ENGINEERING AI-ENABLED SYSTEMS WITH INTERDISCIPLINARY TEAMS

Christian Kästner

@p0nk

https://ckaestne.github.io/seai/

SEMLA'20

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Associate Professor @ CMU

Interests:

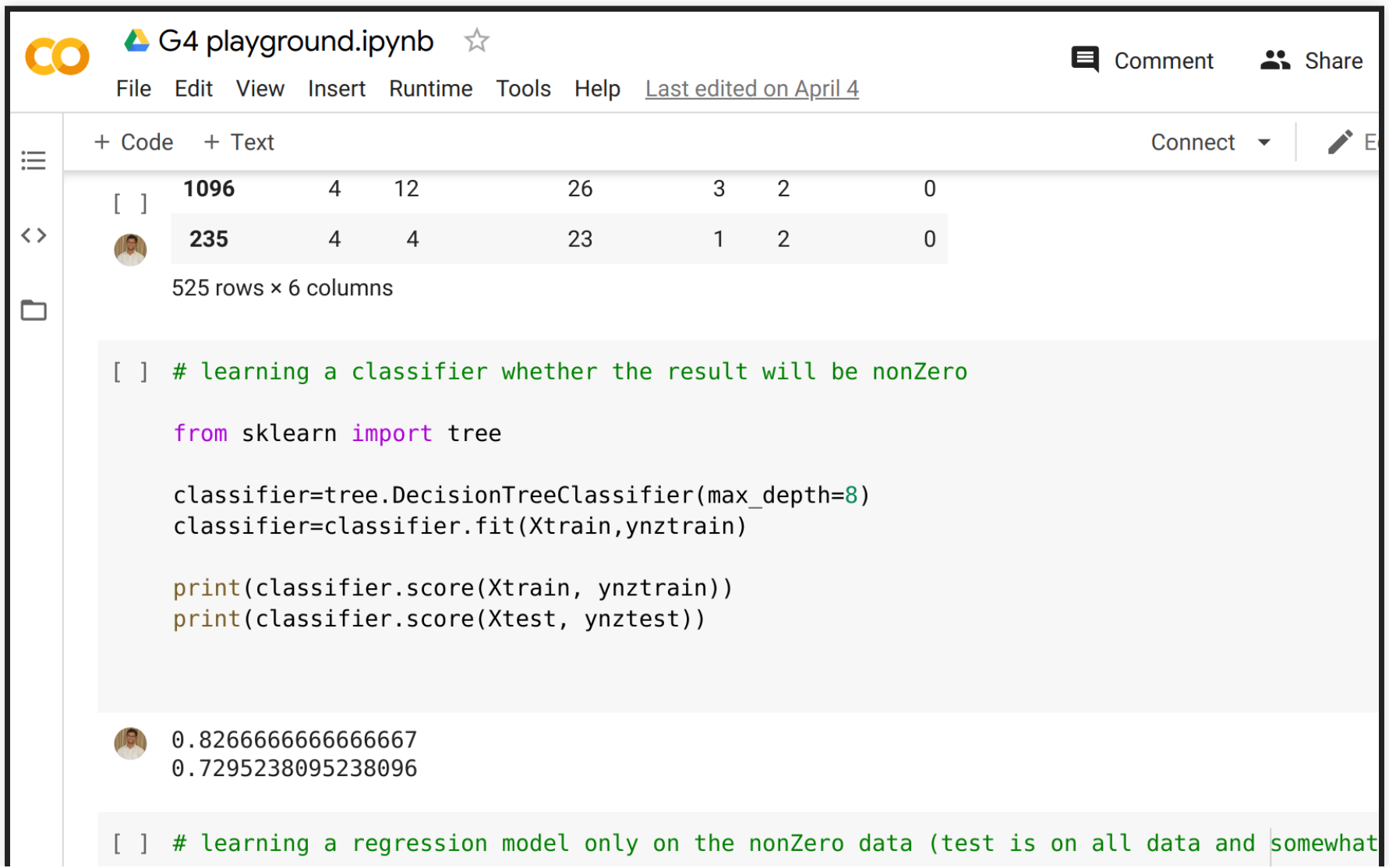
- Software Engineering
- Highly-Configurable Systems & Configuration Engineering
- Sustainability and Stress in Open Source
- Software Engineering for ML-Enabled Systems

SOFTWARE ENGINEERING FOR ML-ENABLED SYSTEMS

Building, operating, and maintaining software systems with machine-learned components

*with interdisciplinary collaborative teams of **data scientists** and **software engineers***

SE FOR ML-ENABLED SYSTEMS != BUILDING MODELS

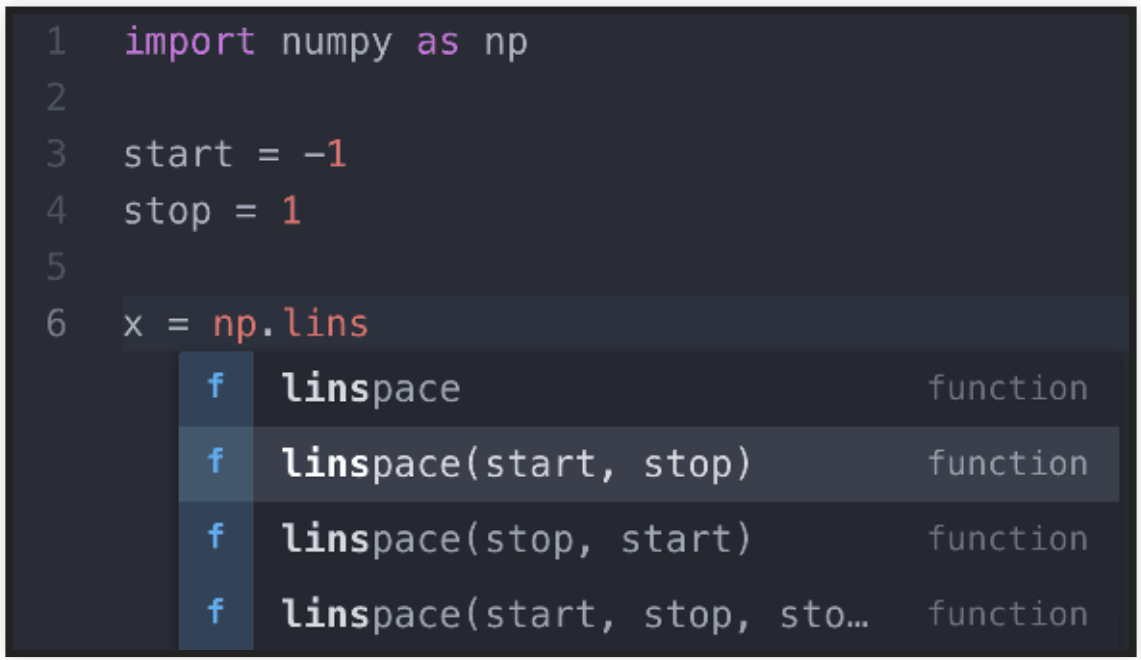


```
from sklearn import tree

predictor=tree.DecisionTreeRegressor(max_depth=8)
predictor=predictor.fit(XnzTrain,YnzTrain)


print(predictor.score(XnzTrain, YnzTrain))
print(predictor.score(Xtest, ytest))
```

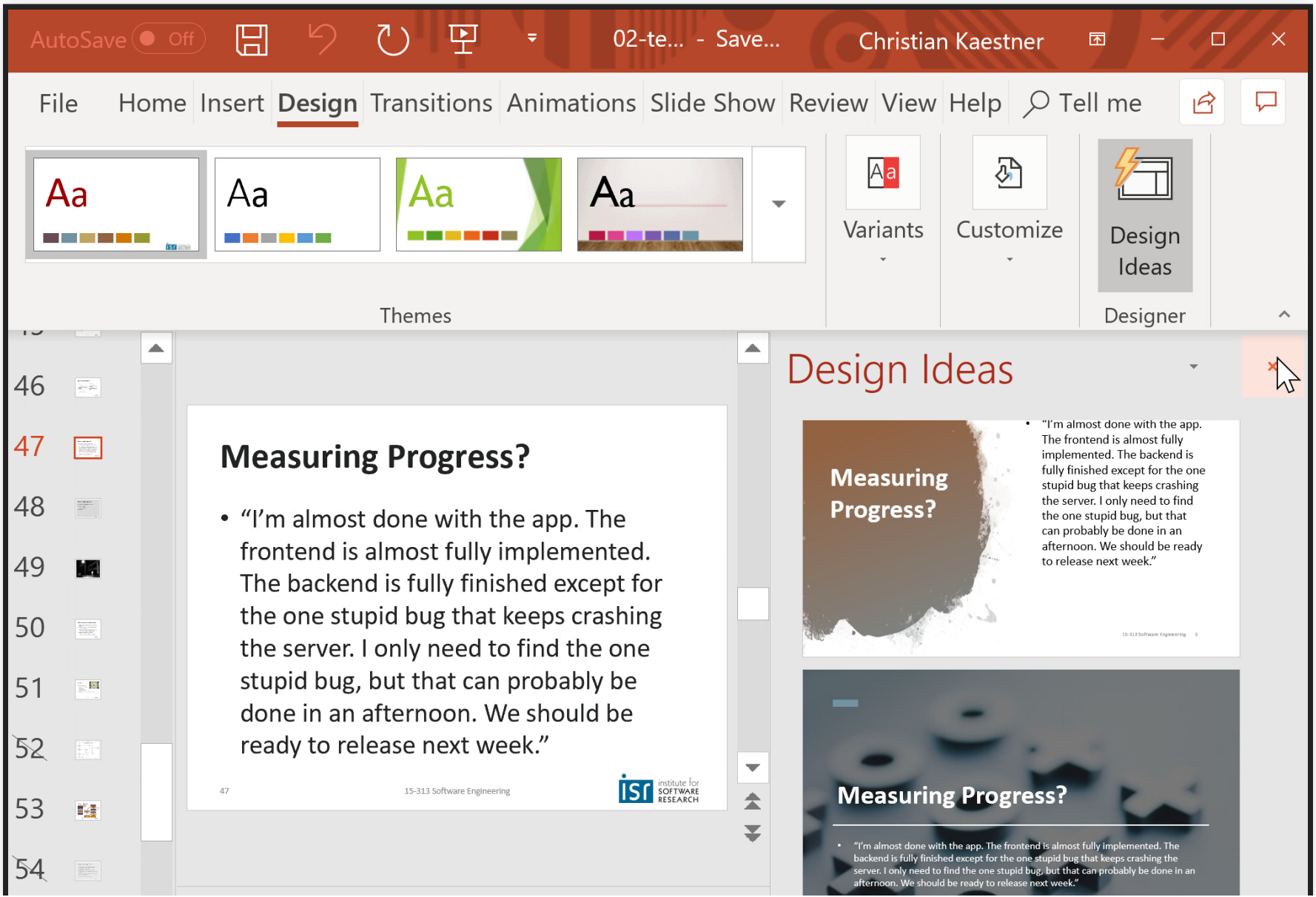
```
0.9376379365613154
-2.437397740412892
```

SE FOR ML-ENABLED SYSTEMS != CODING ML FRAMEWORKS

SE FOR ML-ENABLED SYSTEMS != ML FOR SE TOOLS



SE FOR ML-ENABLED SYSTEMS



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56

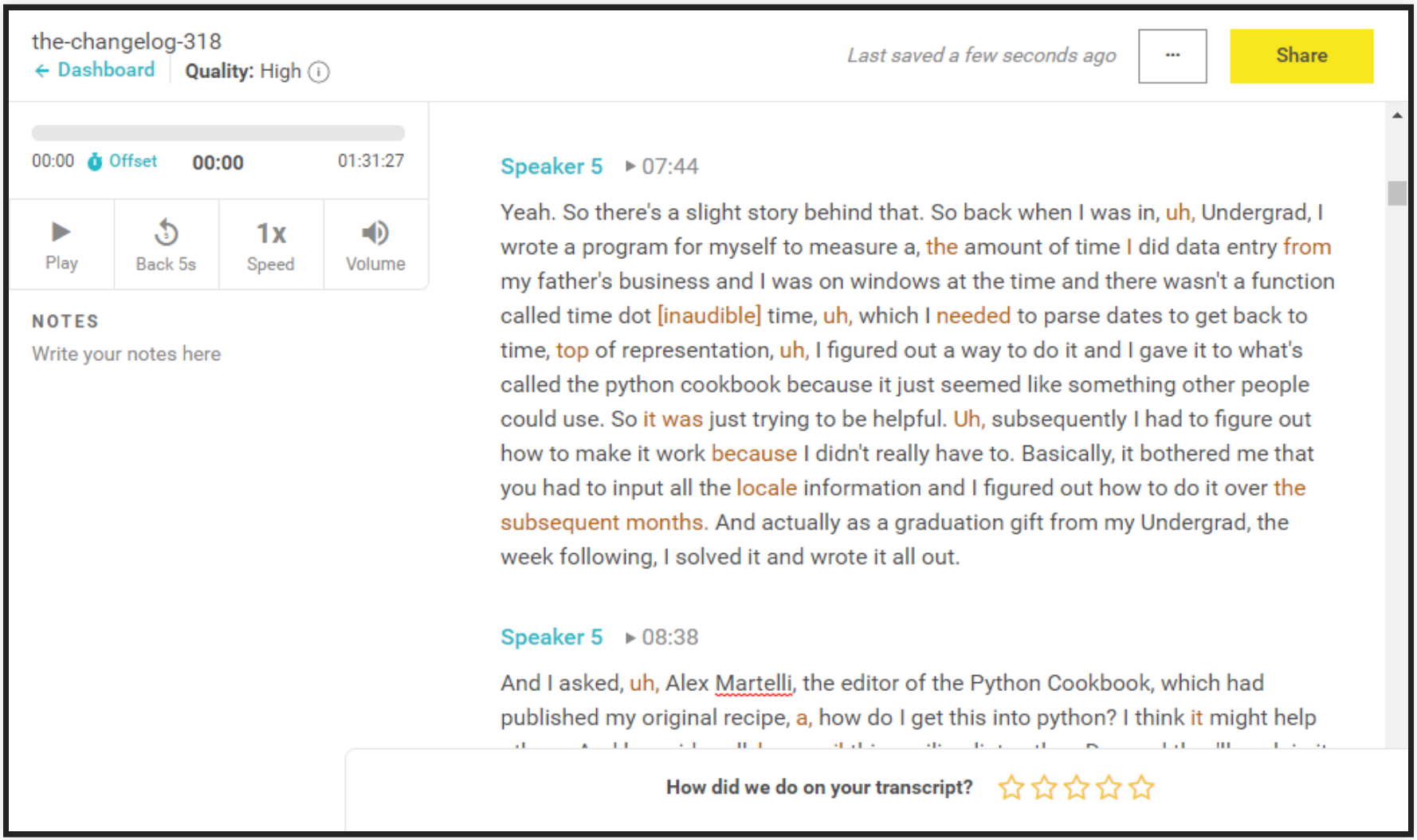
Tap to add notes

Slide 47 of 74

Notes

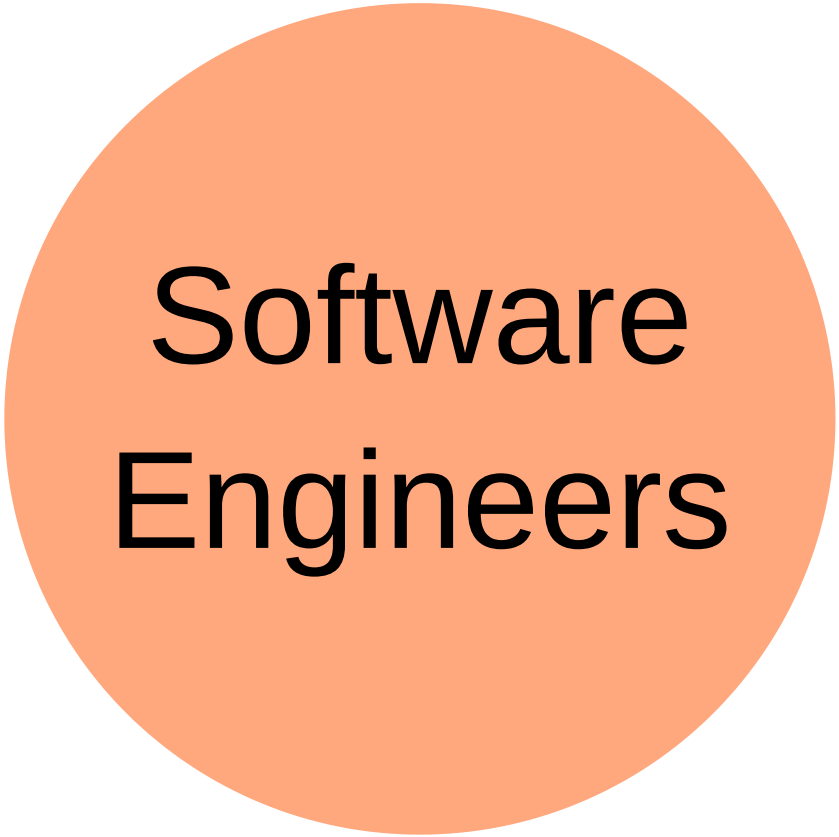
29%

SE FOR ML-ENABLED SYSTEMS



temi.com


Data
Scientists


Software
Engineers

SOFTWARE ENGINEERING

Software engineering is the branch of computer science that creates practical, cost-effective solutions to computing and information processing problems, preferentially by applying scientific knowledge, developing software systems in the service of mankind.

Engineering judgements under limited information and resources

A focus on design, tradeoffs, and the messiness of the real world

Many qualities of concern: cost, correctness, performance, scalability, security, maintainability, ...

"it depends..."

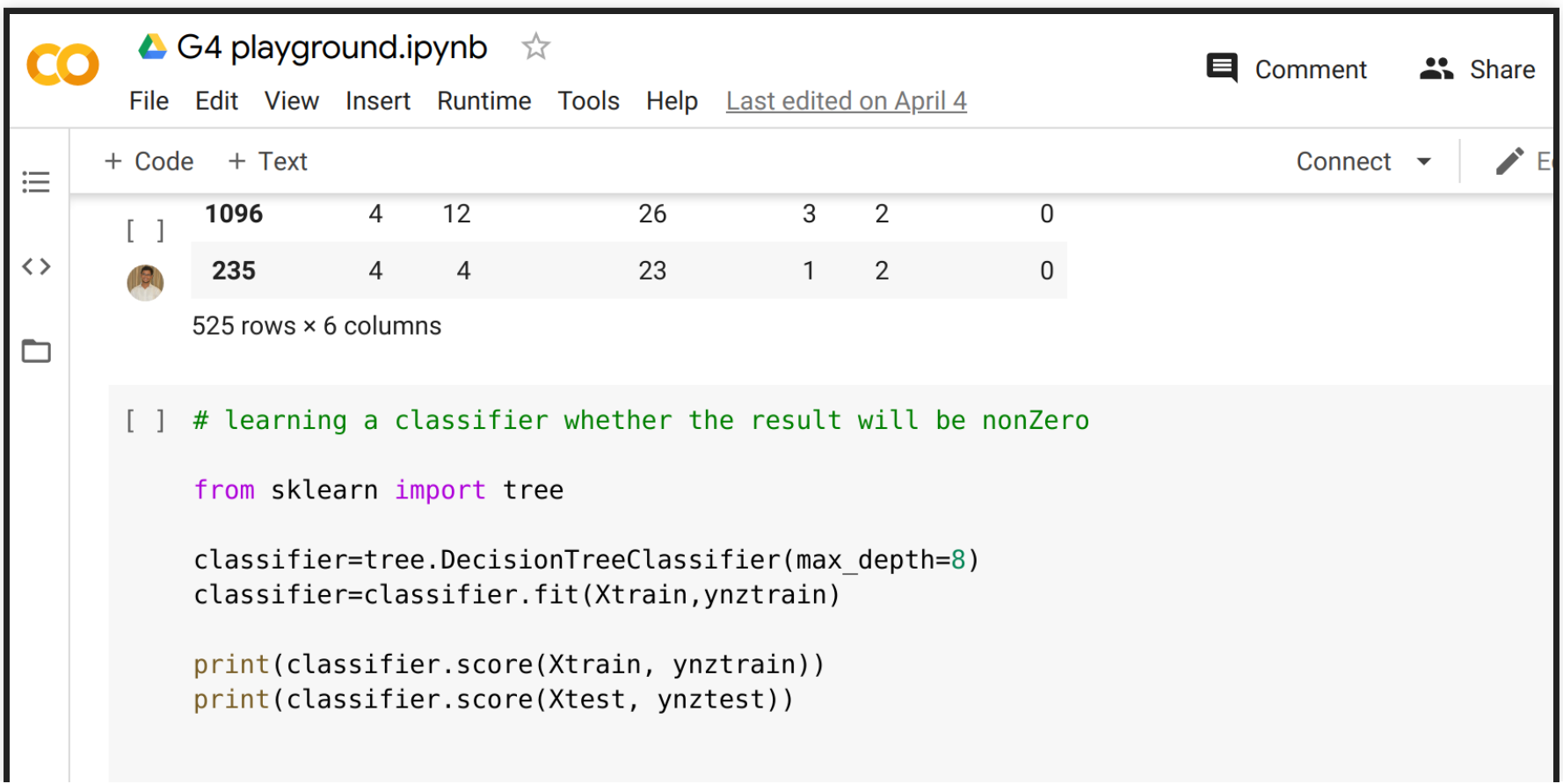
Mary Shaw. ed. Software Engineering for the 21st Century: A basis for rethinking the curriculum. 2005.

MOST ML COURSES/TALKS

Focus narrowly on modeling techniques or building models

Using notebooks, static datasets, evaluating accuracy

Little attention to software engineering aspects of building complete systems



```
0.8266666666666667
0.7295238095238096
```

```
[ ] # learning a regression model only on the nonZero data (test is on all data and somewhat

    from sklearn import tree

    predictor=tree.DecisionTreeRegressor(max_depth=8)
    predictor=predictor.fit(XnzTrain,YnzTrain)


    print(predictor.score(XnzTrain, YnzTrain))
    print(predictor.score(Xtest, ytest))
```

```
0.9376379365613154
-2.437397740412892
```

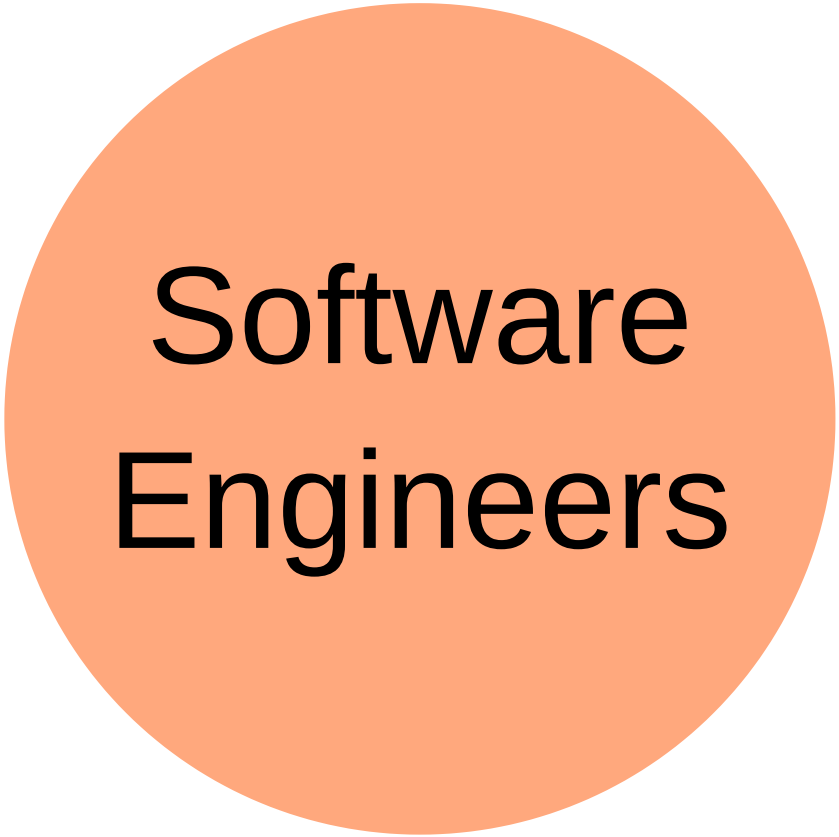
DATA SCIENTIST

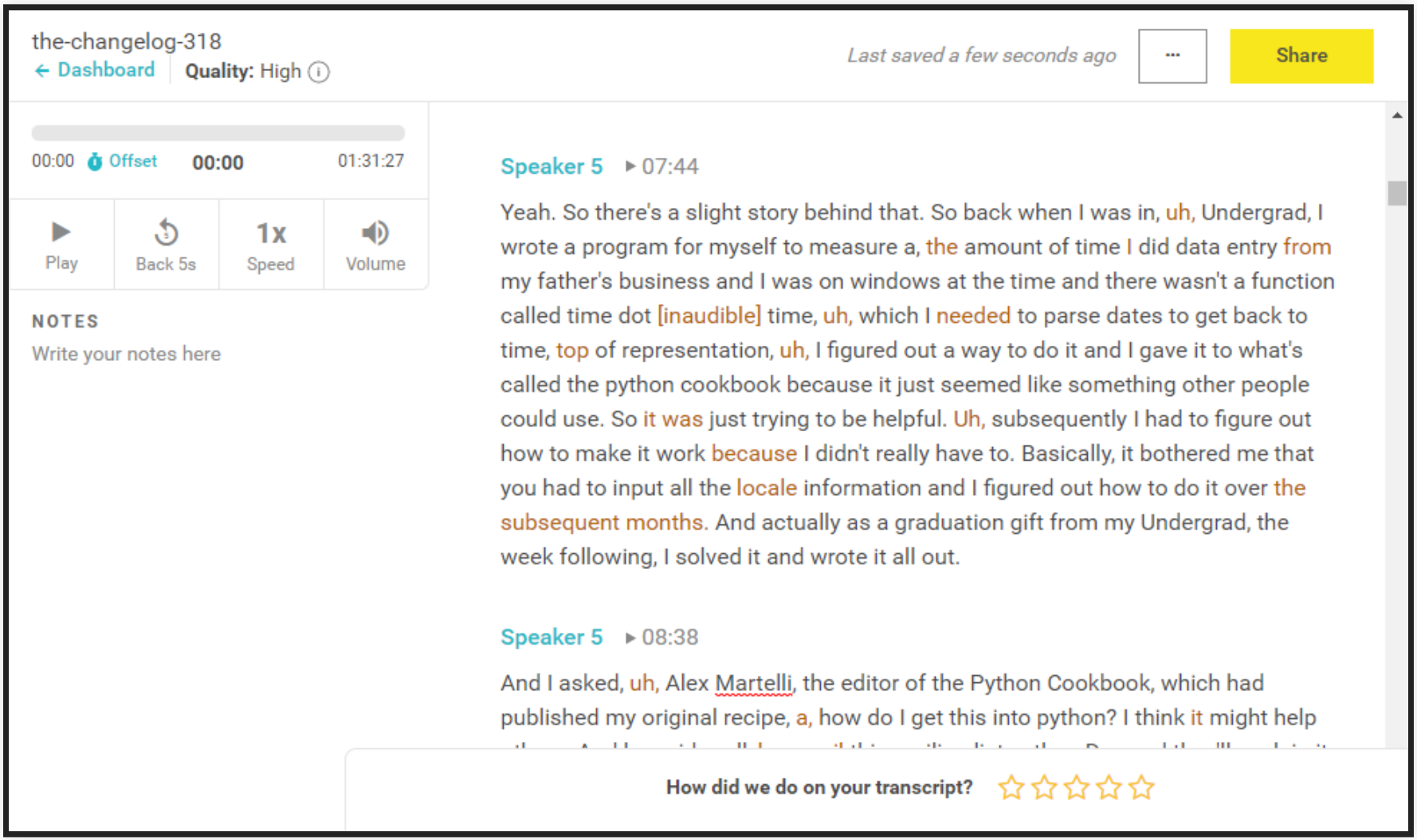
- Often fixed dataset for training and evaluation (e.g., PBS interviews)
- Focused on accuracy
- Prototyping, often Jupyter notebooks or similar
- Expert in modeling techniques and feature engineering
- Model size, updateability, implementation stability typically does not matter
- Starting to worry about fairness, robustness, ...

SOFTWARE ENGINEER

- Builds a product
- Concerned about cost, performance, stability, release time
- Identify quality through customer satisfaction
- Must scale solution, handle large amounts of data
- Plan for mistakes and safeguards
- Maintain, evolve, and extend the product over long periods
- Consider requirements for security, safety, fairness


Data
Scientists


Software
Engineers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Speaker 5 ▸ 07:44
Yeah. So there's a slight story behind that. So back when I was in, uh, Undergrad, I wrote a program for myself to measure a, the amount of time I did data entry from my father's business and I was on windows at the time and there wasn't a function called time dot [inaudible] time, uh, which I needed to parse dates to get back to time, top of representation, uh, I figured out a way to do it and I gave it to what's called the python cookbook because it just seemed like something other people could use. So it was just trying to be helpful. Uh, subsequently I had to figure out how to make it work because I didn't really have to. Basically, it bothered me that you had to input all the locale information and I figured out how to do it over the subsequent months. And actually as a graduation gift from my Undergrad, the week following, I solved it and wrote it all out.
Speaker 5 ▸ 08:38
And I asked, uh, Alex Martelli, the editor of the Python Cookbook, which had published my original recipe, a, how do I get this into python? I think it might help
How did we do on your transcript?

A SOFTWARE ENGINEERING PERSPECTIVE ON ML

WHAT'S DIFFERENT?

- Missing specifications
- Environment is important (feedback loops, data drift)
- Nonlocal and nonmonotonic effects
- Testing in production
- Data management, versioning, and provenance

MISSING SPECIFICATIONS

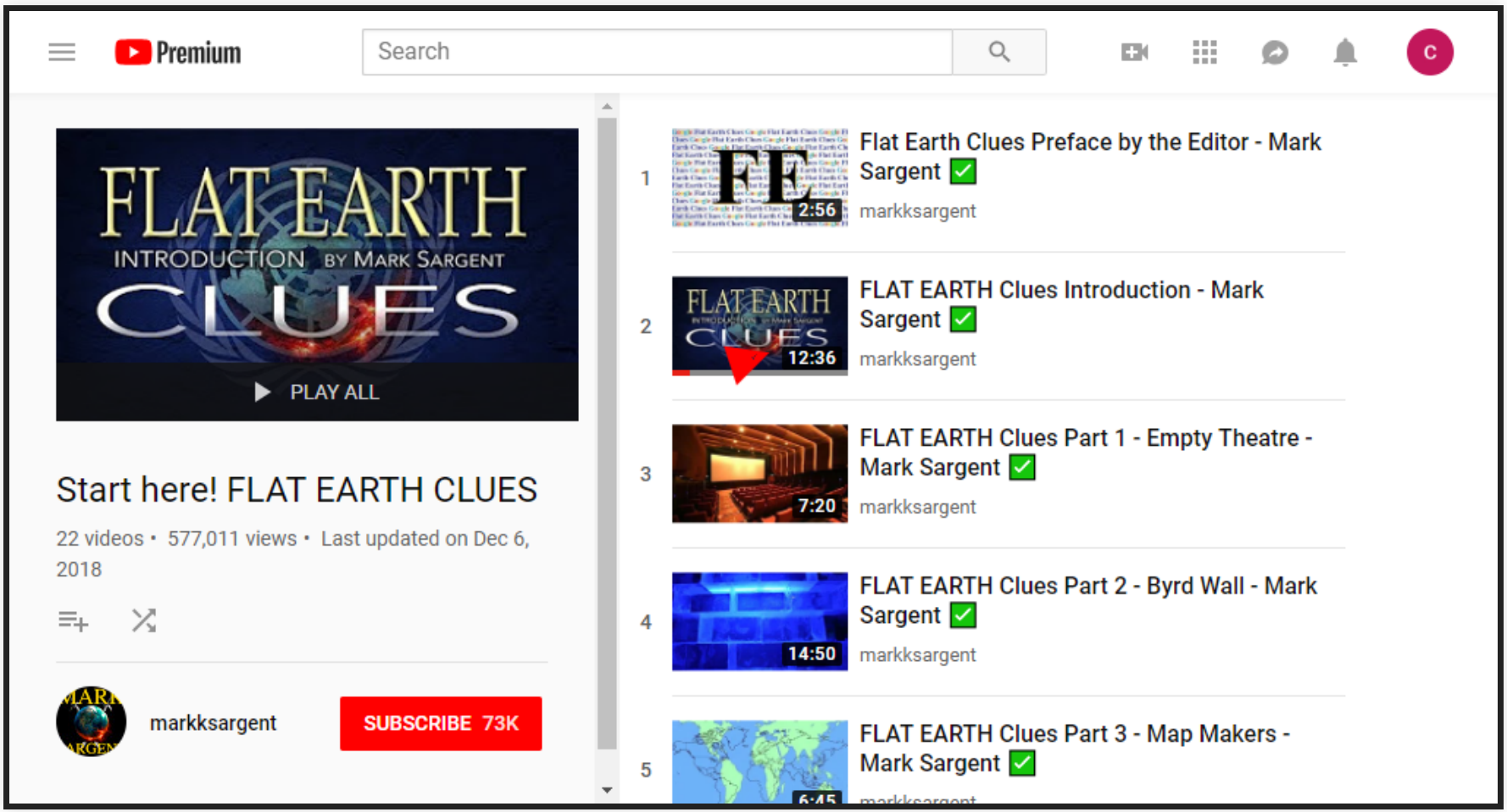
from deductive to inductive reasoning

```
/**
  ????
*/
String transcribe(File audioFile);
```

```
/**
  ????
*/
Boolean predictRecidivism(int age,
                          List<Crime> priors,
                          Gender gender,
                          int timeServed,
                          ...);
```

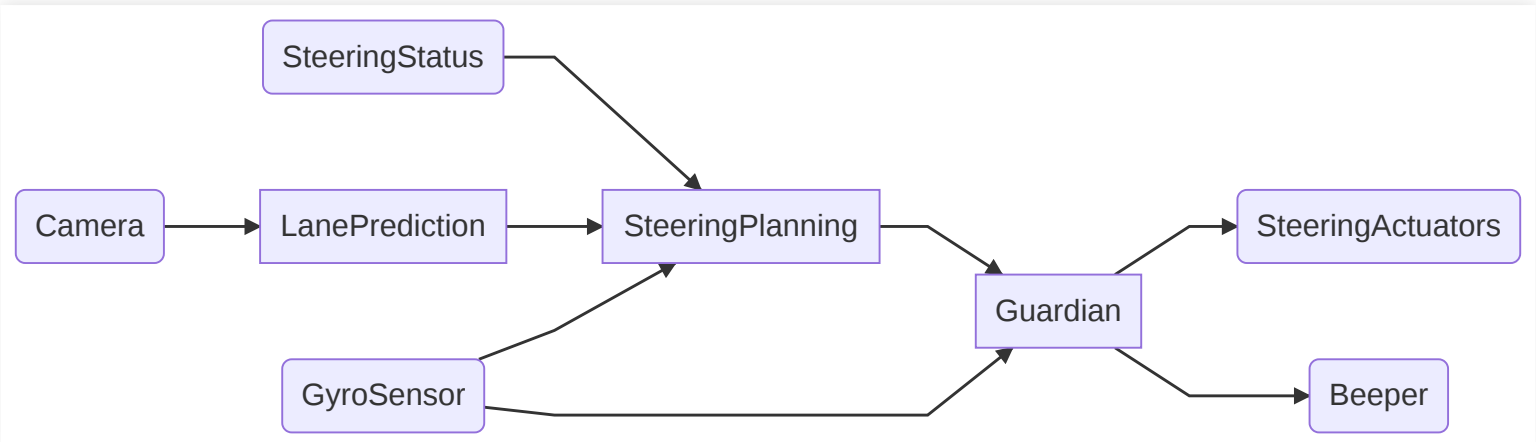
ENVIRONMENT IS IMPORTANT

(feedback loops, data drift)



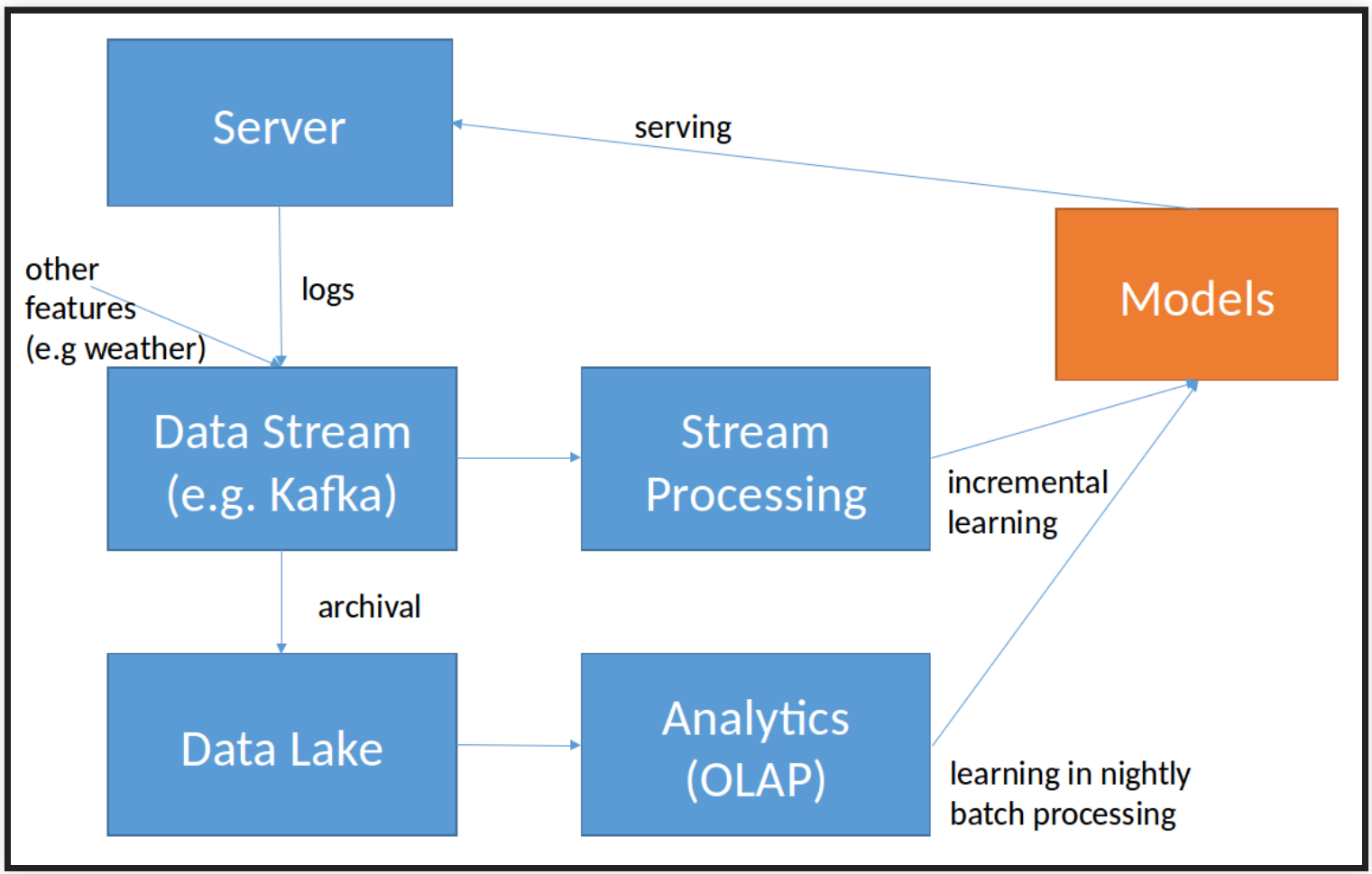
NONLOCAL AND NONMONOTONIC EFFECTS

multiple models in most systems



TESTING IN PRODUCTION

DATA MANAGEMENT, VERSIONING, AND PROVENANCE



BUT REALLY DIFFERENT?

ML: MISSING SPECIFICATIONS

from deductive to inductive reasoning

```
/**
  ????
*/
String transcribe(File audioFile);
```

```
/**
  ????
*/
Boolean predictRecidivism(int age,
                          List<Crime> prio
                          Gender gender,
                          int timeServed,
                          ...);
```

SOFTWARE ENGINEERING:

vague specs very common

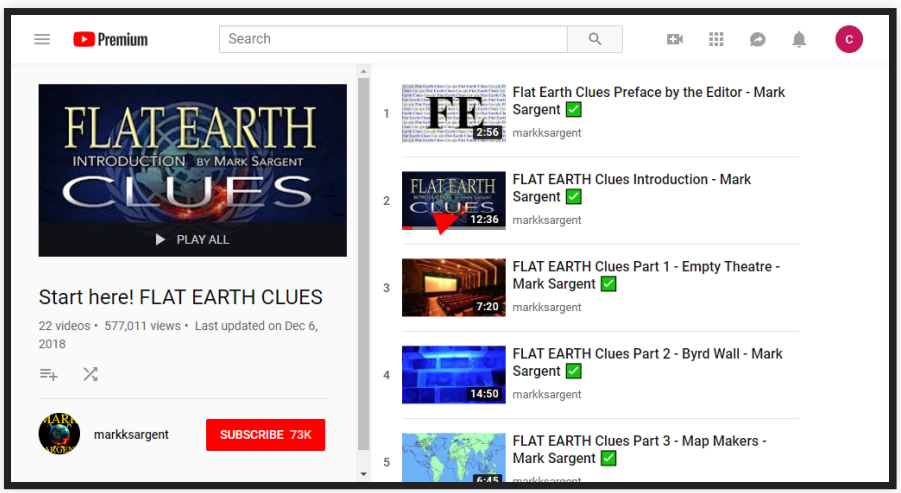
agile methods

safe systems from unreliable components

("ML is requirements engineering")

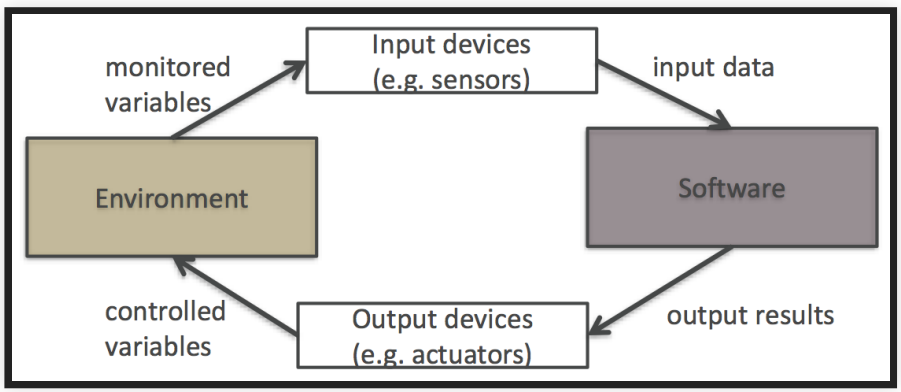
AI: ENVIRONMENT IS IMPORTANT

(feedback loops, data drift)



SOFTWARE ENGINEERING:

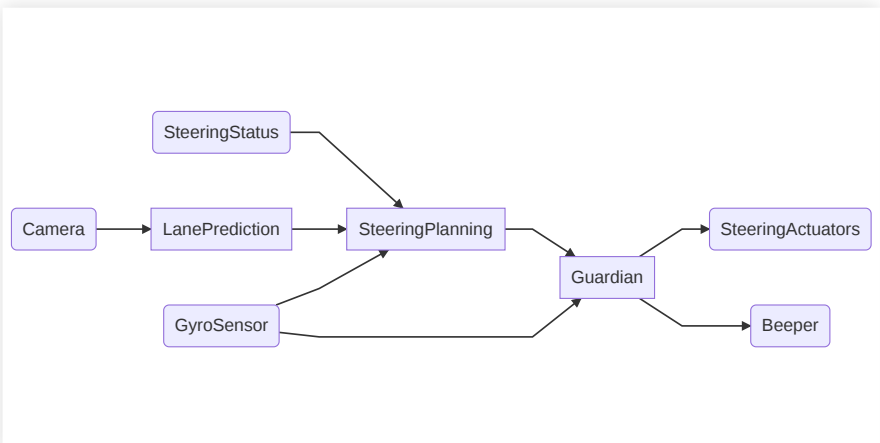
the world and the machine



(Jackson ICSE 95)

AI: NONMONOTONIC EFFECTS

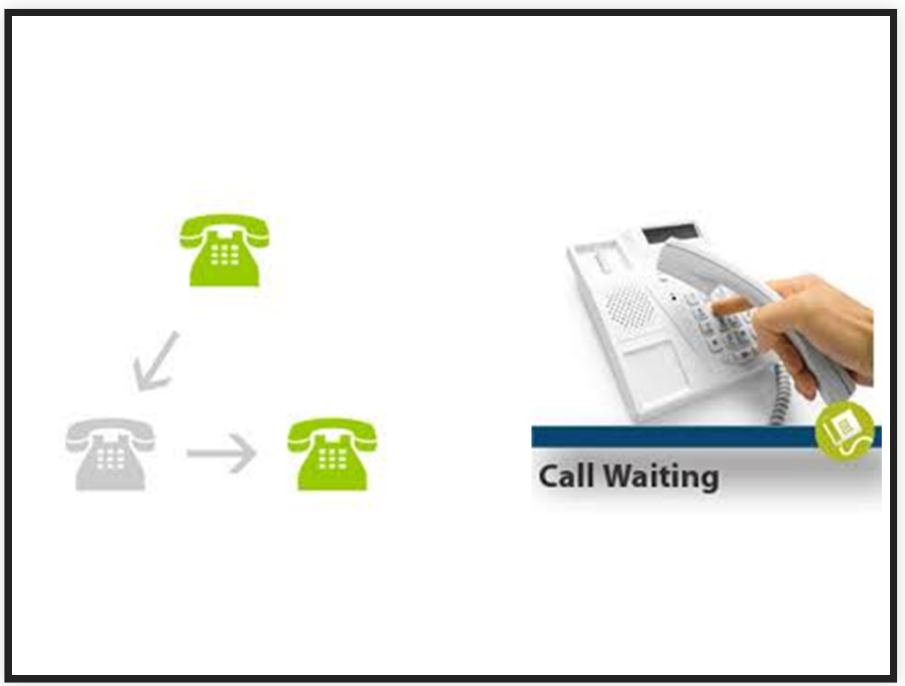
multiple models in most systems



SOFTWARE ENGINEERING:

feature interactions

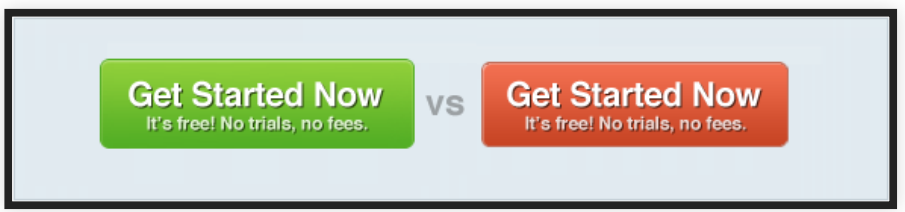
system testing



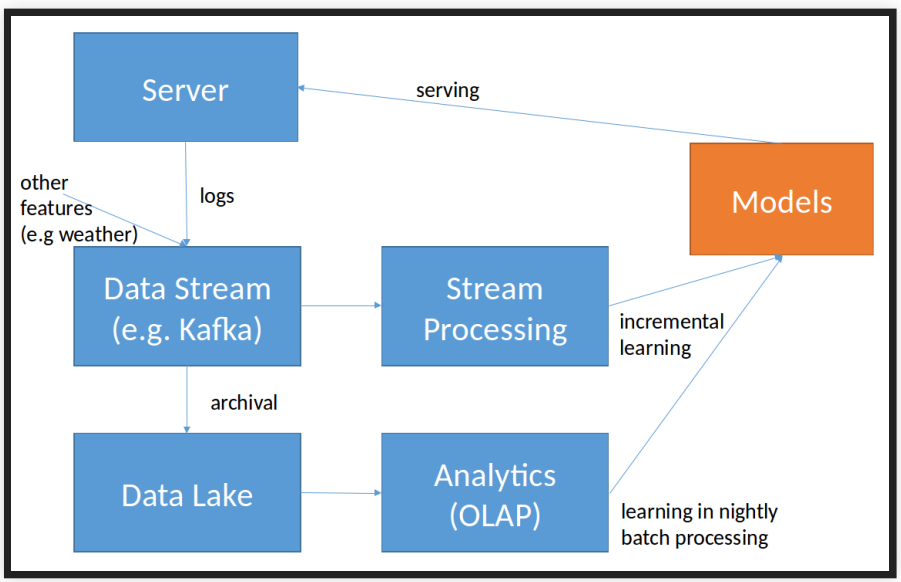
ML: TESTING IN PRODUCTION

SOFTWARE ENGINEERING:

Chaos engineering, A/B testing, continuous deployment, feature flags, canary releases



ML: DATA MANAGEMENT, VERSIONING, AND PROVENANCE



SE/DATABASE COMMUNITIES:

stream processing

event sourcing

data modeling

data flow models

provenance tracking

SOFTWARE ENGINEERS IN AI-ENABLED SYSTEM PROJECTS

- Missing specifications -- *implicit, vague specs very common; safe systems from unreliable components*
- Environment is important -- *the world vs the machine*
- Nonlocal and nonmonotonic effects -- *feature interactions, system testing*
- Testing in production -- *continuous deployment, A/B testing*
- Data management, versioning, and provenance -- *stream processing, event sourcing, data modeling*

EXAMPLES OF SOFTWARE ENGINEERING CONCERNS

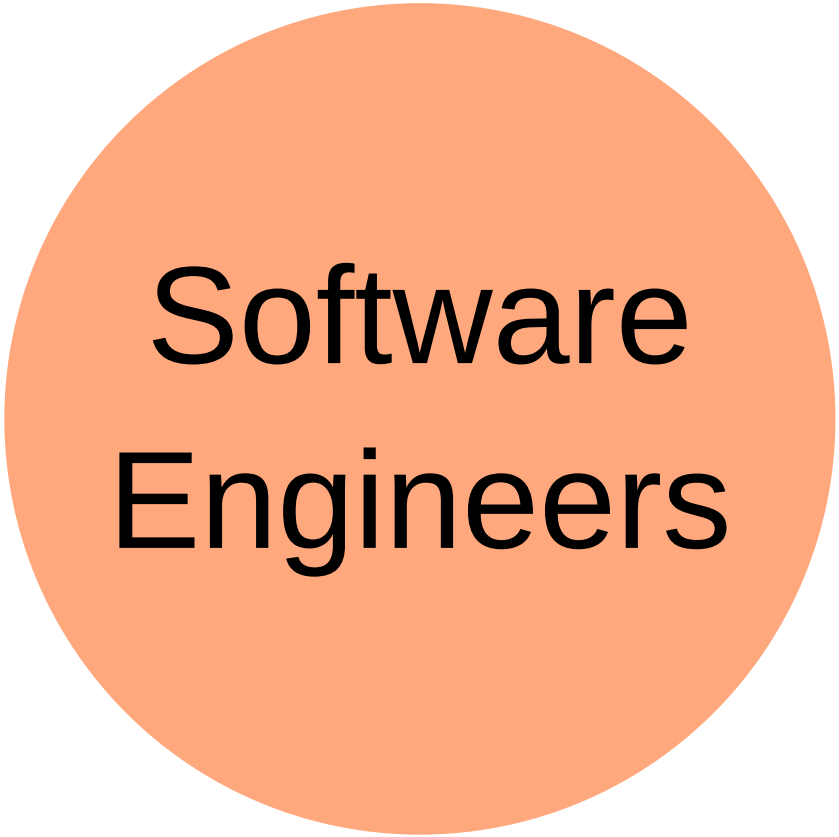
- How to build robust AI pipelines and facilitate regular model updates?
- How to deploy and update models in production?
- How to evaluate data and model quality in production?
- How to deal with mistakes that the model makes and manage associated risk?
- How to trade off between various qualities, including learning cost, inference time, updatability, and interpretability?
- How to design a system that scales to large amounts of data?
- How to version models and data?
- How to manage interdisciplinary teams with data scientists, software engineers, and operators?

MY VIEW

While developers of simple traditional systems may get away with poor practices, most developers of ML-enabled systems will not.

This is an education problem, more than a research problem.

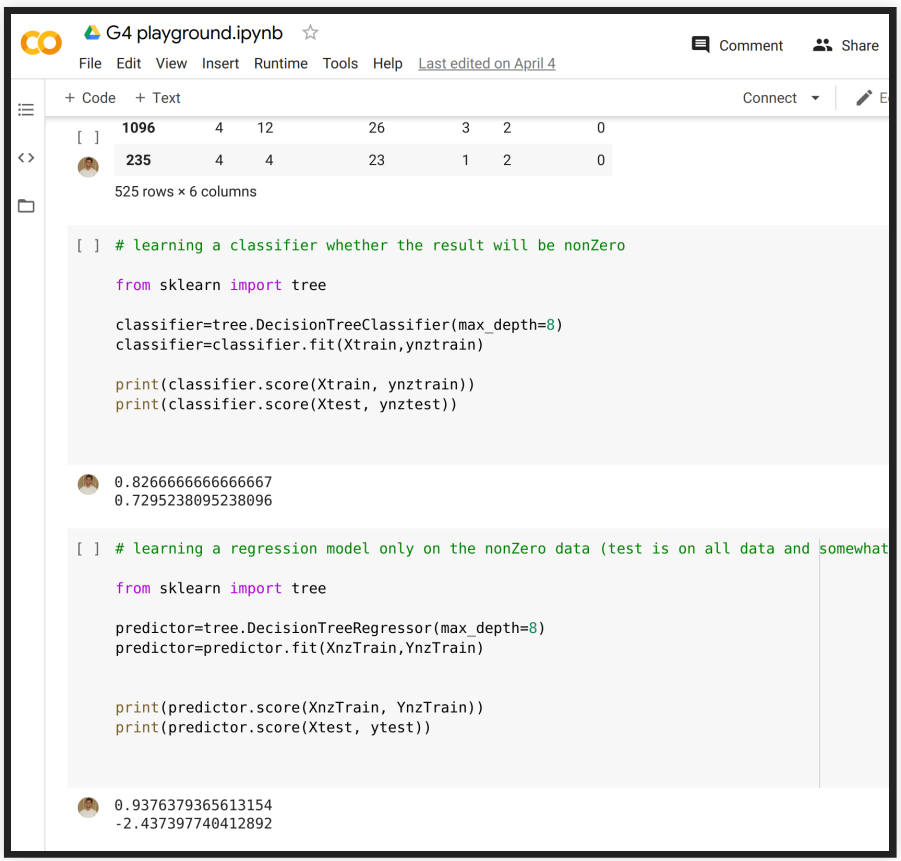

Data
Scientists


Software
Engineers

DATA SCIENTISTS AND SOFTWARE ENGINEERS HAVE DIFFERENT ROLES AND EXPERTISE

that's okay; that's good

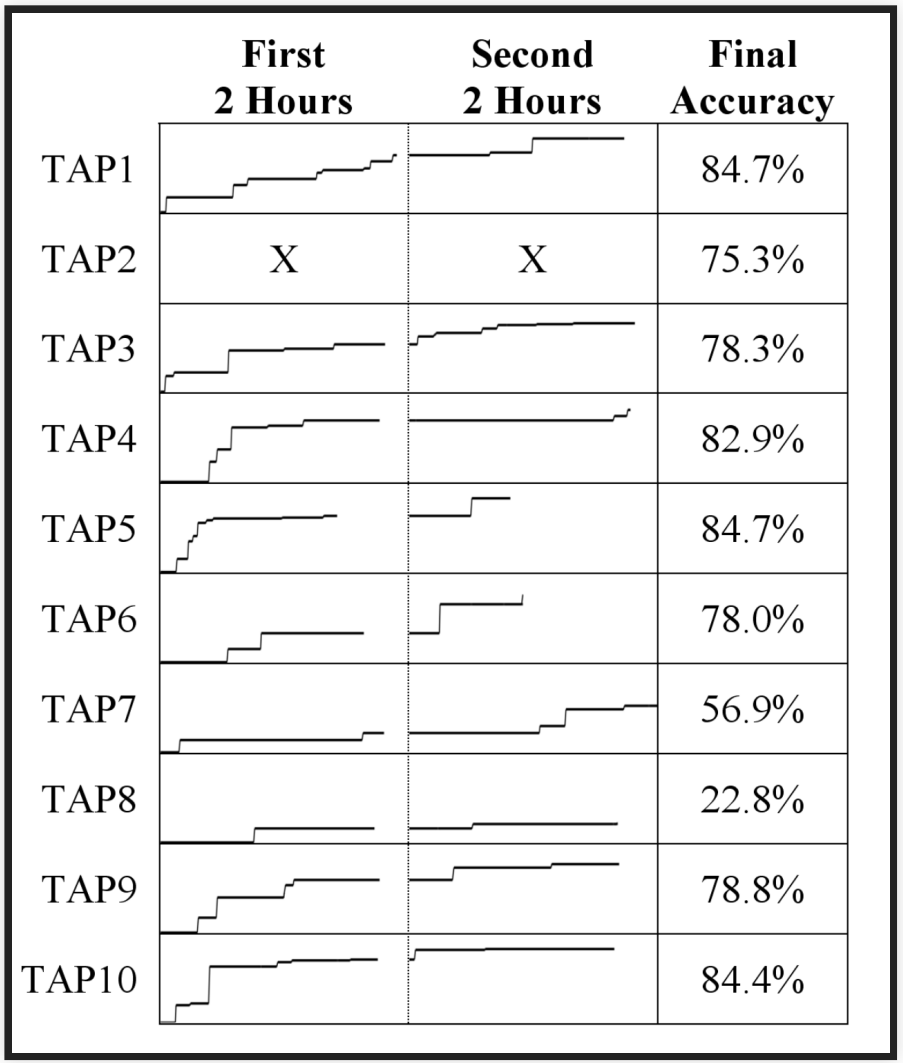
POOR SOFTWARE ENGINEERING PRACTICES IN NOTEBOOKS?



- Little abstraction
- Global state
- No testing
- Heavy copy and paste
- Little documentation
- Poor version control
- Out of order execution
- Poor development features (vs IDE)

UNDERSTANDING BENEFITS OF NOTEBOOKS

- Data science is exploratory and iterative
  - Science mindset
  - No clear specs, unclear whether possible
- Notebooks offer
  - Quick feedback, similar to REPL
  - Visual feedback
  - Incremental computation
  - Easy to edit and share

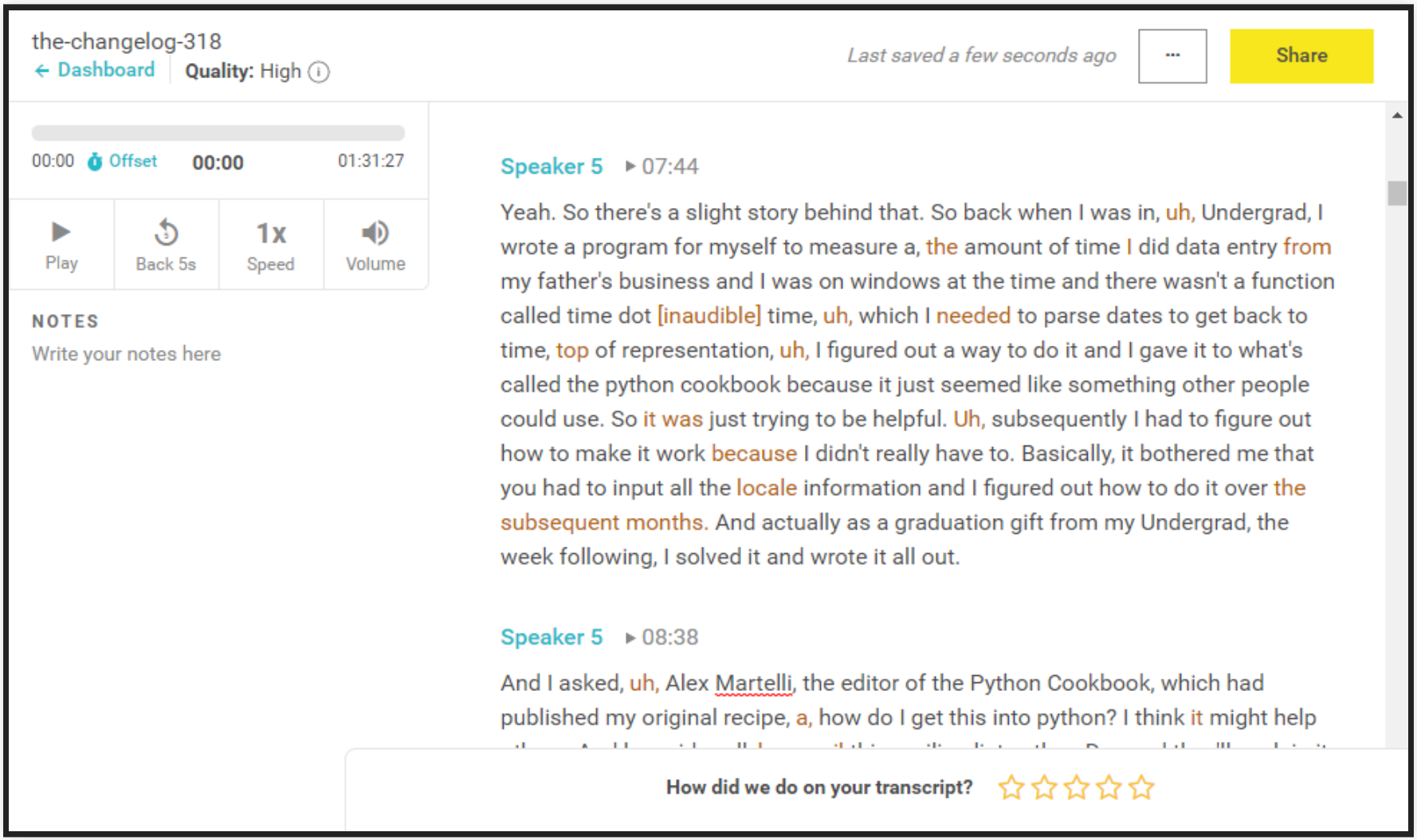


Source: Patel, Kayur, James Fogarty, James A. Landay, and Beverly Harrison. "Investigating statistical machine learning as a tool for software development." In Proc. CHI, 2008.

UNDERSTANDING DATA SCIENTIST WORKFLOWS

- Instead of blindly recommended "SE Best Practices" understand context
- Documentation and testing not a priority in exploratory phase
- Help with transitioning into practice
    - From notebooks to pipelines
    - Support maintenance and iteration once deployed
    - Provide infrastructure and tools

THE SOFTWARE ENGINEERING MINDSET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Speaker 5 ▸ 07:44
Yeah. So there's a slight story behind that. So back when I was in, uh, Undergrad, I wrote a program for myself to measure a, the amount of time I did data entry from my father's business and I was on windows at the time and there wasn't a function called time dot [inaudible] time, uh, which I needed to parse dates to get back to time, top of representation, uh, I figured out a way to do it and I gave it to what's called the python cookbook because it just seemed like something other people could use. So it was just trying to be helpful. Uh, subsequently I had to figure out how to make it work because I didn't really have to. Basically, it bothered me that you had to input all the locale information and I figured out how to do it over the subsequent months. And actually as a graduation gift from my Undergrad, the week following, I solved it and wrote it all out.
Speaker 5 ▸ 08:38
And I asked, uh, Alex Martelli, the editor of the Python Cookbook, which had published my original recipe, a, how do I get this into python? I think it might help
How did we do on your transcript?

THINKING ABOUT SYSTEMS

- Holistic approach, looking at the larger picture, involving all stakeholders
- Looking at relationships and interactions among components and environments
    - Everything is interconnected
    - Combining parts creates something new with emergent behavior
    - Understand dynamics, be aware of feedback loops, actions have effects
- Understand how humans interact with the system

> *A system is a set of inter-related components that work together in a particular environment to perform whatever functions are required to achieve the system's objective -- Donella Meadows*

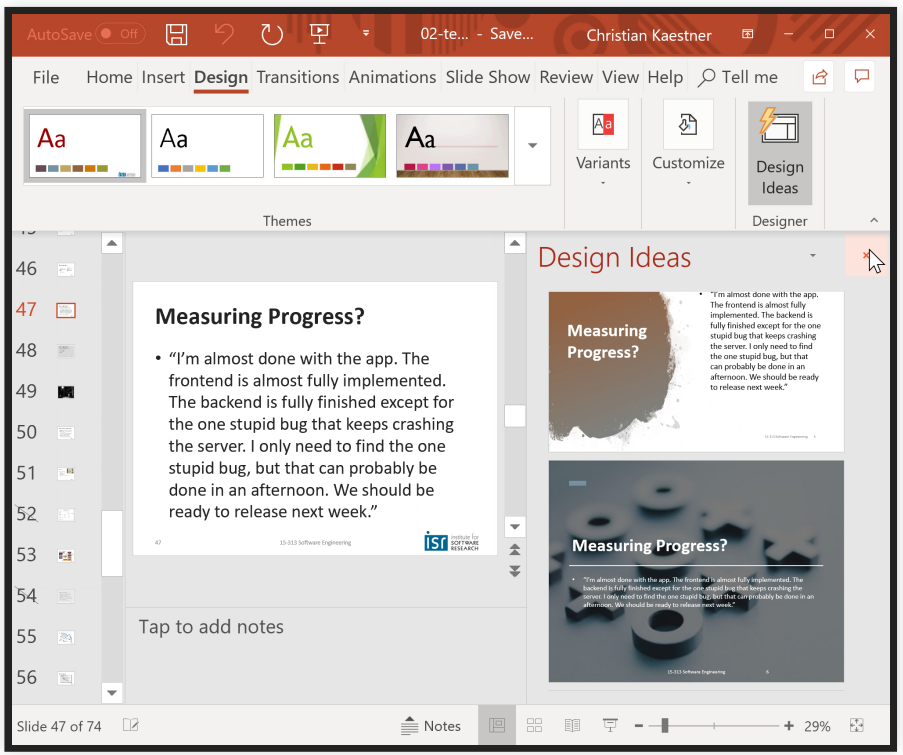
Leyla Acaroglu. "Tools for Systems Thinkers: The 6 Fundamental Concepts of Systems Thinking." Blogpost 2017

FOUR DESIGN CHALLENGES

- **User interaction design**
- Model qualities and deployment tradeoffs
- Risk analysis and safety
- Telemetry design

DESIGNING INTELLIGENT EXPERIENCES

- How to present prediction to a user?
- How to effectively influence the user's behavior toward the system's goal?
- How to minimize the consequences of flawed predictions?
- How to collect data to continue to learn from users and mistakes?



DESIGNING INTELLIGENT EXPERIENCES

- How to present prediction to a user?
- How to effectively influence the user's behavior toward the system's goal?
- How to minimize the consequences of flawed predictions?
- How to collect data to continue to learn from users and mistakes?

(fall detection)

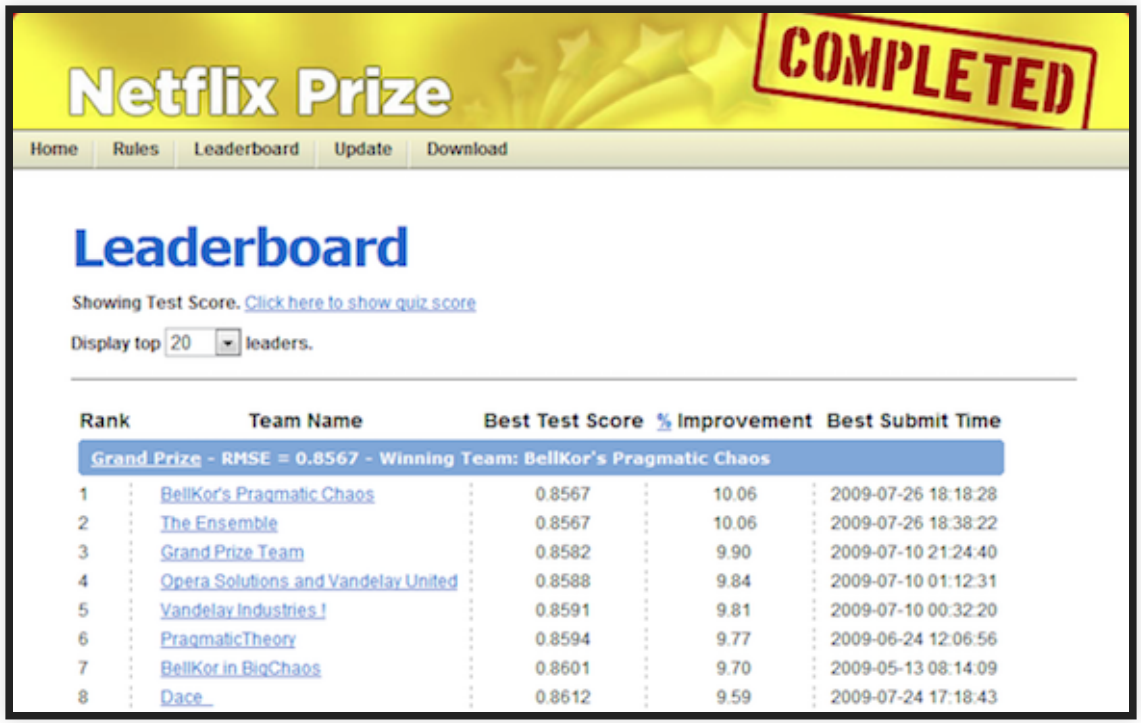
FOUR DESIGN CHALLENGES

- User interaction design
- **Model qualities and deployment tradeoffs**
- Risk analysis and safety
- Telemetry design

BEYOND ACCURACY

- Training time, memory need, model size -- depending on training data volume and feature size
- Inference time, energy efficiency, resources needed, scalability
- Incremental training possible?
- How much data needed? Data quality important? How many features? Interactions among features?
- Interpretability/explainability
- Robustness, reproducibility, stability
- Security, privacy
- Fairness

TRADE-OFFS: COST VS ACCURACY



"We evaluated some of the new methods offline but the additional accuracy gains that we measured did not seem to justify the engineering effort needed to bring them into a production environment."

Amatriain & Basilico. Netflix Recommendations: Beyond the 5 stars, Netflix Technology Blog (2012)

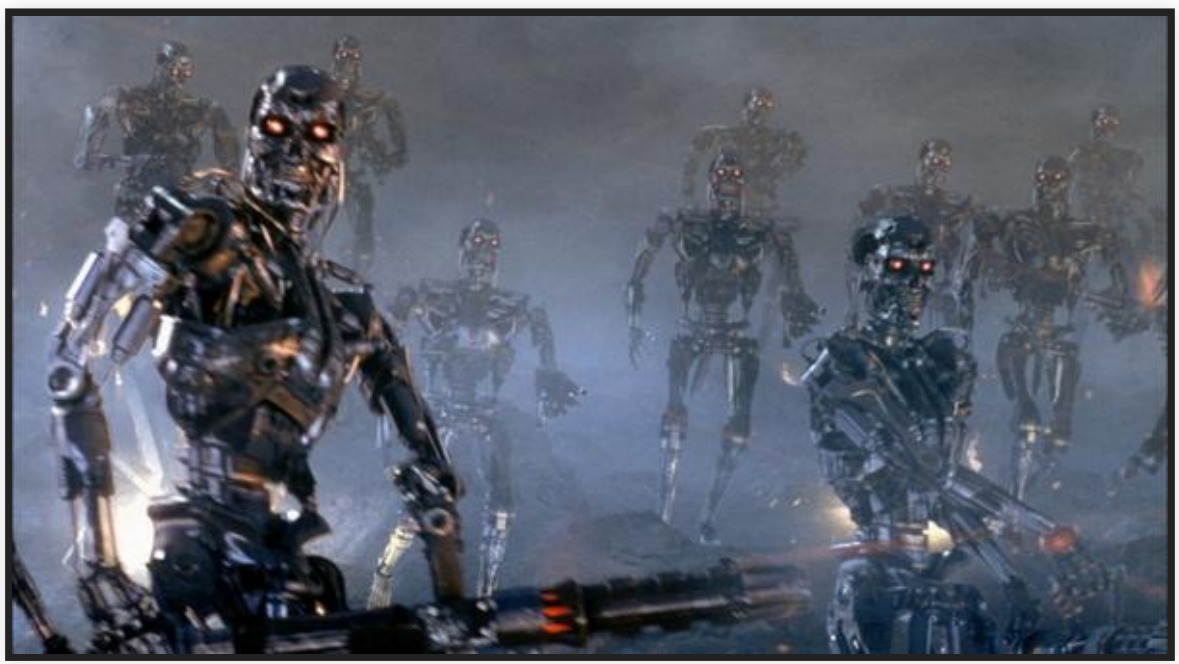
ARCHITECTURE: WHERE SHOULD THE MODEL LIVE?

FOUR DESIGN CHALLENGES

- User interaction design
- Model qualities and deployment tradeoffs
- **Risk analysis and safety**
- Telemetry design

RISK ANALYSIS

What's the worst that could happen?



RISK ANALYSIS

- What can possibly go wrong in my system, and what are potential impacts on system requirements?
- Risk = Likelihood * Impact
- Many established methods:
  - Failure mode & effects analysis (FMEA)
  - Hazard analysis
  - Why-because analysis
  - Fault tree analysis (FTA)
  - Hazard and Operability Study (HAZOP)
  - ...

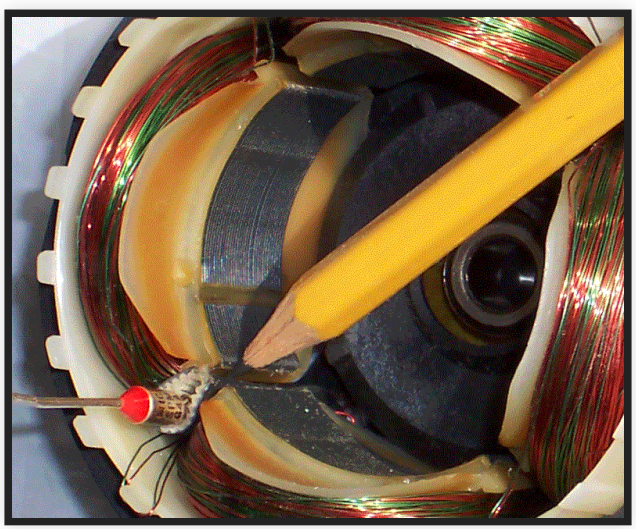
THE SMART TOASTER

$$\text{continueToasting}(\text{camera}_{\text{initial}}, \text{camera}_{\text{now}}, \text{temperatureReading}, \text{userPref}) \rightarrow \text{Boolean}$$

the toaster may (occasionally) burn my toast, but should never burn down my kitchen

SAFEGUARDS / GUARDRAILS

- Hard constraints overrule model
  - `heat = (temperatureReading < MAX) && continueToasting(...)`
- External hardware or software failsafe mechanisms
  - outside the model, external observer, e.g., thermal fuses
- Human in the loop



(Image CC BY-SA 4.0, C J Cowie)

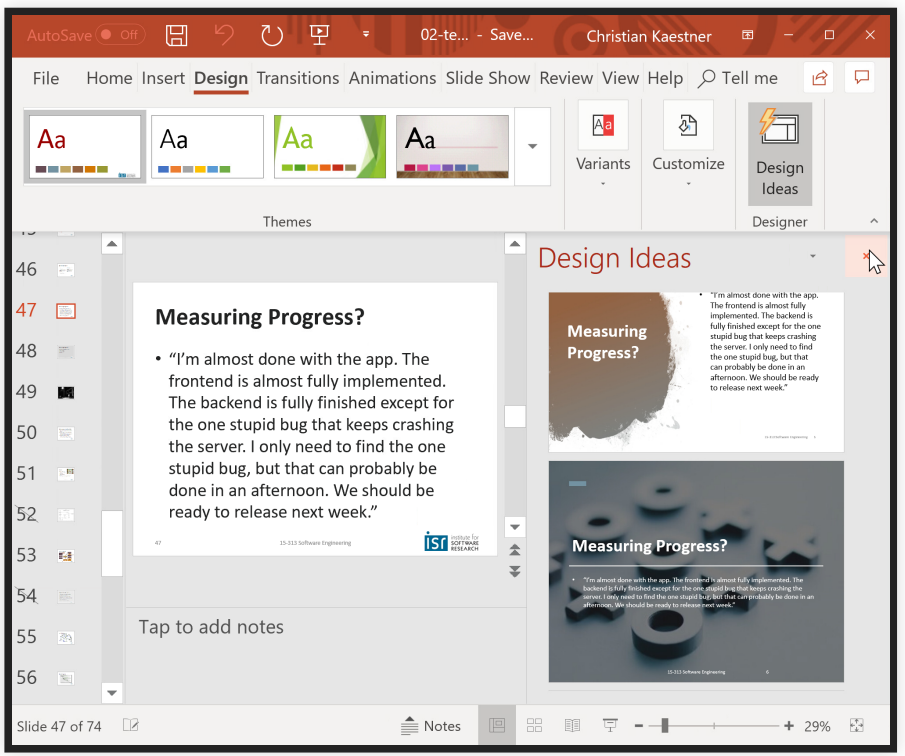
FOUR DESIGN CHALLENGES

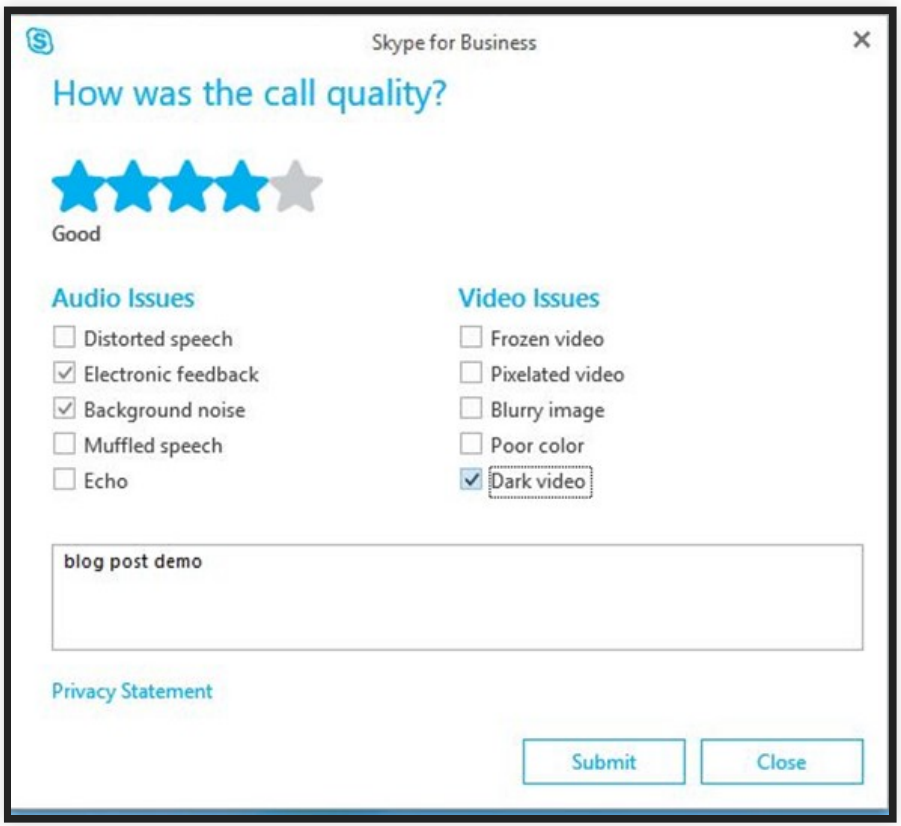
- User interaction design
- Model qualities and deployment tradeoffs
- Risk analysis and safety
- **Telemetry design**

KEY DESIGN CHALLENGE: TELEMETRY

- How can we identify mistakes? Both false positives and false negatives?
- How can we collect feedback without being intrusive (e.g., asking users about every interactions)?
- How much data are we collecting? Can we manage telemetry at scale? How to sample properly?
- How do we isolate telemetry for specific AI components and versions?

Automatic slide design:




Skype for Business
How was the call quality?
Good
Audio Issues
Distorted speech
Electronic feedback
Background noise
Muffled speech
Echo
Video Issues
Frozen video
Pixelated video
Blurry image
Poor color
Dark video
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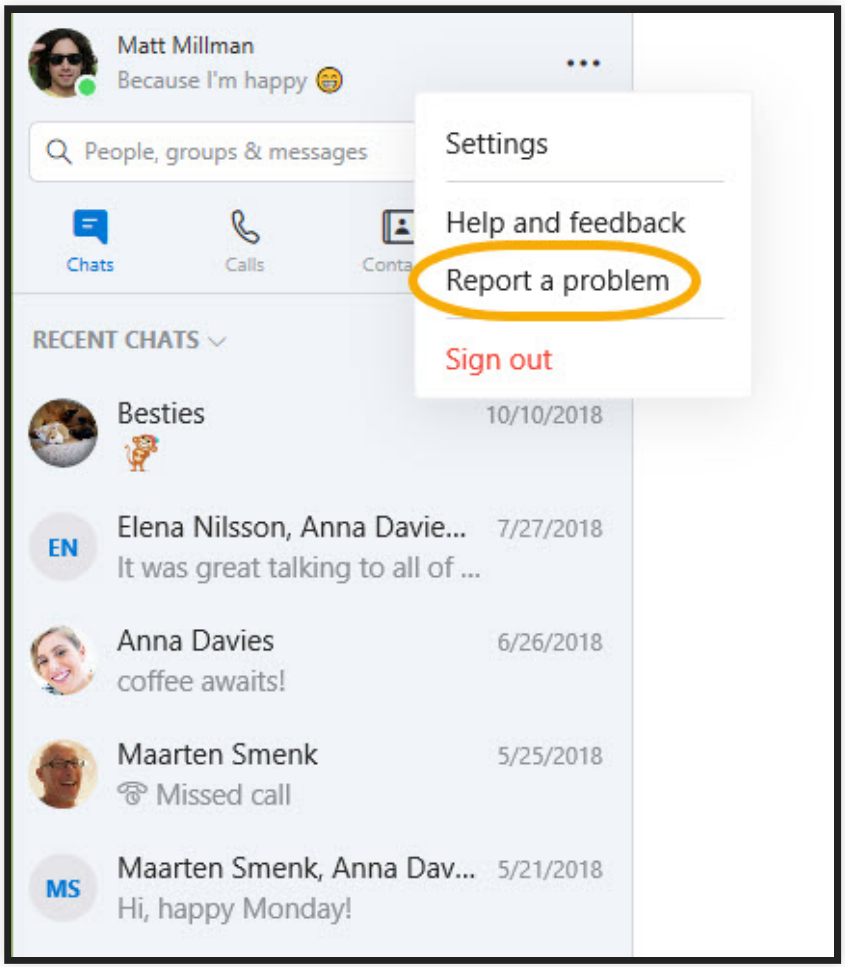
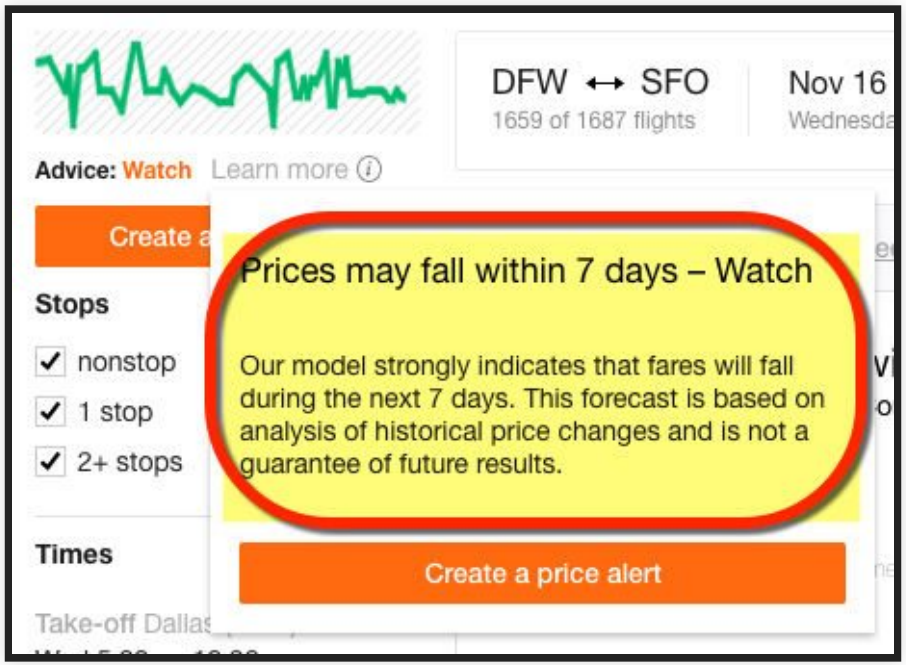

Matt Millman
Because I'm happy
People, groups & messages
Chats
Calls
Settings
Help and feedback
Report a problem
Sign out
RECENT CHATS
Besties
10/10/2018
EN
Elena Nilsson, Anna Davie...
7/27/2018
It was great talking to all of ...
Anna Davies
6/26/2018
coffee awaits!
Maarten Smenk
5/25/2018
Missed call
MS
Maarten Smenk, Anna Dav...
5/21/2018
Hi, happy Monday!

Speaker notes

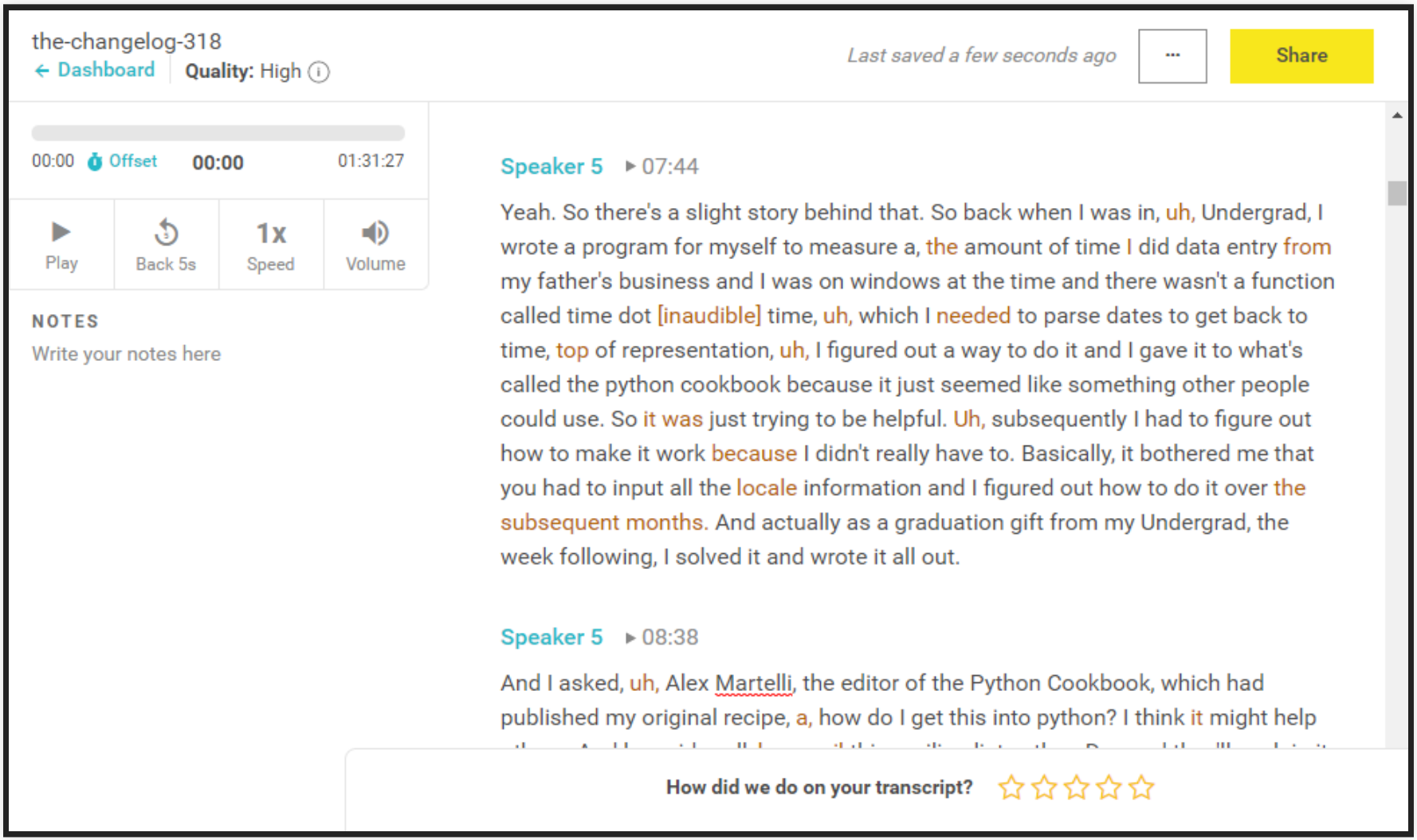
Expect only sparse feedback and expect negative feedback over-proportionally

MANUALLY LABEL PRODUCTION SAMPLES


DFW ↔ SFO
1659 of 1687 flights
Nov 16
Advice: Watch
Learn more
Create a
Stops
nonstop
1 stop
2+ stops
Times
Take-off Dallas
Prices may fall within 7 days – Watch
Our model strongly indicates that fares will fall during the next 7 days. This forecast is based on analysis of historical price changes and is not a guarantee of future results.
Create a price alert

Speaker notes

Can just wait 7 days to see actual outcome for all predictions


the-changelog-318
← Dashboard
Quality: High
Last saved a few seconds ago
...
Share
00:00
Offset
00:00
01:31:27
Play
Back 5s
1x
Speed
Volume
NOTES
Write your notes here
Speaker 5 ▸ 07:44
Yeah. So there's a slight story behind that. So back when I was in, uh, Undergrad, I wrote a program for myself to measure a, the amount of time I did data entry from my father's business and I was on windows at the time and there wasn't a function called time dot [inaudible] time, uh, which I needed to parse dates to get back to time, top of representation, uh, I figured out a way to do it and I gave it to what's called the python cookbook because it just seemed like something other people could use. So it was just trying to be helpful. Uh, subsequently I had to figure out how to make it work because I didn't really have to. Basically, it bothered me that you had to input all the locale information and I figured out how to do it over the subsequent months. And actually as a graduation gift from my Undergrad, the week following, I solved it and wrote it all out.
Speaker 5 ▸ 08:38
And I asked, uh, Alex Martelli, the editor of the Python Cookbook, which had published my original recipe, a, how do I get this into python? I think it might help
How did we do on your transcript?

Speaker notes

Clever UI design allows users to edit transcripts. UI already highlights low-confidence words, can observe changes in editor (UI design encourages use of editor). In addition 5 star rating for telemetry.

MEASURING MODEL QUALITY WITH TELEMETRY

- Telemetry can provide insights for correctness
    - sometimes very accurate labels for real unseen data
    - sometimes only mistakes
    - sometimes indicates severity of mistakes
    - sometimes delayed
    - often just samples, may be hard to catch rare events
    - often just weak proxies for correctness
- Often sufficient to approximate precision/recall or other measures
- Mismatch to (static) evaluation set may indicate stale or unrepresentative test data
- Trend analysis can provide insights even for inaccurate proxy measures

ENGINEERING CHALLENGES FOR TELEMETRY

techradar

TRENDING Buying Guides Note 10 Best Laptops iOS 13 Best Phones

Amazon Alexa stores voice recordings for as long as it likes (and shares them too)

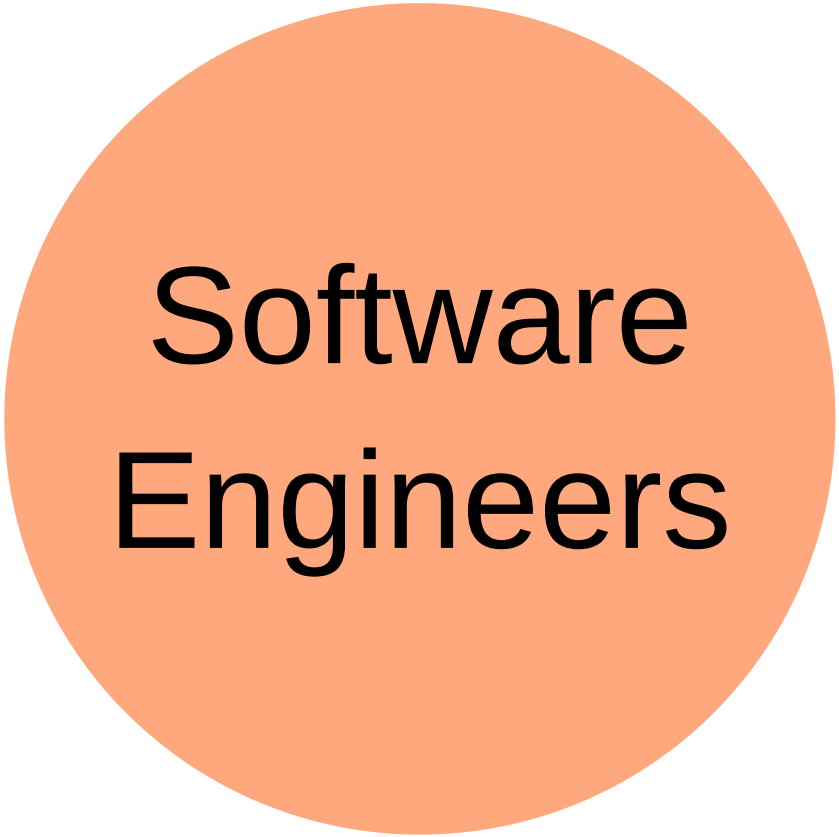
By Olivia Tambini 21 days ago Digital Home

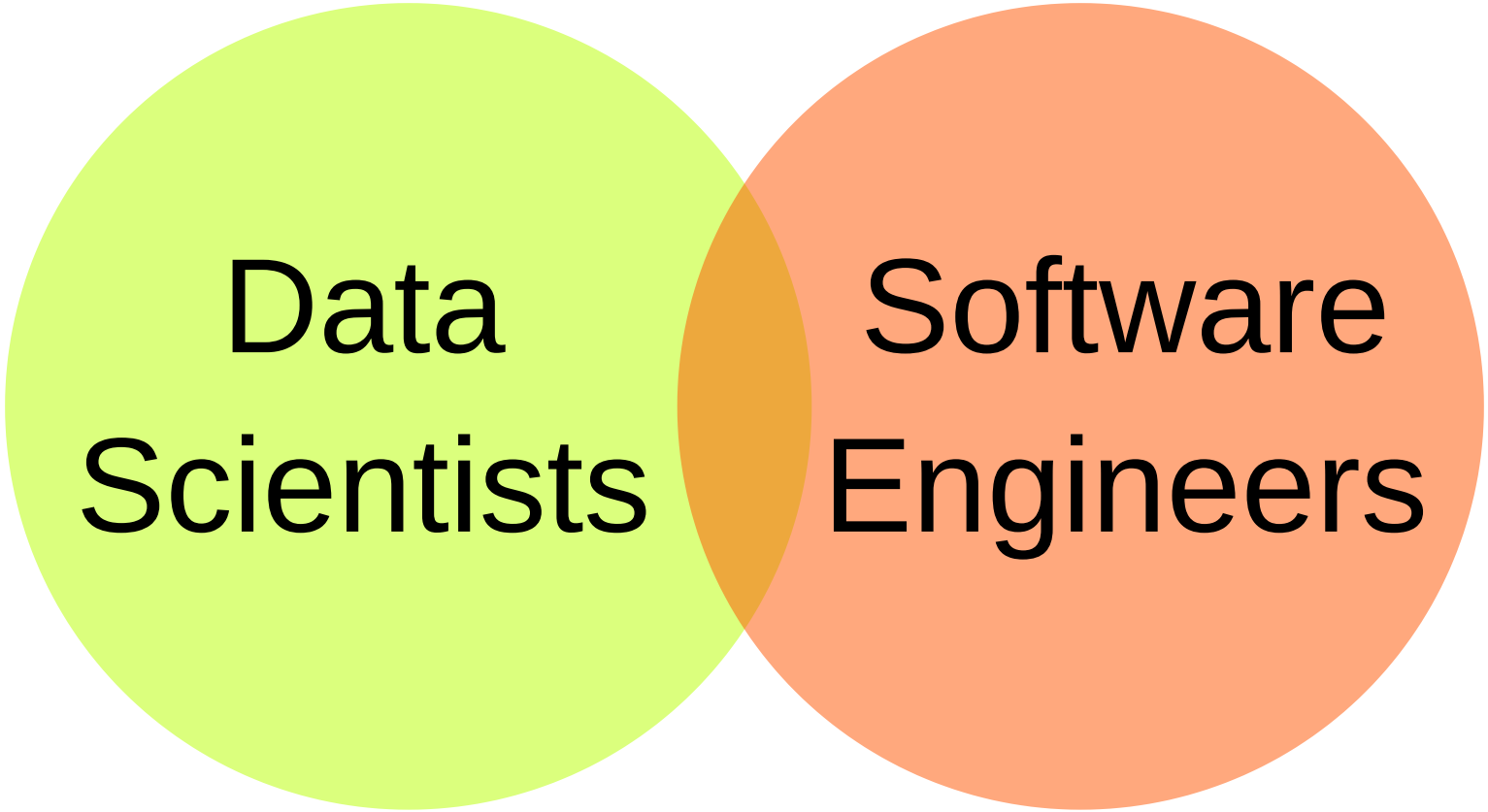
A letter from Amazon reveals all

SOFTWARE ENGINEERS BUILD SYSTEMS

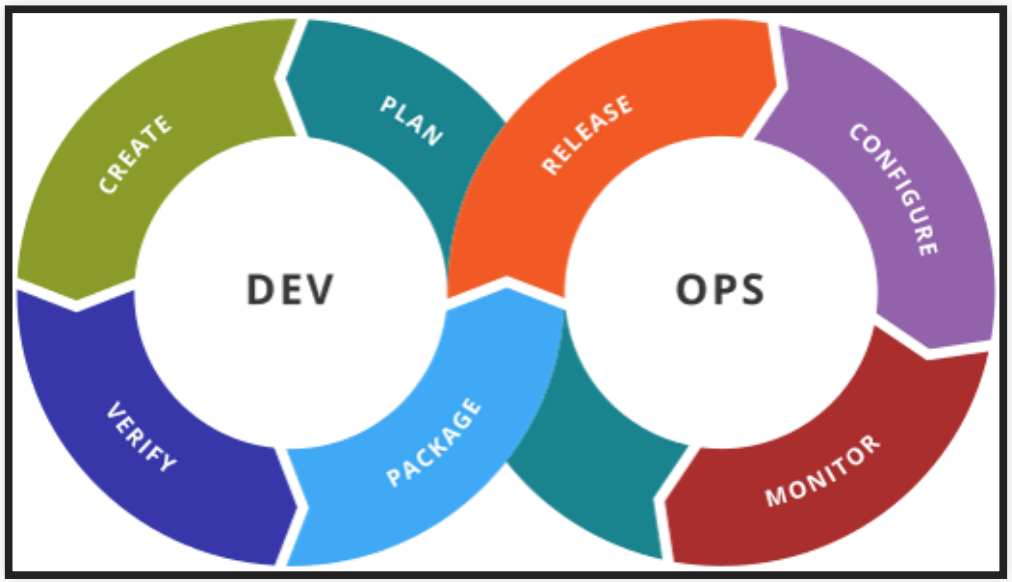
- ML model one component of a larger system
- Understanding the system goals, business case, and success measures
- Requirements and risk analysis
- Architecture, deployment, telemetry
- Automating pipelines at scale
- Continuous delivery and testing in production
- ...


Data
Scientists


Software
Engineers


Data
Scientists
Software
Engineers

LET'S LEARN FROM DEVOPS



Distinct roles and expertise, but joint responsibilities, joint tooling

TOWARD BETTER ML-SYSTEMS ENGINEERING

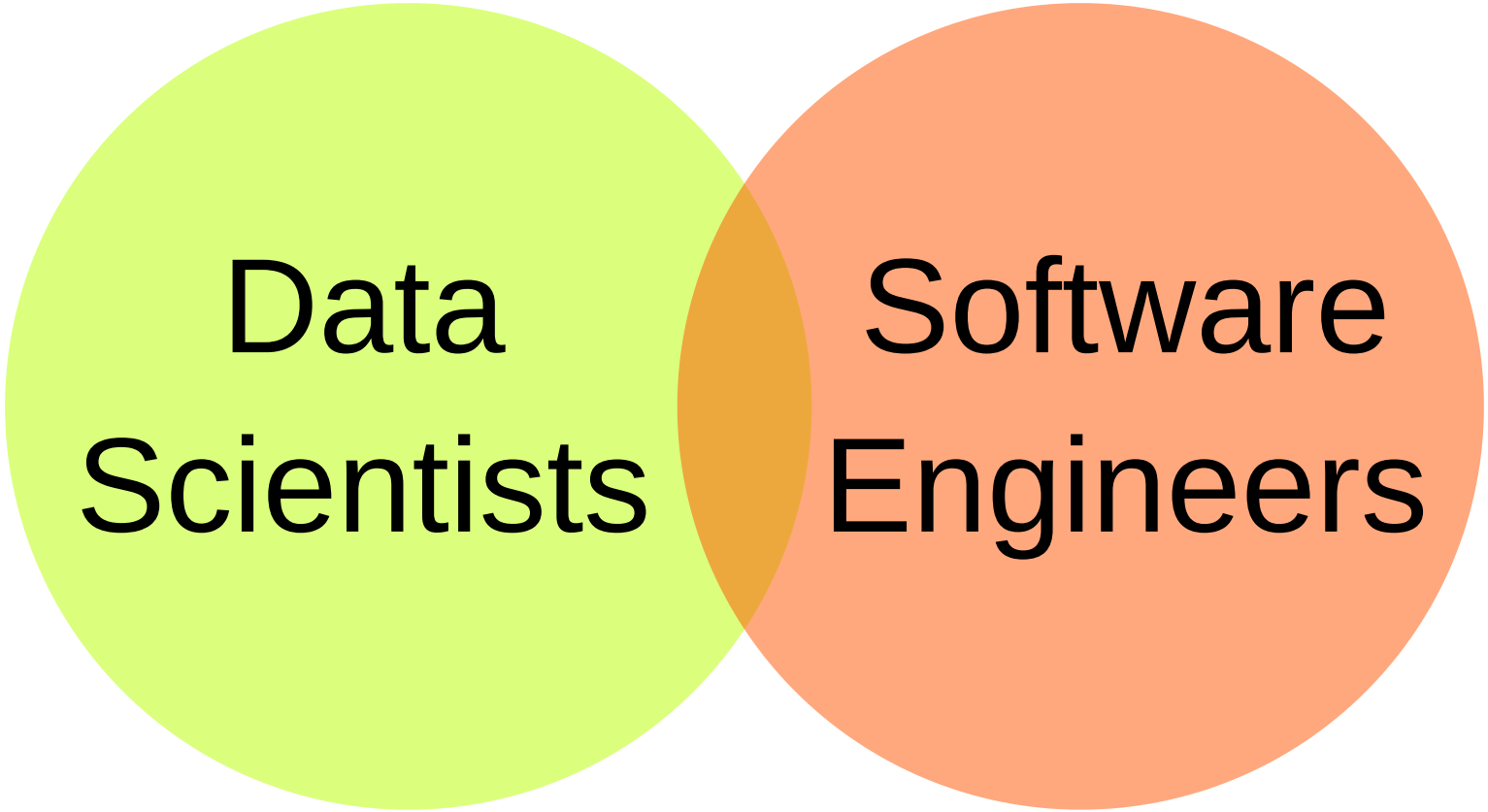
Interdisciplinary teams, split expertise, but joint responsibilities

Joint vocabulary and tools

Foster system thinking

Awareness of production quality concerns

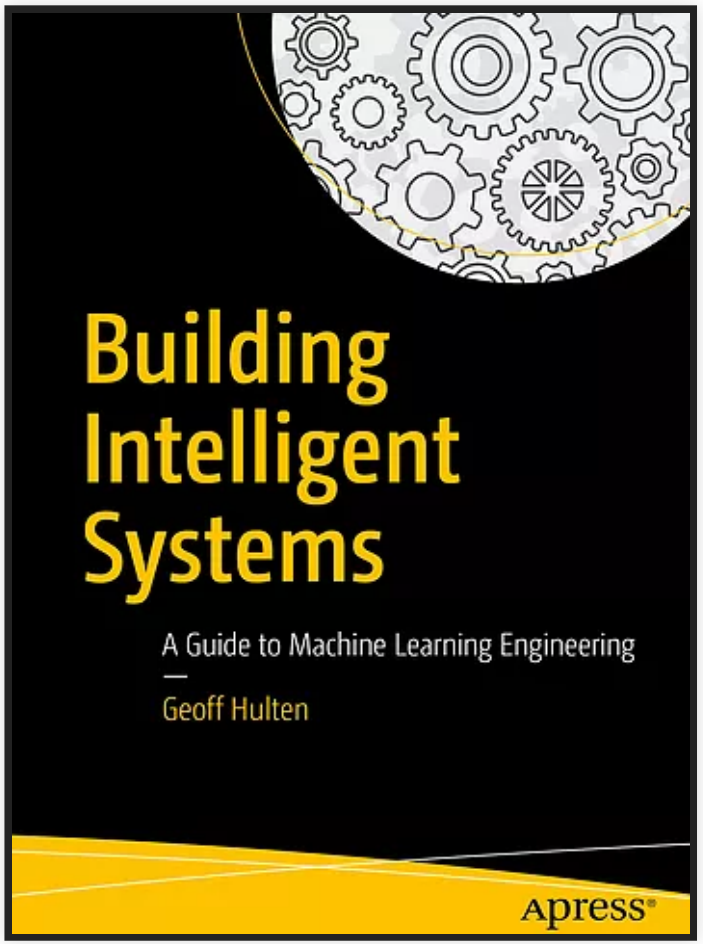
Understand goals and requirements, perform risk analysis


Data
Scientists
Software
Engineers

FURTHER READINGS

All lecture material for "Software Engineering for AI-Enabled Systems": https://ckaestne.github.io/seai/

Annotated bibliography: https://github.com/ckaestne/seaibib



SUMMARY: SOFTWARE ENGINEERING FOR ML-ENABLED SYSTEMS

- Building, operating, and maintaining systems with ML component
- Data scientists and software engineers have different expertise, both needed
- Many engineering concerns at the system level:
  - User interaction design
  - Model qualities and deployment tradeoffs
  - Risk analysis and safety
  - Telemetry design
- Interdisciplinary teams, joint vocabulary, and awareness

kaestner@cs.cmu.edu -- @p0nk -- https://ckaestne.github.io/seai/