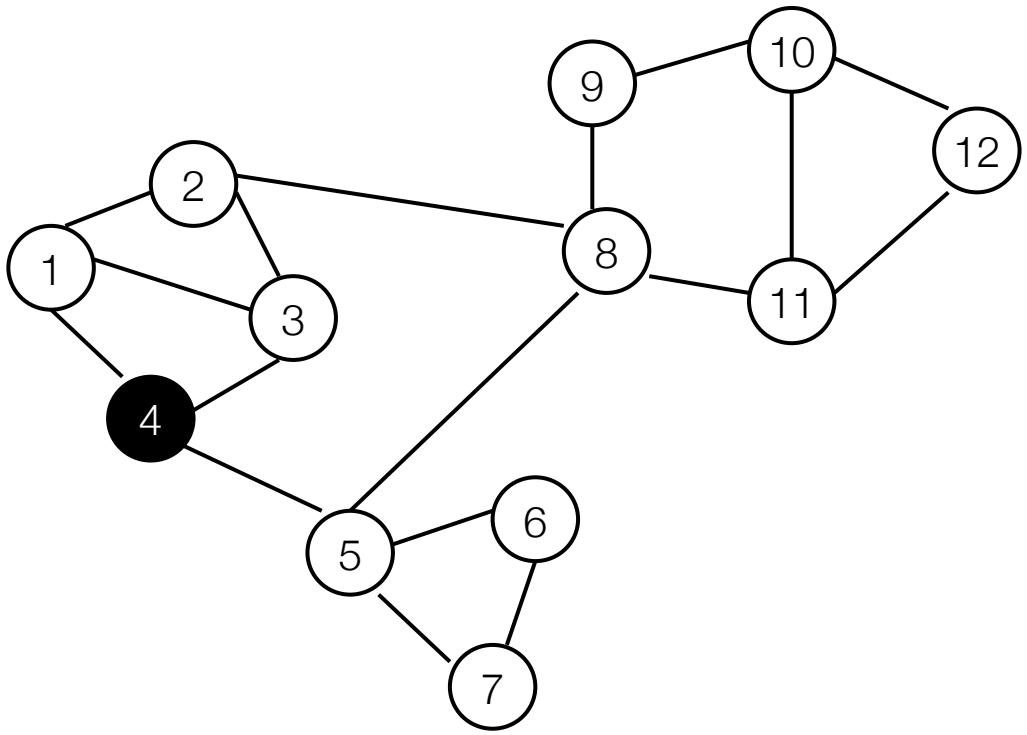
1. Parallel query processing: Scalability



2. Generalizing Dynamic Programming

- DP: solves optimization problems that show the "optimal subproblem property":
  - an optimal solution for the problem needs to include optimal solutions to any subproblem
  - Forward pointer: algebraic properties that allow such "factorization"
- Assume you don't just want to find the optimal solution = top-1
  - But you want to *enumerate* all solution. First best (top-1), then 2nd best, then 3rd, etc.
- Can you do this in an "optimal time"? How do define "optimal"?

3. Graphs (Matrix Algebra)



$\mathbf{W}^{\text{col}}$

column-normalized adjacency matrix

$$\begin{bmatrix}
0 & 1/3 & 1/3 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1/3 & 0 & 1/3 & 0 & 0 & 0 & 0 & 1/4 & 0 & 0 & 0 & 0 \\
1/3 & 1/3 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1/3 & 0 & 1/3 & 0 & 1/4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1/3 & 0 & 1/2 & 1/2 & 1/4 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1/4 & 0 & 1/2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1/4 & 1/2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1/3 & 0 & 0 & 1/4 & 0 & 0 & 0 & 1/2 & 0 & 1/3 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/4 & 0 & 1/3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/2 & 0 & 1/3 & 1/2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/4 & 0 & 1/3 & 0 & 1/2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/3 & 1/3 & 0
\end{bmatrix}$$

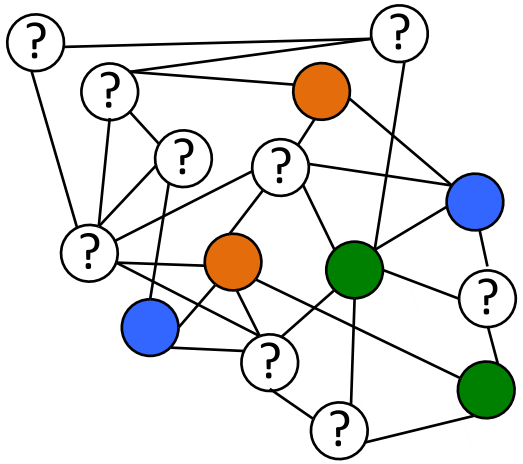
"How close" is each node to node 4?

→ "Personalized PageRank"

Linear algebra ☺

3. A problem where algebra gives surprising speed-ups

Graph & seed labels



Compatibilities

$$H = \begin{bmatrix} 0.2 & 0.6 & 0.2 \\ 0.6 & 0.2 & 0.2 \\ 0.2 & 0.2 & 0.6 \end{bmatrix} \quad \Sigma=1$$

Prob 1: Propagating arbitrary compatibilities

Given:
- undirected graph **W**
- seed labels
- compatibilities **H**

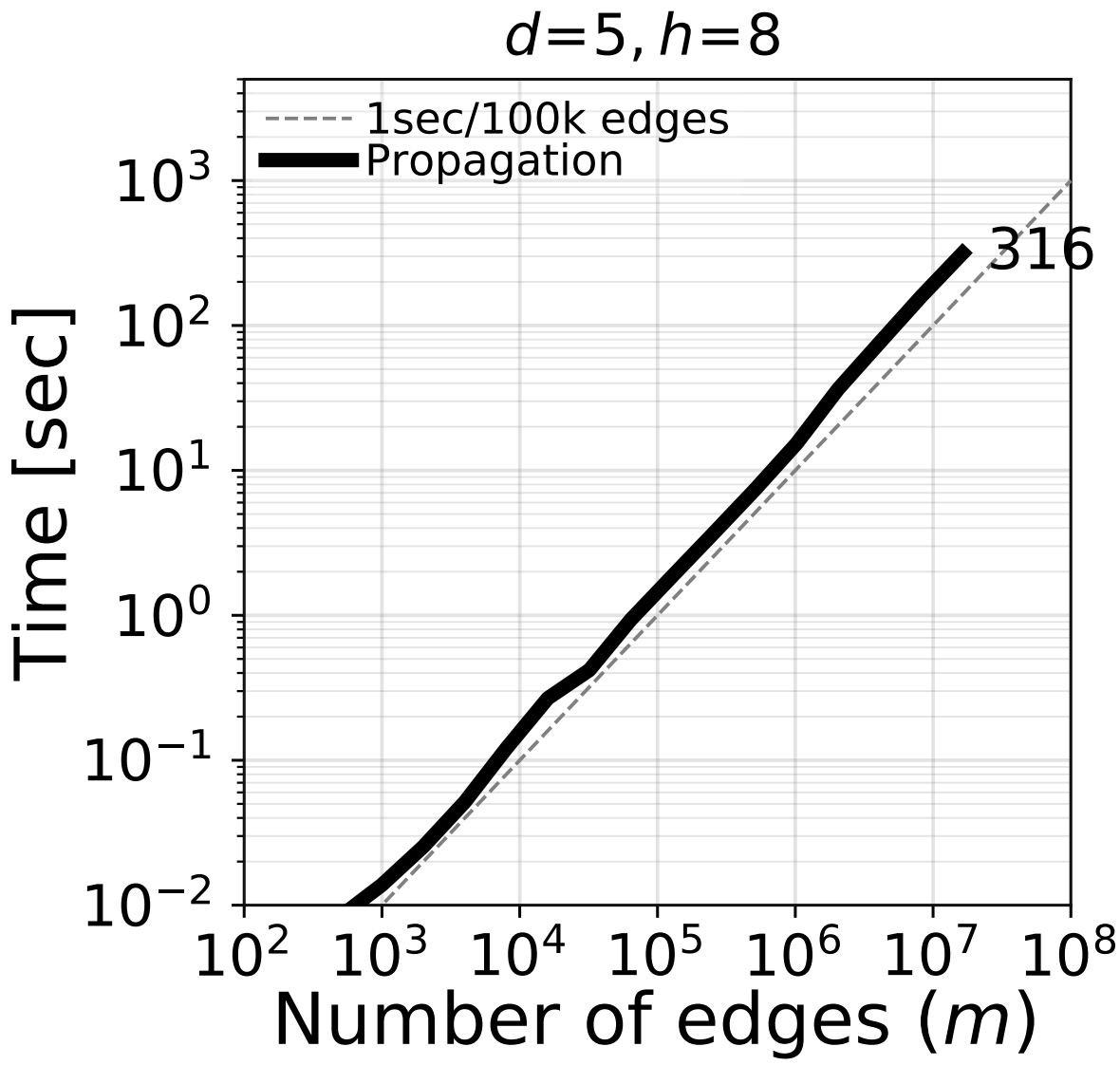
Find:
- remaining labels

Prob 2: Learning & prop. compatibilities

Given

Find

3. What is the overhead of compatibility estimation?



Propagation scales linearly with graph size (number of edges)

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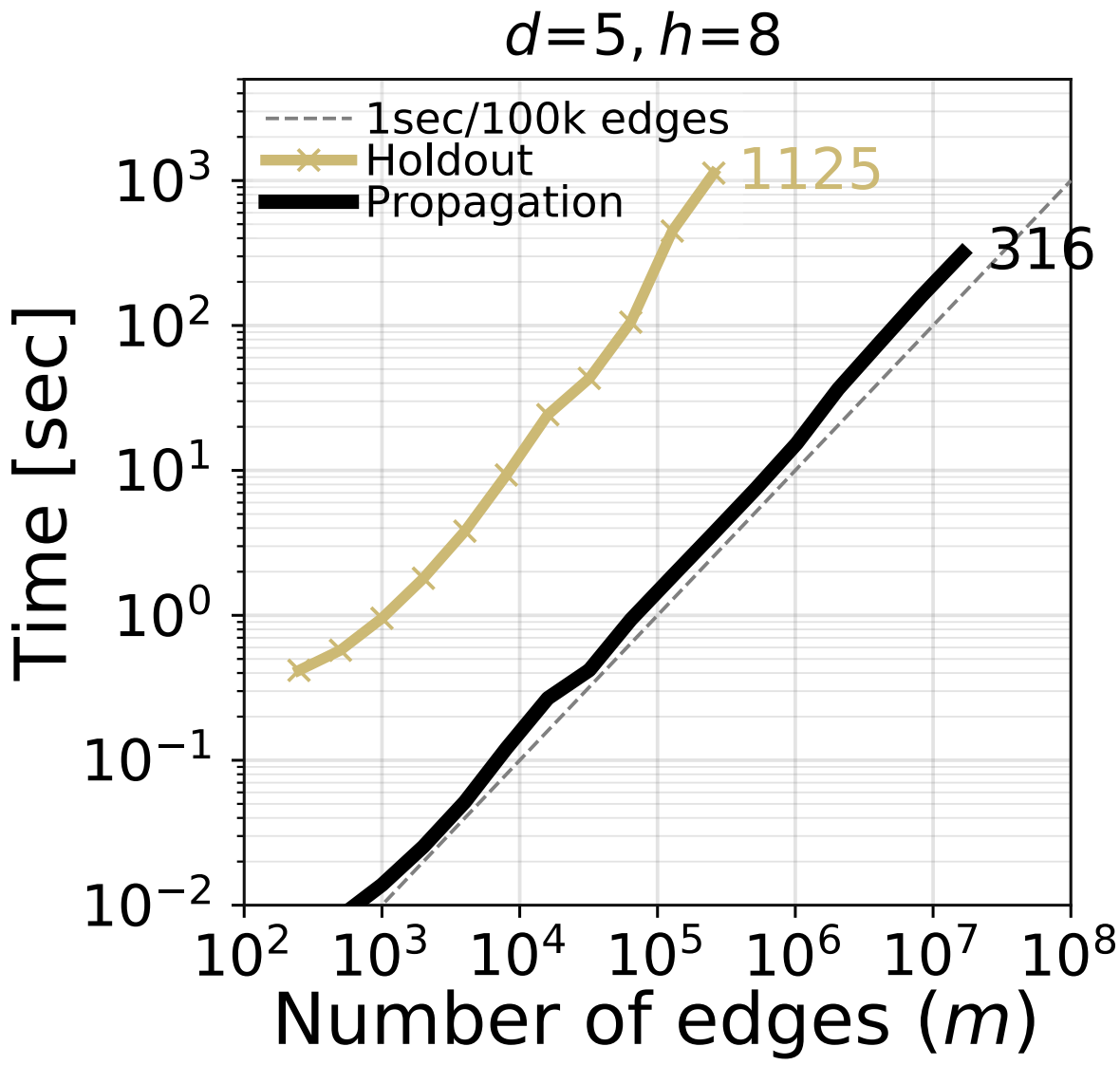

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Learning commonly uses inference as subroutine (> 10^2 times slower)

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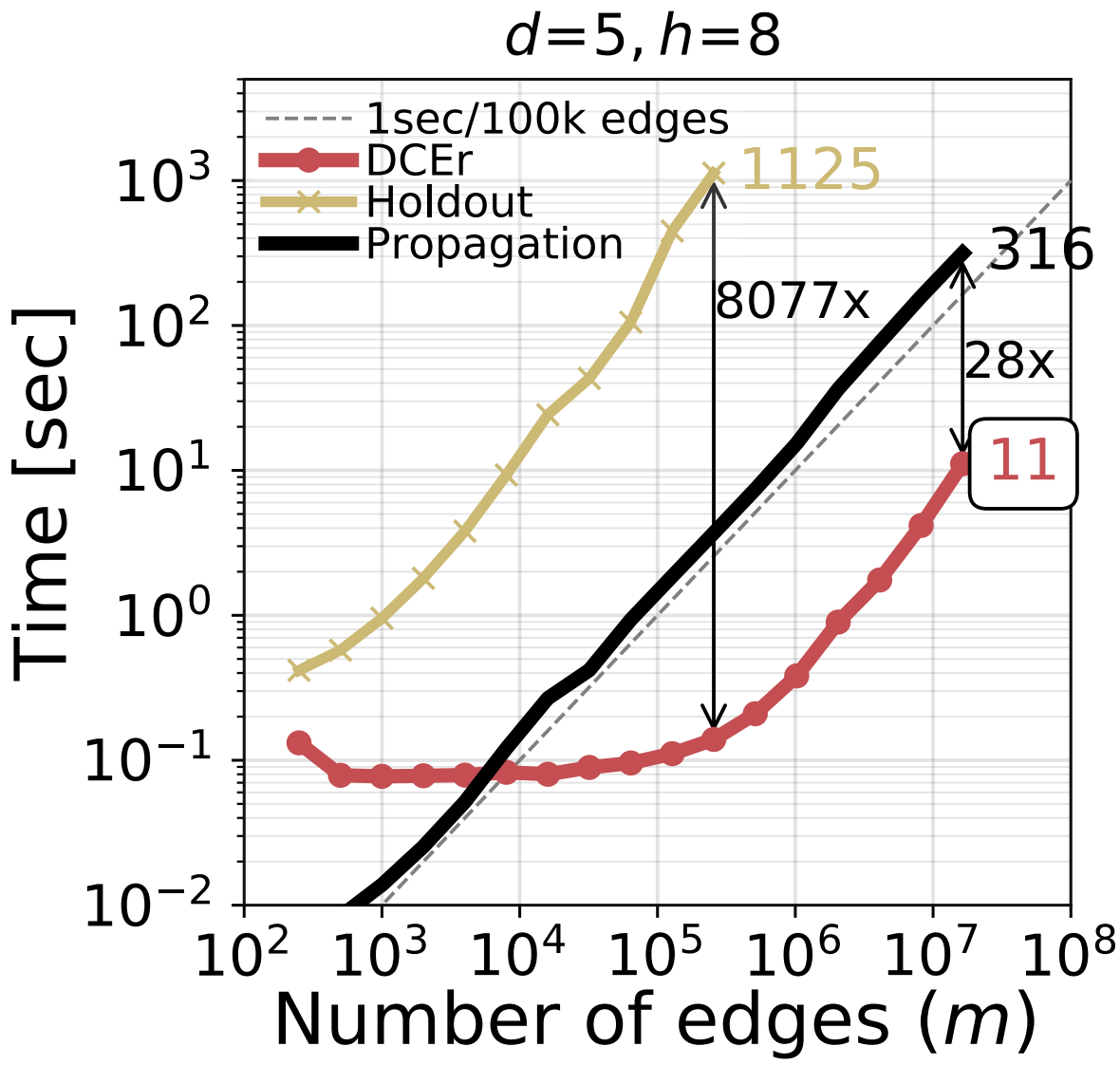


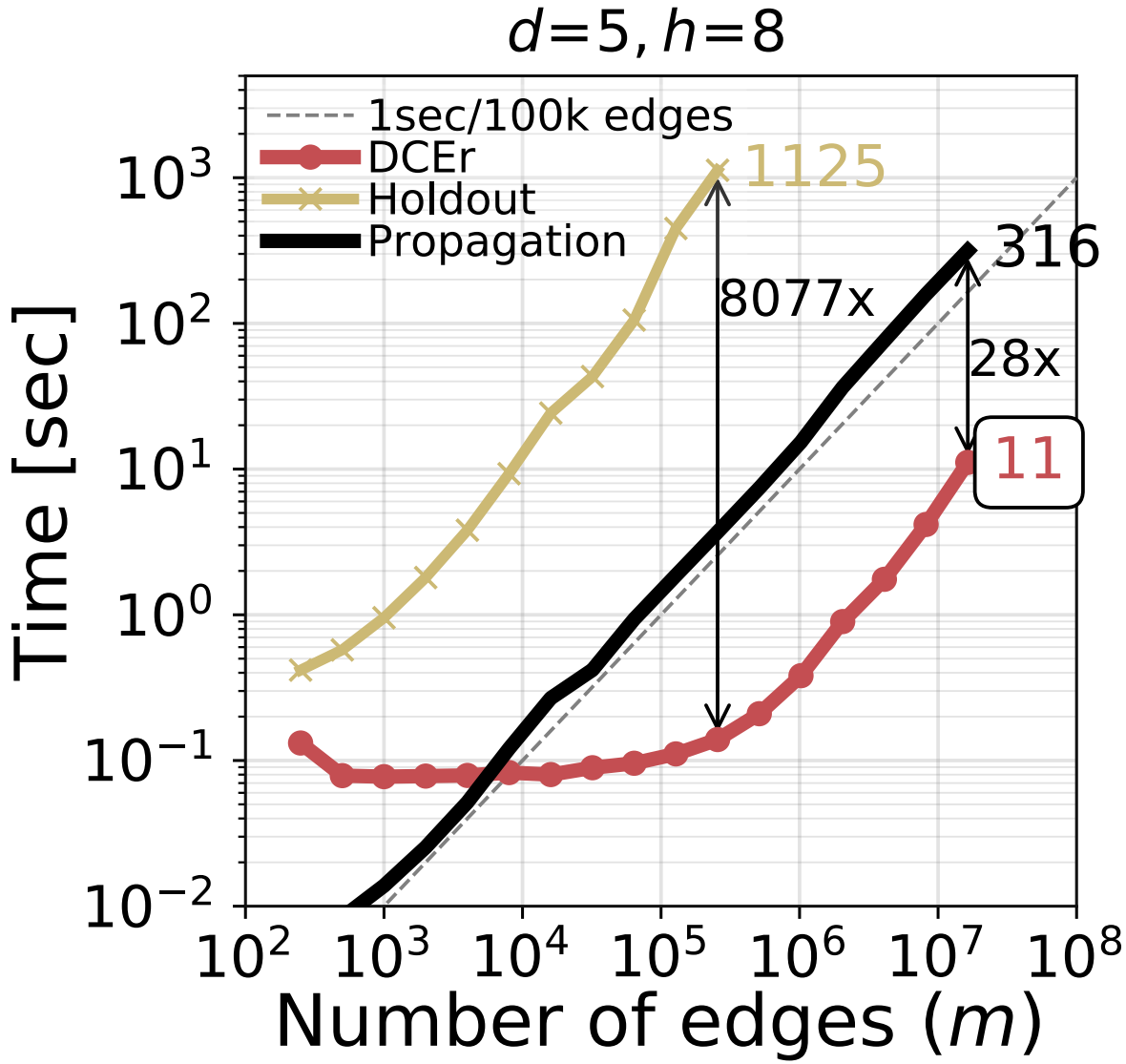
Propagation scales linearly with graph size (number of edges)

Learning commonly uses inference as subroutine (> 10^2 times slower)

Our estimation is *faster* then inference (> 10 times faster)

3. What is the overhead of compatibility estimation?

Basically for free!



Propagation scales linearly with graph size (number of edges)

Learning commonly uses inference as subroutine (> 10^2 times slower)

Our estimation is *faster* then inference (> 10 times faster)

It is basically for free. No more need for heuristics or domain experts!

"Factors": a common idea

Assume for each course, we can independently choose a lecturer and a book. Can we represent this table more compactly?

Classes

Course	Lecturer	Book
cs3200	Renee	Complete book
cs3200	Wolfgang	Complete book
cs3200	Renee	Cow book
cs3200	Wolfgang	Cow book

=

?

"Factors": a common idea

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cs3200	Wolfgang	Cow book

Multiplication distributes over Addition

=

Lecturer

Course	Lecturer
cs3200	Renee
cs3200	Wolfgang

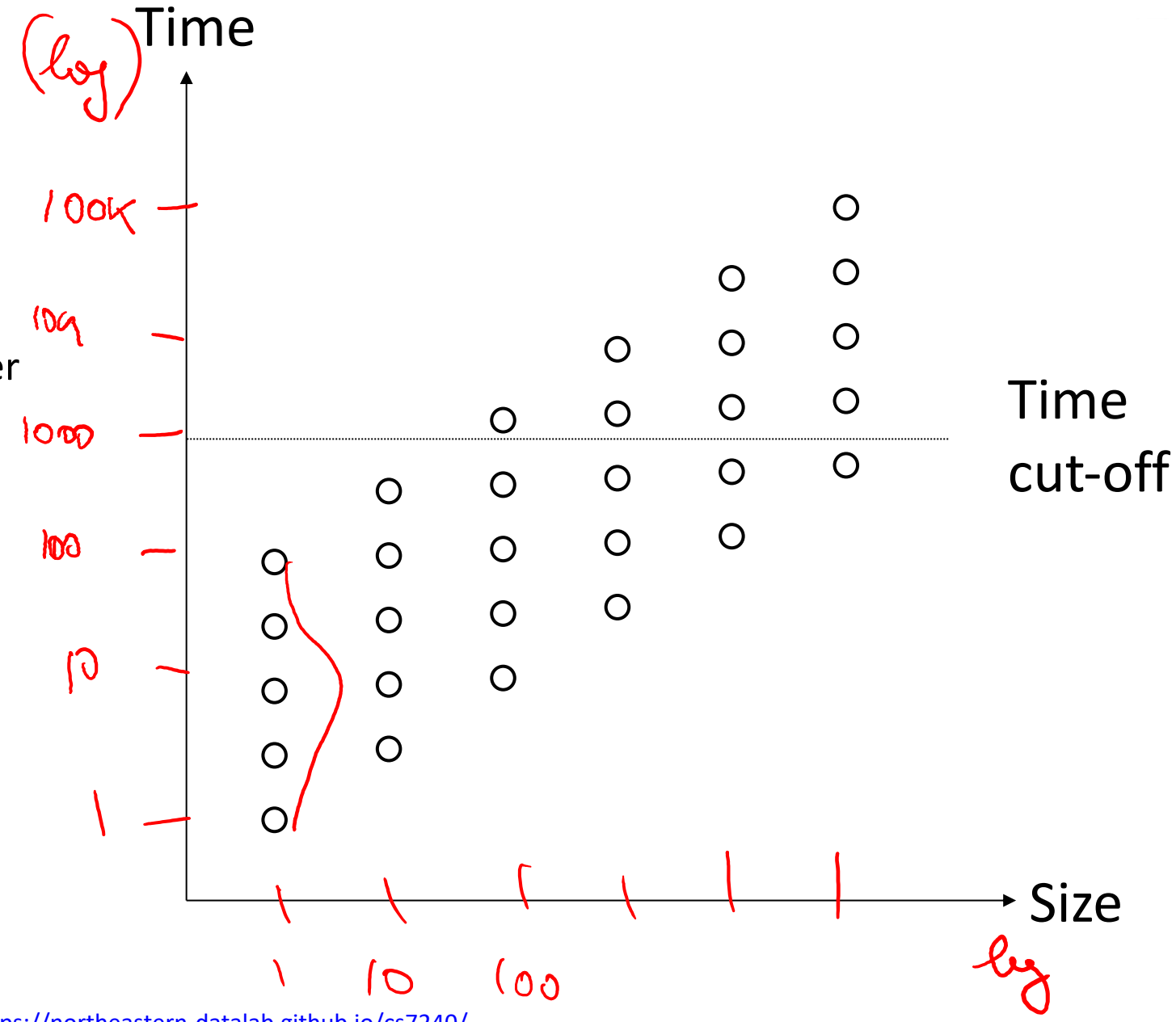
⋈

Book

Course	Book
cs3200	Complete book
cs3200	Cow book

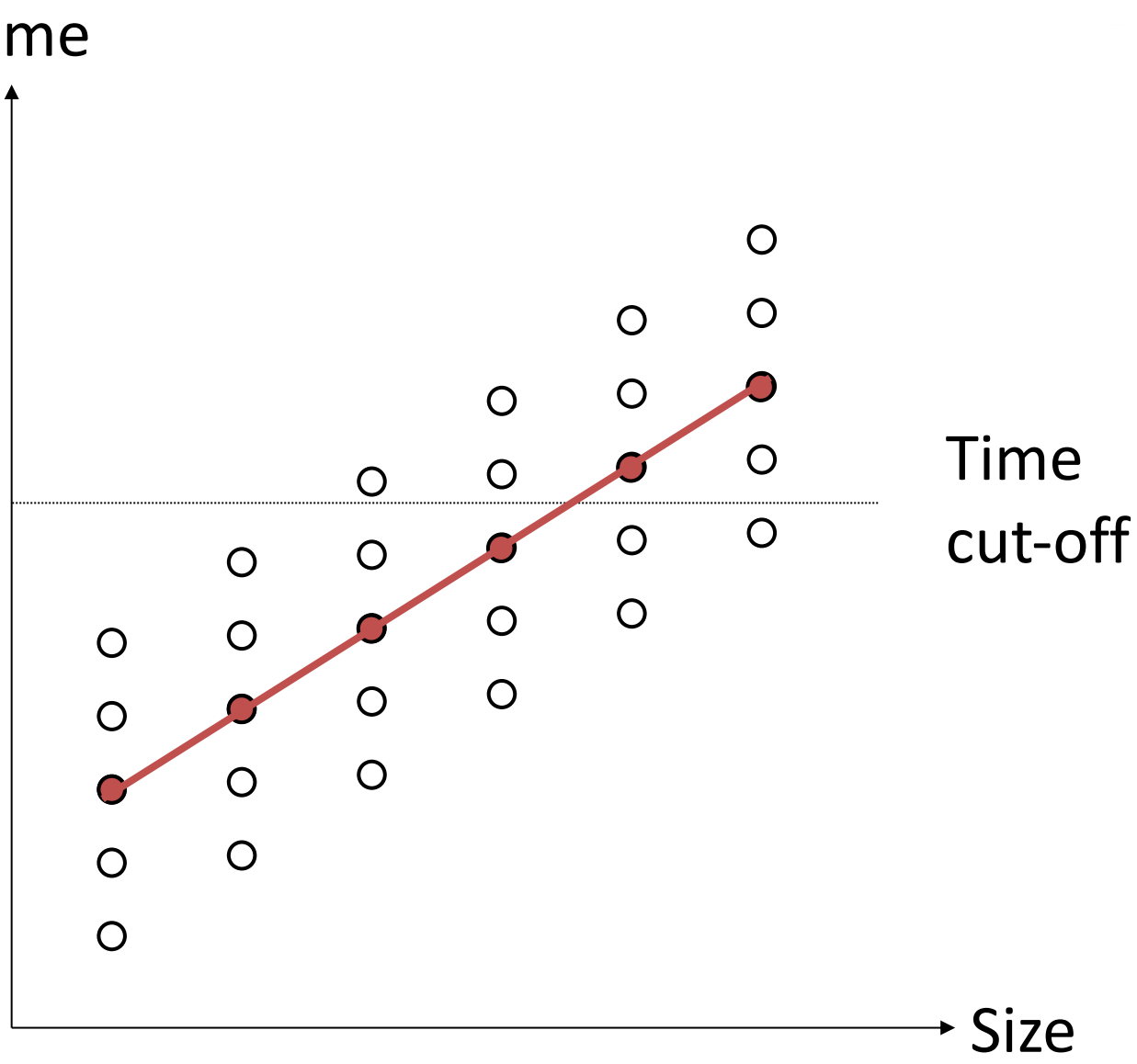
Question: How to deal with cut-offs when binning

- These are the true points that you would get if you could run the experiments long enough.
  - Assume loglog scale
- However, we can't and thus in practice cut-off the experiments after some time.
- There is an overall trend, yet some variation for each experiment. We would still like to capture the trend with some smart aggregations



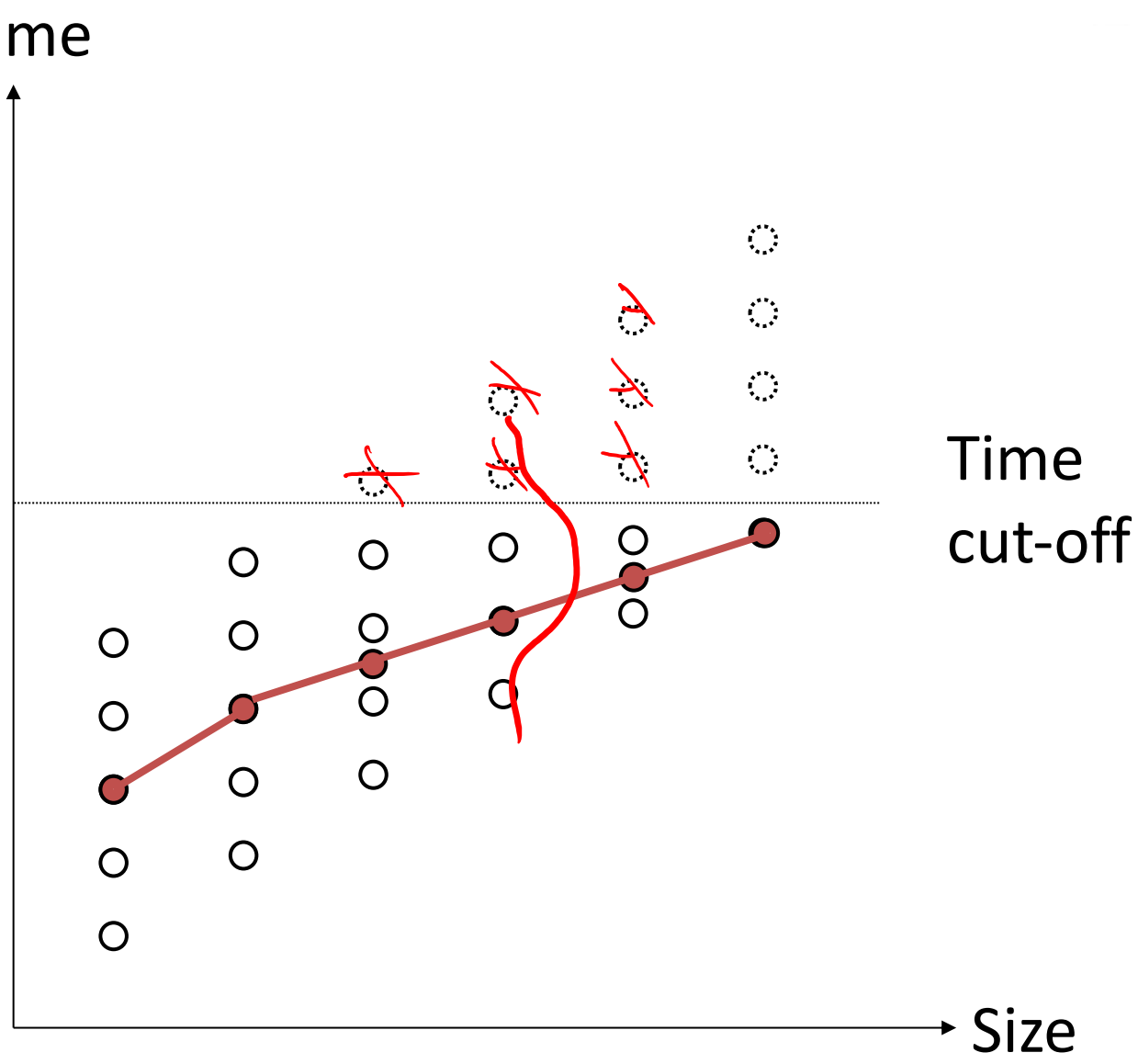
Question: How to deal with cut-offs when binning

- Here is what the aggregate would look like like if we could get all points and then aggregated for each size



Question: How to deal with cut-offs when binning

- Here is what happens if we throw away all those points that take longer than the cut-off, and only average over the "seen points"

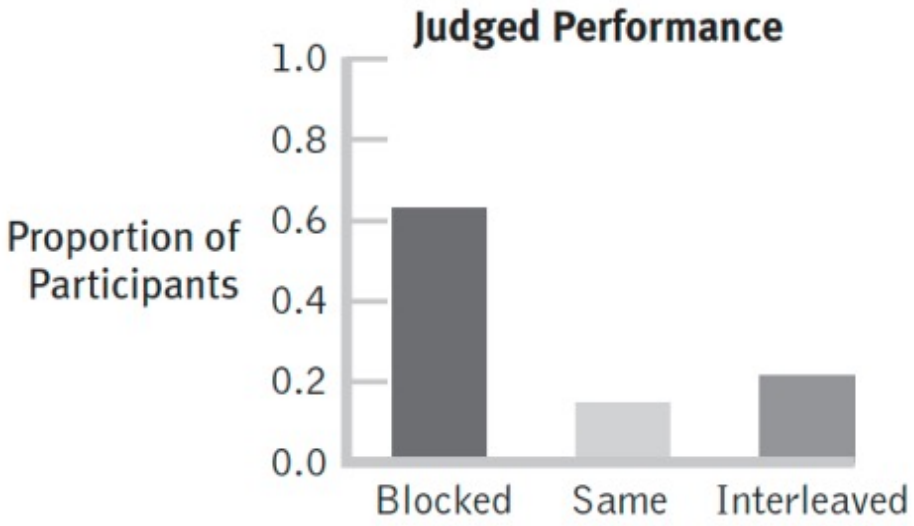


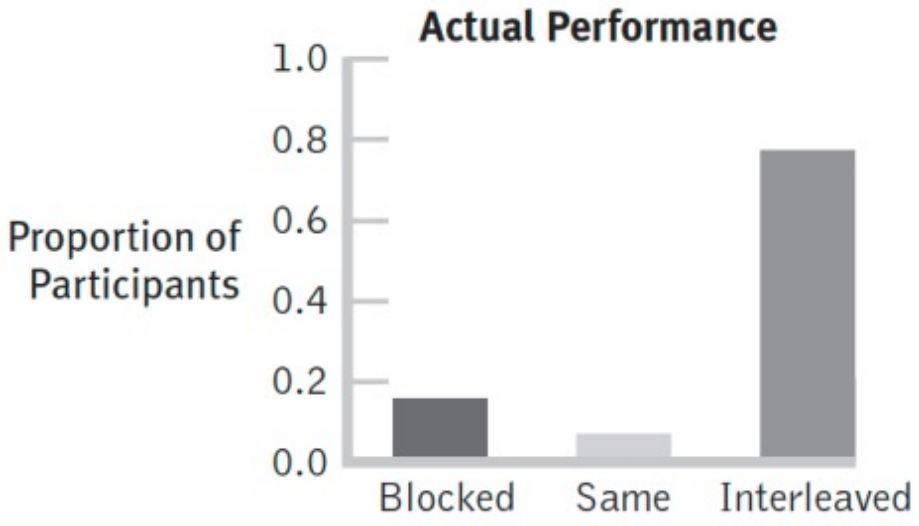
What would you do ?

We will discuss next class

Pedagogy & Logistics

Sequencing Material: "Under which teaching condition do you think you learn better?"





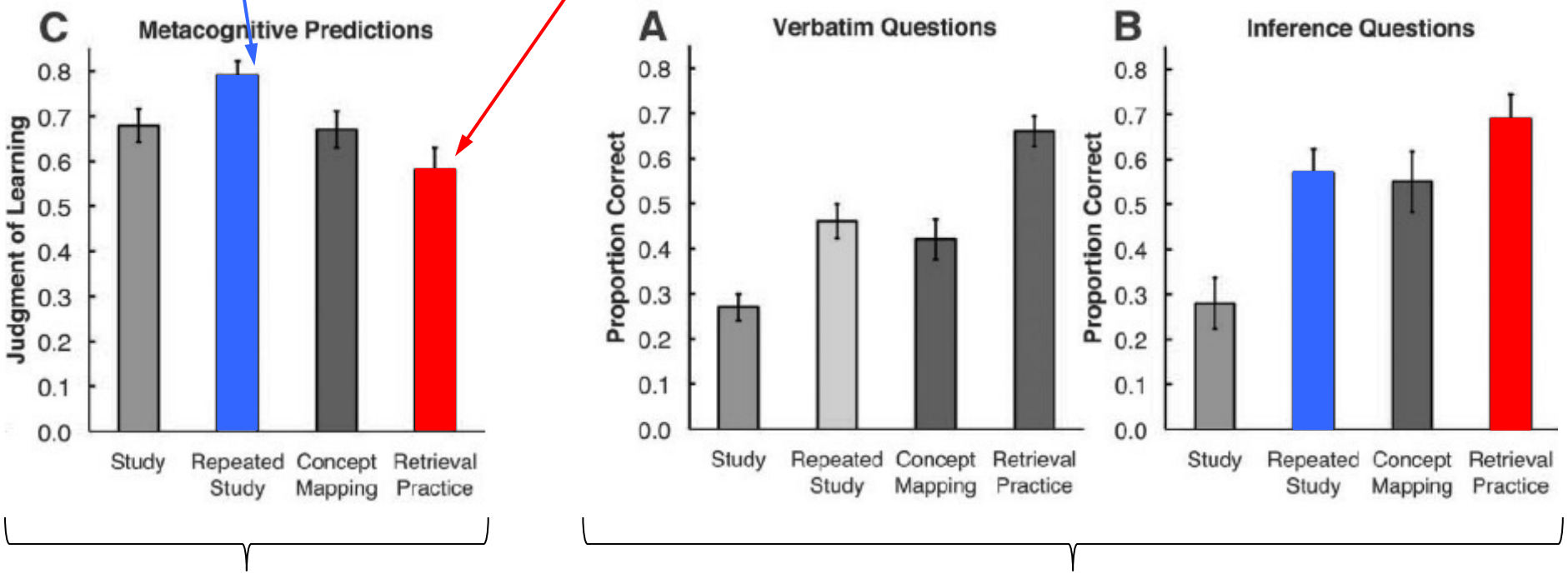
The mix of chapter and cases is also meant to provide a holistic view of how technology and business interrelate. Don't look for an "international" chapter, an "ethics" chapter, a "mobile" chapter, or a "systems development and deployment" chapter. Instead, you'll see these topics woven throughout many of our cases and within chapter examples. This is how professionals encounter these topics "in the wild," so we ought to study them not in isolation but as integrated parts of real-world examples. Examples are consumer-focused and Internet-heavy for approachability, but the topics themselves are applicable far beyond the context presented.

Data from: Bjork & Bjork, "Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning," 2011. https://psycnet.apa.org/record/2011-19926-008
Paragraph from:"Information Systems: A Manager's Guide to Harnessing Technology (book v1.4)," Gallaugher, 2012. https://gallaugher.com/book/
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

Studying new material: "Under which study condition do you think you learn better?"

passive reading

active Q&A



Judged performance
(=what people think)

Actual performance
(=what is actually working)

Data from: Karpicke & Blunt, "Retrieval Practice Produces More Learning than Elaborative Studying with Concept Mapping," Science, 2011. https://doi.org/10.1126/science.1199327

Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

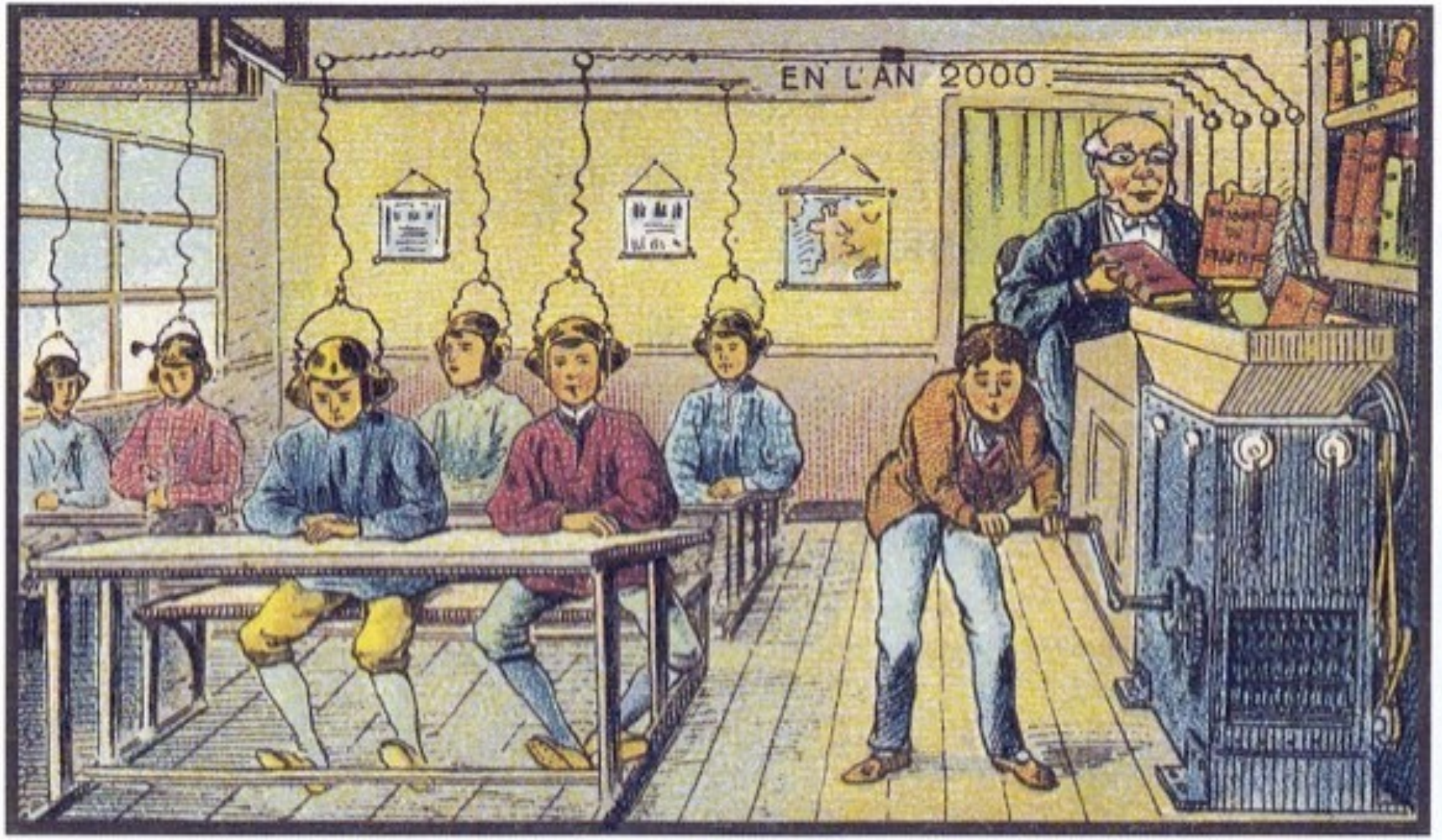
Coursework/Evaluation

50%: Course project: The main component of this course will be a research project in the latter part of this class. This project can be a new application of one of the techniques presented or theoretically-oriented. The topic will be flexible, allowing students to explore scalable data management and analysis aspects related to their PhD research. This will involve an initial project proposal, an intermediate report, a project presentation and a final report. The final report should resemble a conference paper, and will be evaluated on the basis of soundness, significance, novelty, and clarity. Deliverables and dates are posted on the project page.

35%: Class scribes: Students take turns in "illustrating" 7 lectures (to be consistent with standard notation we refer to it as "scribes"). Graduate theory classes often ask students to scribe the lecture content. Yet since I already provide you with well-curated lectures slides, we change the rule of the game. Rather than scribing (= repeating and summarizing) the content of the class, I ask you to *"illustrate" some interesting aspect in the covered topics with imaginative and ideally tricky illustrating examples*. Those illustrations are great if they in turn can help other students practice and solidify their understanding of the topics discussed. Georg Cantor is quoted as saying: "To ask the right question is harder than to answer it." In that spirit, our class scribes are closer to research than assignments: What particular aspect in a class is worthy to be "illustrated"? That's already part of the question. Scribes are done in PowerPoint and are due 1 week after class at midnight (Tue for Tue classes, Fri for Fri classes). They can be done individually or in teams of two (if you work in teams of two, you are expected to illustrate 14 classes instead of 7 classes). Please use our PPTX template, and name your document "cs7240-sp21-[YOUR NAME]-scribe[NUMBER]-[SOME DESCRIBTIVE TITLE].pptx" before submitting via Canvas.
For some more pedagogic motivation see videos by Tim Brown on asking questions and reframing problems being key to creativity, Dan Meyer on formulating problem being more important than just solving them, Derek Muller on increasing learning by including possible misconceptions into stories, and an older text of mine of the educational value of temporarily misleading the spectator before giving the correct answer.

15%: Class participation: Classes will be interactive and require concentration and participation of the students. Participate when we discuss the merits or shortcomings of algorithms covered or small group break-out sessions with exercises. Ask questions, during class or on Canvas. Questions that make me ponder or create new illustrating examples are all great instances of class participation. Also, *never* hesitate to point out to me errors you spot in my slides or any links or other material. It can only count towards class participation. Finally notice that while the class provides extensive readings for those interested, these pointers are almost exclusively optional (unless otherwise stated in class).

The year 2000 imagined in 1900



At School

Source: https://publicdomainreview.org/collection/a-19th-century-vision-of-the-year-2000

Lectures are not recorded (1/2)

If gaps in knowledge are the seeds of curiosity, exploration is the sunlight. Hundreds of studies with thousands of students have shown that when science, technology and math courses include active learning, students are less likely to fail and more likely to excel. A key feature of active learning is interaction. But too many online classes have students listening to one-way monologues instead of having two-way dialogues. Too many students are sitting in front of a screen when they could be exploring out in the world.

Source: https://www.nytimes.com/2020/09/07/opinion/remote-school.html

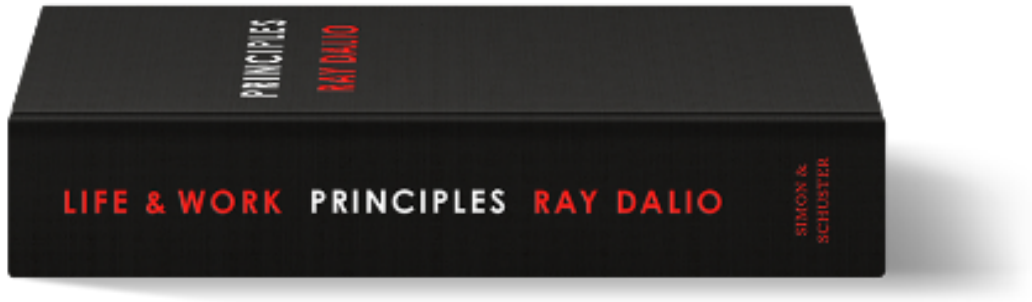
Lectures are not recorded (2/2)

- We would like to have an encouraging environment in which everyone can speak up and discuss ideas freely without concern that discussions will be available outside of classroom.
- The course slides are comprehensive and should allow you to be able to remember the key lessons from class (except for background stories I may tell you). Lecture slides will be posted after each class, usually by end of the day.
- Do not record or otherwise share the classroom video calls yourself. The Commonwealth of Massachusetts's wiretapping law requires "two-party consent". It is a felony to secretly record a conversation, whether the conversation is in person or taking place by telephone or another electronic medium. [See Mass. Gen. Laws ch.272, § 99].

Mass. Gen. Laws ch. 272, §99: https://malegislature.gov/laws/generallaws/partiv/titlei/chapter272/section99
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

A suggestion on how to best use class time!

- It is ok to make mistakes in class. Making mistakes in class is actually the best thing that can happen to you. You learn and will never make it again ☺
- From Ray Dalio's Principles (2017):
  - "Create a Culture in Which It Is Okay to Make Mistakes and Unacceptable Not to Learn from Them"
  - "Recognize that mistakes are a natural part of the evolutionary process."
  - "Don’t feel bad about your mistakes or those of others. Love them!"



Source: https://www.principles.com/

One reason why I don't post slides *before* lecture

From the preamble of one of the best physics books ever: „How to read this book"

The best way to use this book is NOT to simply read it or study it, but to read a question and STOP. Even close the book. Even put it away and THINK about the question. Only after you have formed a reasoned opinion should you read the solution. Why torture yourself thinking? Why jog? Why do push-ups?

If you are given a hammer with which to drive nails at the age of three you may think to yourself, "OK, nice." But if you are given a hard rock with which to drive nails at the age of three, and at the age of four you are given a hammer, you think to yourself, "What a marvelous invention!" You see, you can't really appreciate the solution until you first appreciate the problem.

...

...

Let this book, then, be your guide to mental push-ups. Think carefully about the questions and their answers *before* you read the answers offered by the author. **You will find many answers don't turn out as you first expect. Does this mean you have no sense for physics? Not at all. Most questions were deliberately chosen to illustrate those aspects of physics which seem contrary to casual surmise. Revising ideas, even in the privacy of your own mind, is not painless work.** But in doing so you will revisit some of the problems that haunted the minds of Archimedes, Galileo, Newton, Maxwell, and Einstein.* The physics you cover here in hours took them centuries to master. Your hours of thinking will be a rewarding experience. Enjoy!

Lewis Epstein

Source: "Thinking Physics: Understanding Practical Reality", Lewis Carroll Epstein, 1979-2009. https://www.goodreads.com/book/show/268266.Thinking_Physics
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...

...

You must avoid the temptation to look at answers until you have tried to find and ideally write out the solution yourself!

Source: "Thinking Physics: Understanding Practical Reality", Lewis Carroll Epstein, 1979-2009. https://www.goodreads.com/book/show/268266.Thinking_Physics
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

Study groups are great for learning material!

- "... The groups of students who were doing best spontaneously formed study groups...
- Students who were not doing as well tended to do as the instructor suggested-study two hours out of class for every hour in class-but did it by themselves with little social support...
- ... even well-prepared students (high math SATs) are often disadvantaged by high school experiences that lead them to work alone."

Source: Craig Nelson, Dysfunctional Illusions of Rigor: Part 1 - Basic Illusions, http://cgi.stanford.edu/~dept-ctl/tomprof/posting.php?ID=1058
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

Class scribes

"To ask the right question is harder than to answer it."

Georg Cantor

Quote: https://www.azquotes.com/quote/909685
Also see: https://www.inc.com/lisa-calhoun/elon-musk-on-the-1-creative-skill-every-founder-needs-now.html
Wolfgang Gatterbauer. Principles of scalable data management: https://northeastern-datalab.github.io/cs7240/

Tools

- Canvas:
  - Links to website: with preliminary calendar, optional readings, administrative details, lectures slides
  - Links to Piazza: discussions, questions, errors, follow-up instructions beyond web page; but please let me know if there is a strong preference for Canvas announcements!
  - Canvas calendar: project milestones, submission for scribes
  - link to Zoom

Let's look through the website (project topics)

Other Thoughts

- Active participation is important in this class. If you spot any errors or inconsistencies across slides/web page, typos (even if minor) do let me know, in class, office hours, or via Piazza! I appreciate, and it counts towards class participation.
- If we have online classes, please keep your webcams on, so we reproduce our in-person setting as much as possible. One camera off encourages all others to switch off (think externalities).
- Project topics: do look also through the preliminary class calendar
  - Individual project (except in rare circumstances)
  - But you should work together on everything else in the class!

Two concrete questions

- Canvas discussions & announcements vs Piazza
- Online vs. in-person vs. hybrid
- …