

# SOFTWARE ENGINEERING FOR ML-ENABLED SYSTEMS

Christian Kästner

@p0nk

<https://github.com/ckaestne/seai>



# CHRISTIAN KÄSTNER

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Associate Professor @ CMU

Interests:

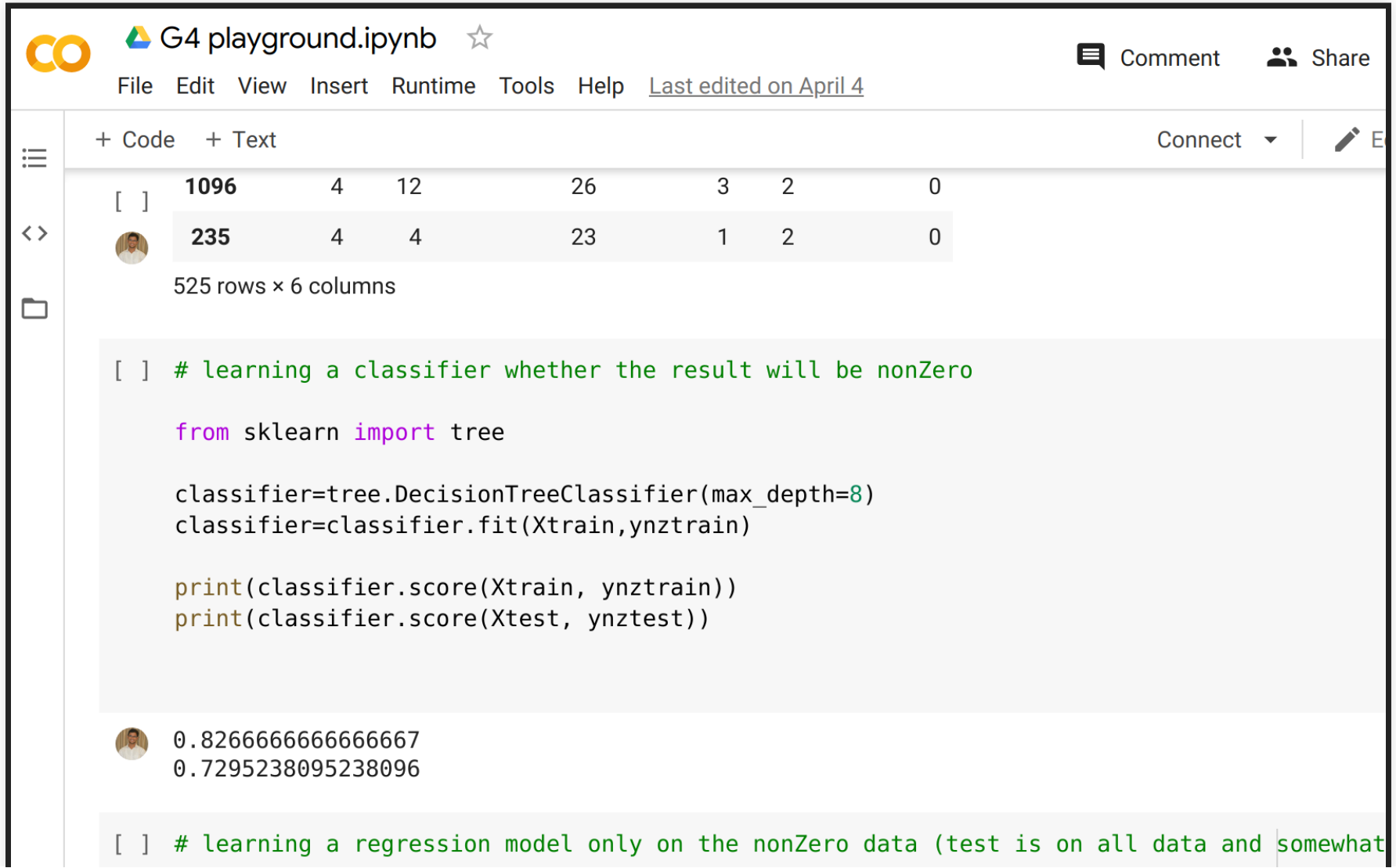
- Software Engineering
- Highly-Configurable Systems & Configuration Engineering
- Sustainability and Stress in Open Source
- Software Engineering for ML-Enabled Systems

# 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



The screenshot shows a Jupyter Notebook interface with the following elements:

- Header:** "G4 playground.ipynb" with a star icon, "Comment", and "Share" buttons.
- Menu:** File, Edit, View, Insert, Runtime, Tools, Help. A status bar indicates "Last edited on April 4".
- Left Sidebar:** Contains icons for a menu, expand/collapse, and a file explorer.
- Code Cell:**
  - Buttons: "+ Code", "+ Text", "Connect", and a pencil icon.
  - Output: A data preview showing the first two rows of a 525x6 dataset. The first row has a value of 1096, and the second row has a value of 235. The text "525 rows x 6 columns" is displayed below the preview.
  - Code:

```
[ ] # learning a classifier whether the result will be nonZero

from sklearn import tree

classifier=tree.DecisionTreeClassifier(max_depth=8)
classifier=classifier.fit(Xtrain, ynztrain)

print(classifier.score(Xtrain, ynztrain))
print(classifier.score(Xtest, ynztest))
```
  - Output: The results of the classifier's score calculations:

```
0.8266666666666667
0.7295238095238096
```
  - Next Code Cell (partially visible):

```
[ ] # 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
```

# SE FOR ML-ENABLED SYSTEMS != CODING ML FRAMEWORKS





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

```
1 import numpy as np
```

```
2
```

```
3 start = -1
```

```
4 stop = 1
```

```
5
```

```
6 x = np.linspace
```

f	linspace	function
---	----------	----------


f	linspace(start, stop)	function
---	-----------------------	----------

f	linspace(stop, start)	function
---	-----------------------	----------

f	linspace(start, stop, sto...	function
---	------------------------------	----------



# **SE FOR ML-ENABLED (AI-ML-BASED, ML-INFUSED) SYSTEMS**

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

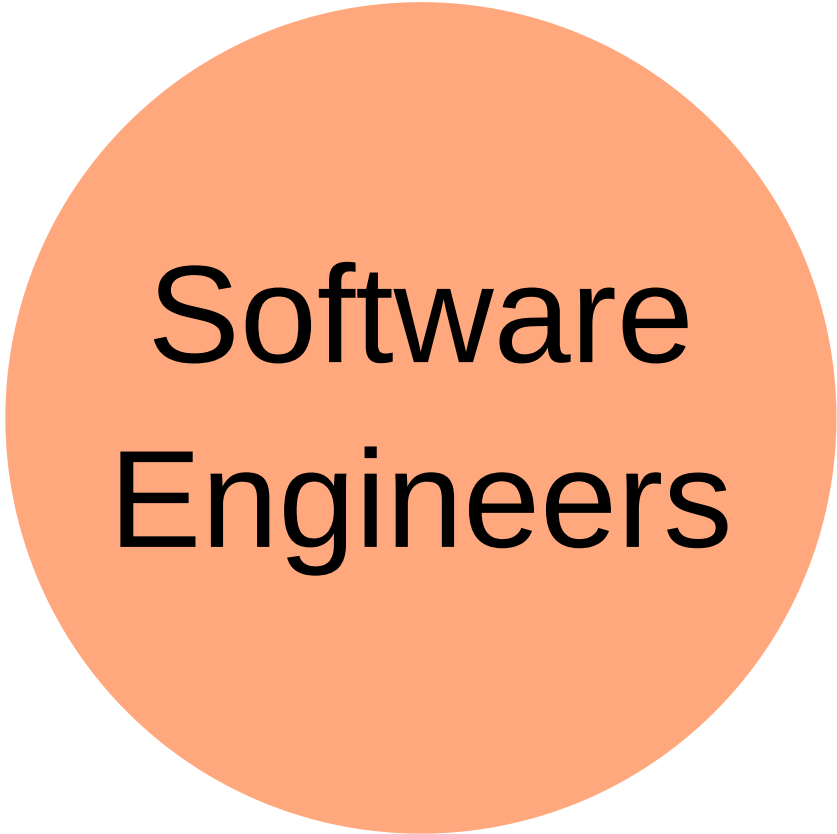
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How did we do on your transcript? ☆☆☆☆☆

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..."**

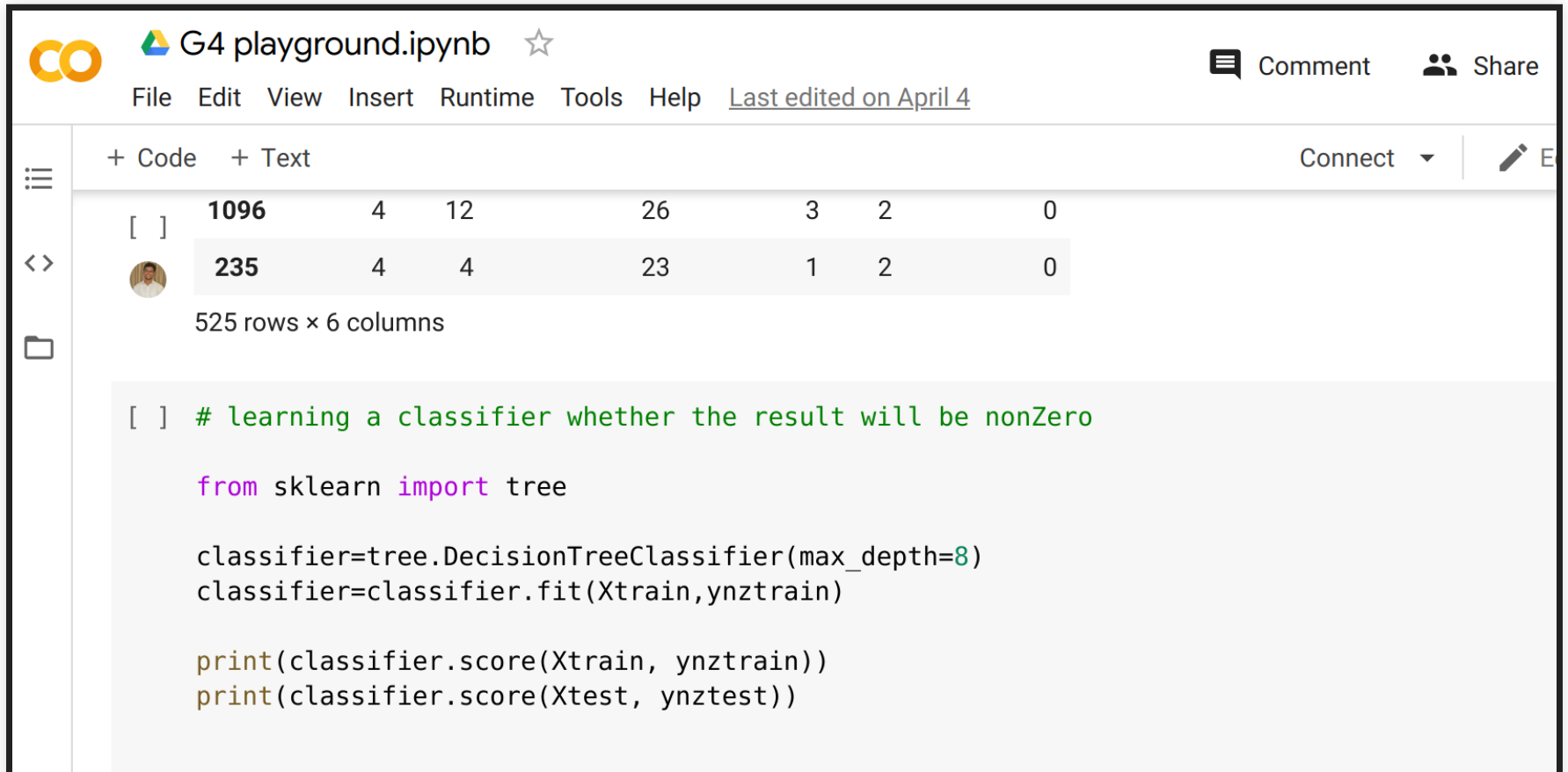
Mary Shaw. ed. [Software Engineering for the 21st Century: A basis for rethinking the curriculum](#). 2005.

# 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



The screenshot shows a Jupyter Notebook interface with the title "G4 playground.ipynb". The top bar includes a menu (File, Edit, View, Insert, Runtime, Tools, Help) and a status bar indicating "Last edited on April 4". On the right, there are buttons for "Comment" and "Share".

The notebook content is divided into two sections: "Code" and "Text". The "Code" section displays a dataset preview with the following data:

	1096	4	12	26	3	2	0
[ ]	235	4	4	23	1	2	0

Below the preview, it indicates "525 rows x 6 columns".

The "Text" section contains a code cell with the following Python code:

```
[ ] # learning a classifier whether the result will be nonZero

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classifier=tree.DecisionTreeClassifier(max_depth=8)
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print(predictor.score(Xtest, ytest))
```



0.9376379365613154  
-2.437397740412892

# DATA SCIENTIST

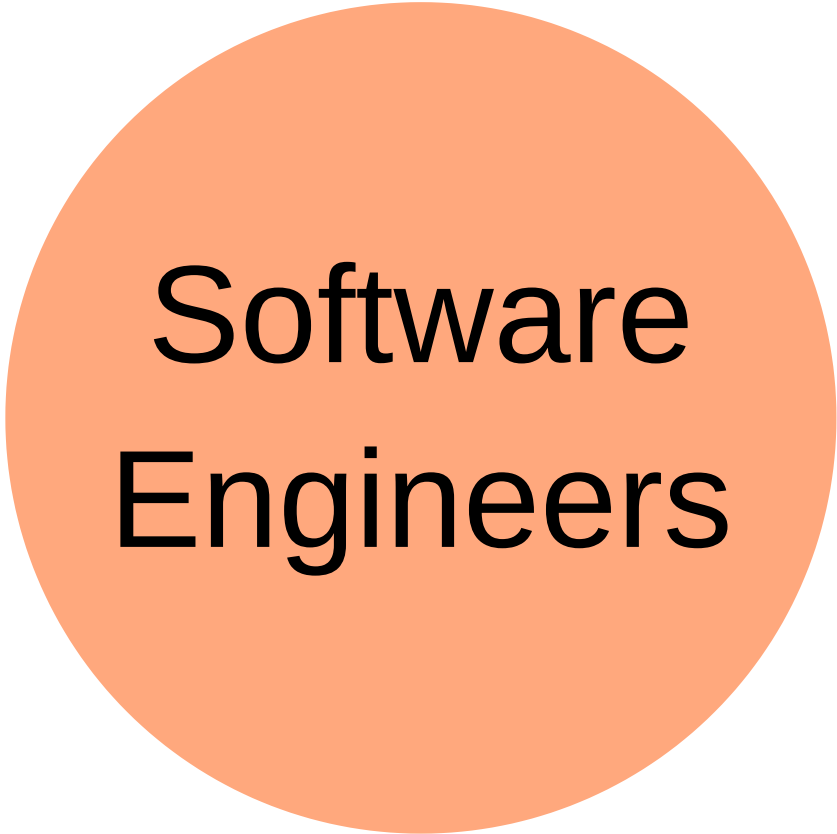
- Often fixed dataset for training and evaluation (e.g., PBS interviews)
- Focused on accuracy
- Prototyping, often Jupyter notebooks or similar
- Expert in modeling techniques and feature engineering
- Model size, updateability, implementation stability typically does not matter
- Starting to worry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



the-changelog-318


[← Dashboard](#)

Quality: High ⓘ

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...

Share

00:00  Offset 00:00 01:31:27



Play



Back 5s

1x

Speed



Volume

## NOTES

Write your notes here

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How did we do on your transcript?



# A SOFTWARE ENGINEERING PERSPECTIVE ON ML

# WHAT'S DIFFERENT?

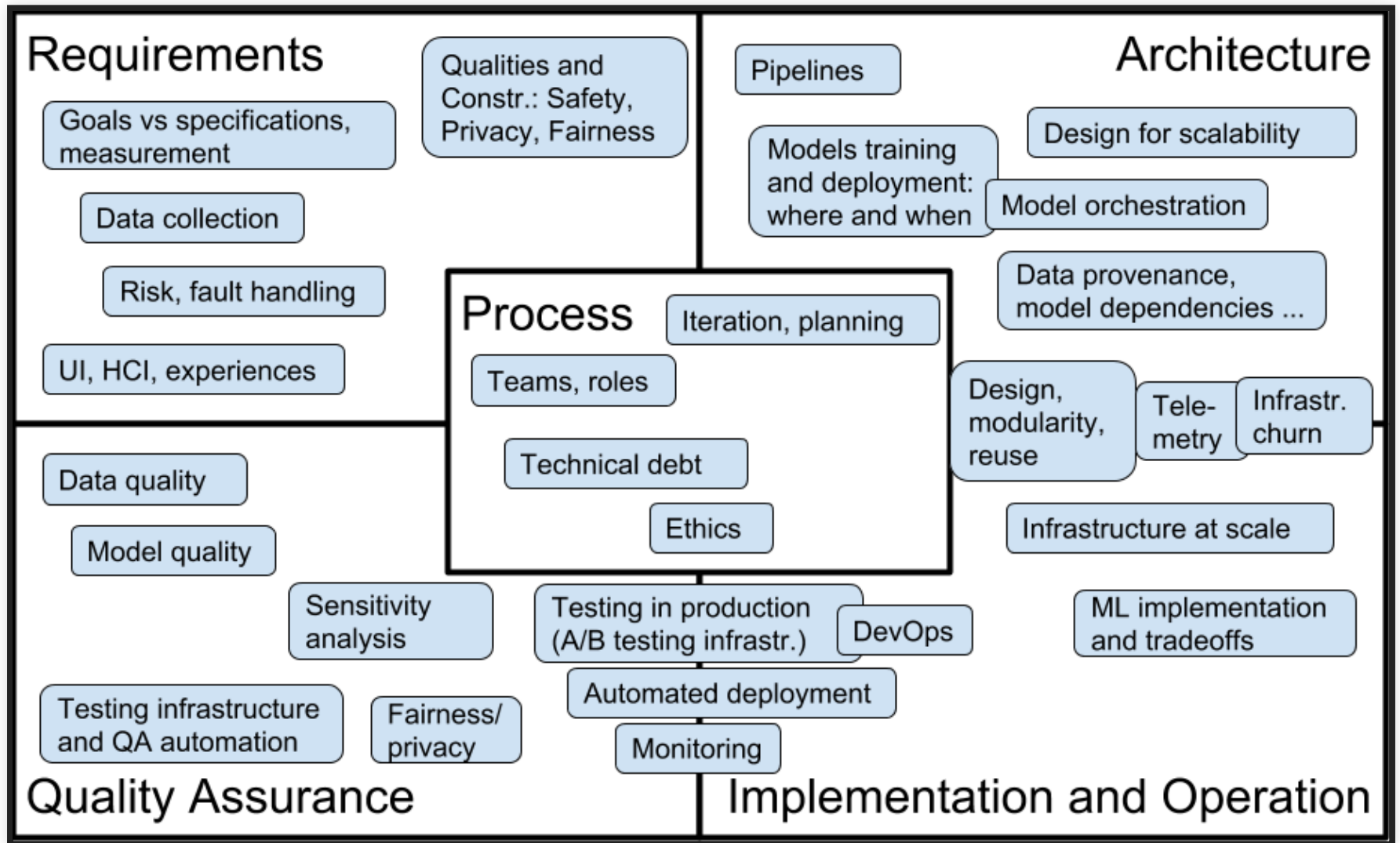
- Missing specifications
- Environment is important (feedback loops, data drift)
- Nonlocal and nonmonotonic effects
- Testing in production
- Data management, versioning, and provenance

# REALLY DIFFERENT?

- Missing specifications -- *implicit, vague specs very common; safe systems from unreliable components* ("ML is requirements engineering")
- Environment is important -- *the world vs the machine* (paper)
- 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

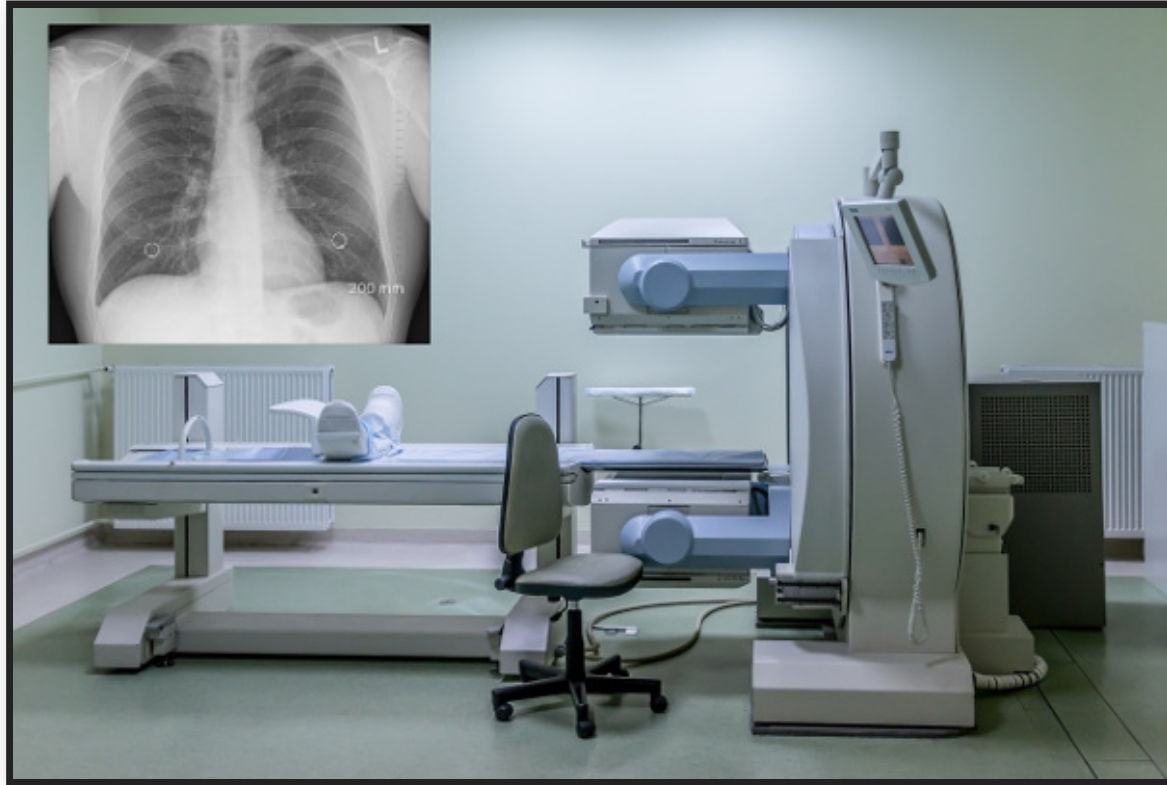
*While developers of simple traditional systems may get away with poor practices, most developers of ML-enabled systems will not.*



# **QUALITY ASSURANCE FOR ML-ENABLED SYSTEMS**

# TRADITIONAL FOCUS: MODEL ACCURACY

- Train and evaluate model on fixed labeled data set
- Compare prediction with labels



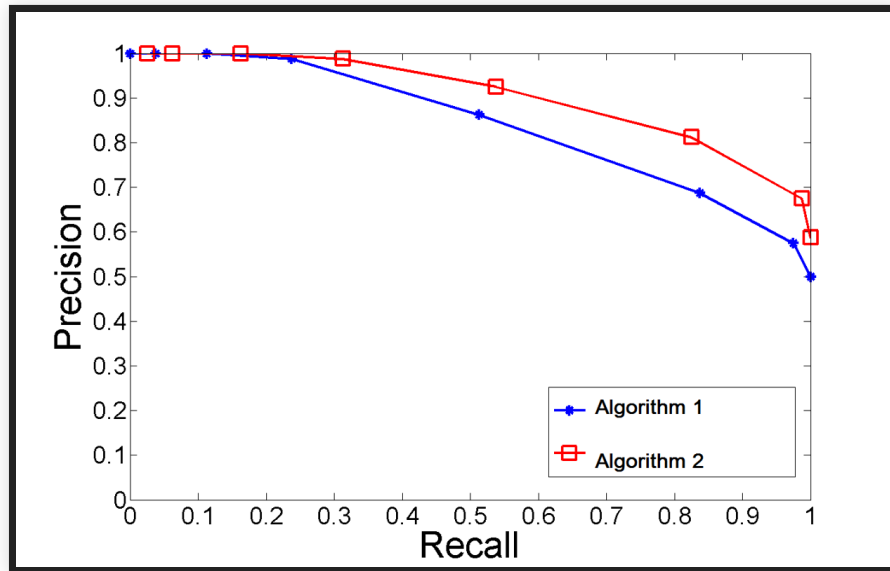
# TRADITIONAL FOCUS: MODEL ACCURACY

	Actually A	Actually not A
AI predicts A	True Positive (TP)	False Positive (FP)
AI predicts not A	False Negative (FN)	True Negative (TN)

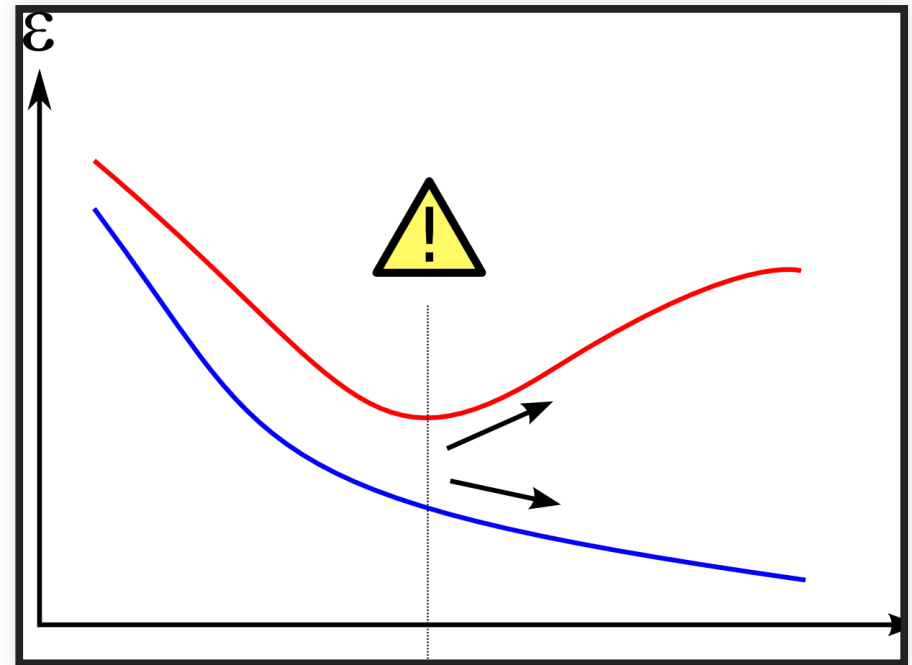
Accuracy, Recall, Precision, F1-Score

# MORE TRADITIONAL MODEL QUALITY DISCUSSIONS

Many model quality metrics (recall, MAPE, ROC, log loss, top-k, ...)



Generalization/overfitting (train/test/eval split, crossvalidation)



(CC SA 3.0 by [Dake](#))

# NOT ALL MISTAKES ARE EQUAL

- False positives vs false negatives (e.g., cancer detection)
- Fairness across subpopulations
- Learn from black-box testing:
  - Equivalence classes
  - Boundary conditions
  - Critical test cases ("call mom")
  - Combinatorial testing
  - Fuzzing

# AUTOMATING MODEL EVALUATION

- Continuous integration, automated measurement, tracking of results
- Data and model versioning, provenance



← 2017-08-19-06-29-22-855-UTC

SUMMARY

DEPLOY

RETRAIN



PERFORMANCE

MODEL VIS

FEATURES

## Test Data Performance

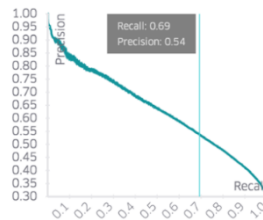
threshold 0.0584 0.288 0.925

0.7936

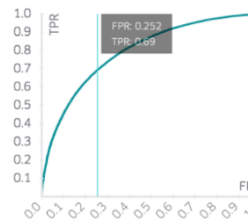
auc

performance

Precision-Recall



ROC



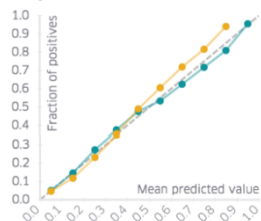
Confusion Matrix

Positive label: true

		Predicted	
		YES	NO
Actual	YES	TP 0.21 17604 Samples	FN 0.093 7891 Samples
	NO	FP 0.18 15005 Samples	TN 0.52 44549 Samples

calibration

reliability



The reliability diagram shows how reliable (or "well-calibrated") the model's probability estimates are when evaluated on the test data. For example, A well calibrated (binary) model should classify the samples such that among the samples to which it gives a probability close to 0.8 of belonging to the positive class, approximately 80% of those samples actually belong to the positive class. [More info](#)

data

# QUALITY CONCERNS FOR ML-ENABLED SYSTEMS

- Learning time, cost and scalability
- Update cost, incremental learning
- Inference cost
- Size of models learned
- Amount of training data needed
- Fairness
- Robustness
- Safety, security, privacy
- Explainability, reproducibility
- Time to market
- Overall operating cost (cost per prediction)



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← [Dashboard](#)

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## NOTES

Write your notes here

Speaker 5 ▶ 07:44

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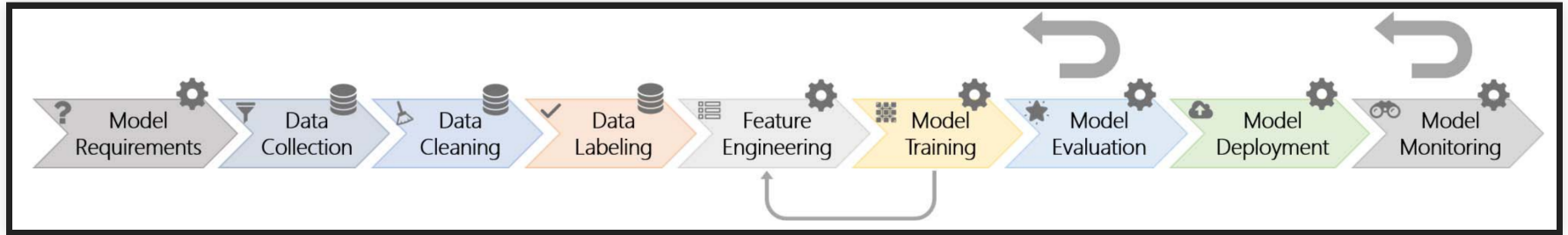
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How did we do on your transcript?



# INFRASTRUCTURE QUALITY

# THINK OF PIPELINES, NOT MODELS, NOT NOTEBOOKS



Many steps: Data collection, data cleaning, labeling, feature engineering, training, evaluation, deployment, monitoring

Automate each step -- test each step

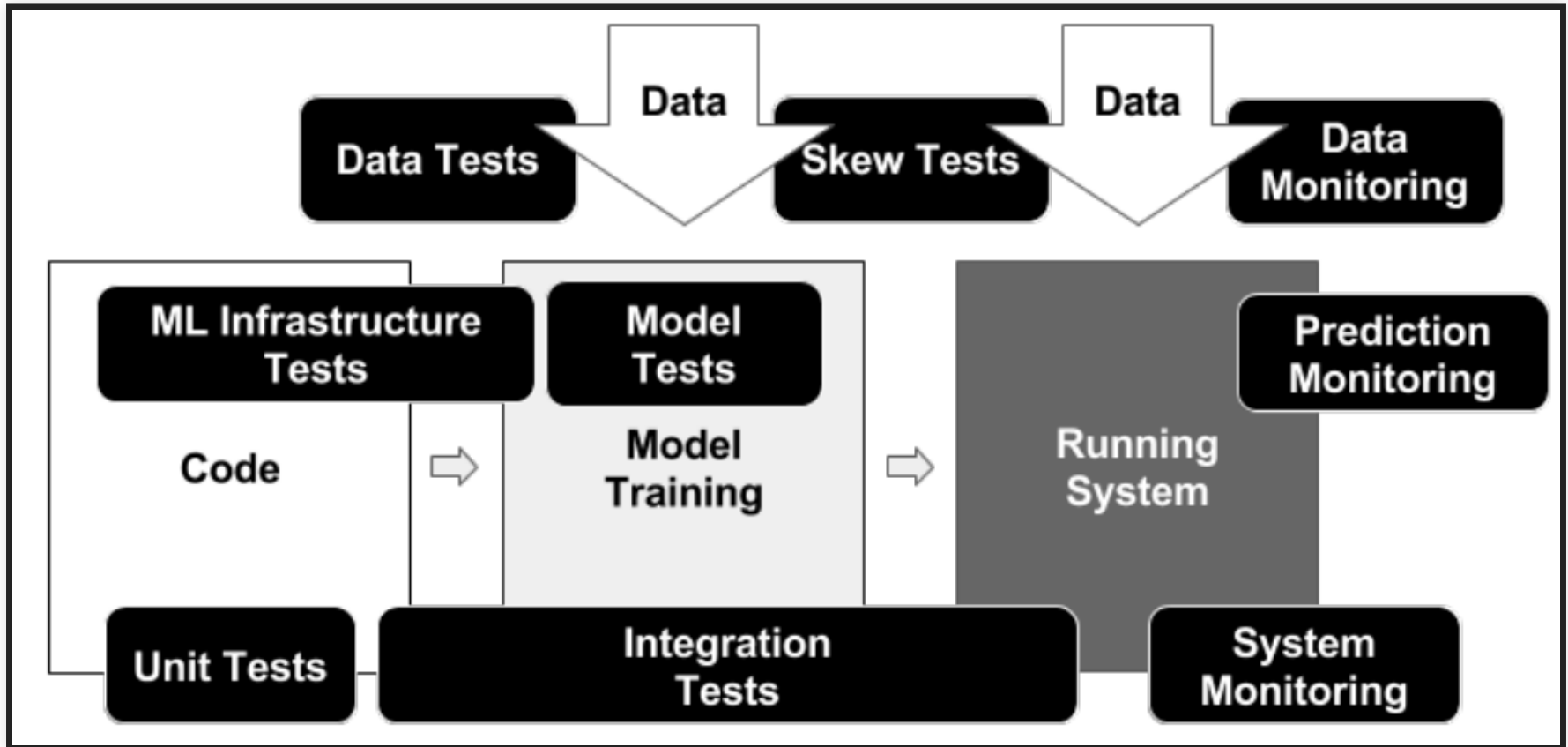
Graphic: Amershi, Saleema, Andrew Begel, Christian Bird, Robert DeLine, Harald Gall, Ece Kamar, Nachiappan Nagappan, Besmira Nushi, and Thomas Zimmermann. "[Software engineering for machine learning: A case study.](#)" In 2019 IEEE/ACM 41st International Conference on Software Engineering: Software Engineering in Practice (ICSE-SEIP), pp. 291-300. IEEE, 2019.

# POSSIBLE MISTAKES IN ML PIPELINES

Danger of "silent" mistakes in many phases:

- Dropped data after format changes
- Failure to push updated model into production
- Incorrect feature extraction
- Use of stale dataset, wrong data source
- Data source no longer available (e.g web API)
- Telemetry server overloaded
- Negative feedback (telemtr.) no longer sent from app
- Use of old model learning code, stale hyperparameter
- Data format changes between ML pipeline steps
- ...

# QUALITY ASSURANCE FOR THE ENTIRE PIPELINE



Source: Eric Breck, Shanqing Cai, Eric Nielsen, Michael Salib, D. Sculley. [The ML Test Score: A Rubric for ML Production Readiness and Technical Debt Reduction](#). Proceedings of IEEE Big Data (2017)

# PIPELINE TESTING

- Unit tests (e.g., data cleaning)
- End to end pipeline tests
- Testing with stubs, test error handling (e.g., test model redeployment after dropped connection)
- Test monitoring infrastructure (e.g., "fire drills")

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[← Dashboard](#)

Quality: High ⓘ

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# THINKING OF THE ENTIRE SYSTEM

*ML models are "just" one component*



# LIVING WITH MISTAKES

*The smart toaster may occasionally burn my toast, but it should not burn down my kitchen.*





## Speaker notes

A smart toaster may occasionally burn the toast, but it should never burn down the kitchen. The latter can be achieved without relying on perfect accuracy of a smart component, just stop it when it's overheating.

Plan for mistakes: User interaction, undo, safeguards

# MODEL ACCURACY VS SYSTEM GOALS

- System goals are supported by AI components, e.g.,
  - maximizing sales
  - minimizing loss
  - maximizing community growth
  - retaining customers
  - maximizing engagement time
- A better model will support system goals better
  - more accurate
  - faster answers
  - fewer bad mistakes
  - more explainable
  - easier to evolve

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← Dashboard

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# TESTING IN PRODUCTION

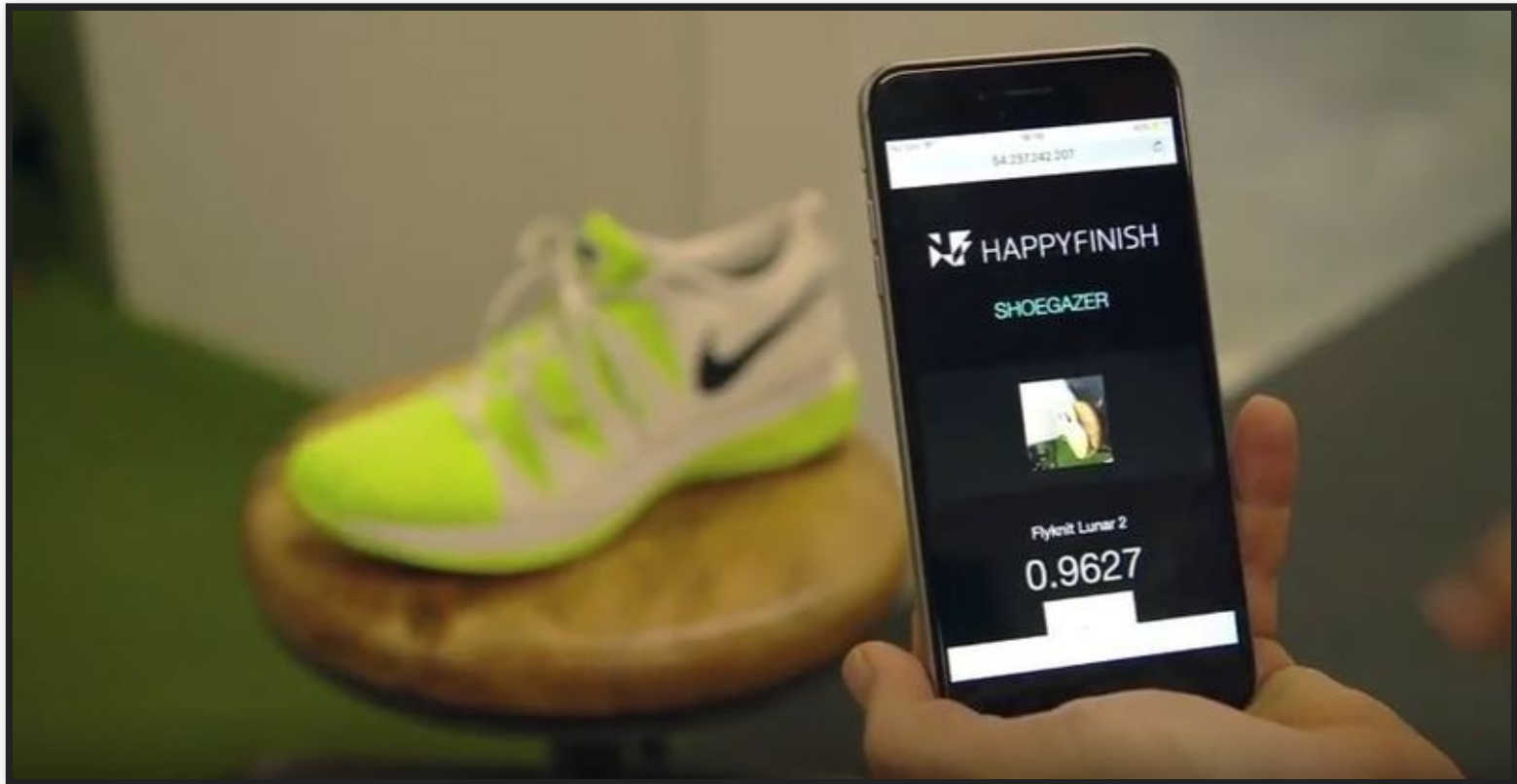
*Production data = ultimate unseen data*

Focus on system goals, not model accuracy

Monitoring performance over time, canary releases

Finding and debugging common mistakes

Experimentation with A/B tests



Source: <https://www.trendhunter.com/trends/shoegazer>

# KEY DESIGN CHALLENGE: TELEMETRY

- Identify mistakes in production (“what would have been the right prediction?”)
- Many challenges:
  - 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?



# TELEMETRY DESIGN EXAMPLES

- Was there actually cancer in a scan?
- Did we identify the right soccer player?
- Did we correctly identify tanks?
- Was a Youtube recommendation good?
- Was the ranking of search results good?
- Was the weather prediction good?
- Was the translation correct?
- Did the self-driving car break at the right moment?

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

blog post demo

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Matt Millman  
Because I'm happy 😊

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### RECENT CHATS

- Besties 10/10/2018
- 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
- 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

Wednesday

Advice: **Watch** [Learn more](#) ⓘ

Create a price alert

### Stops

- ☒ nonstop
- ☒ 1 stop
- ☒ 2+ stops

### Times

Take-off Dallas

Mon 11:58 AM - 12:33 PM

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 ⓘ

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## 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

# MONITORING MODEL QUALITY IN PRODUCTION

- Watch for jumps after releases
  - roll back after negative jump
- Watch for slow degradation
  - Stale models, data drift, feedback loops, adversaries
- Debug common or important problems
  - Mistakes uniform across populations?
  - Challenging problems -> refine training, add regression tests

# ENGINEERING CHALLENGES FOR TELEMETRY

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)

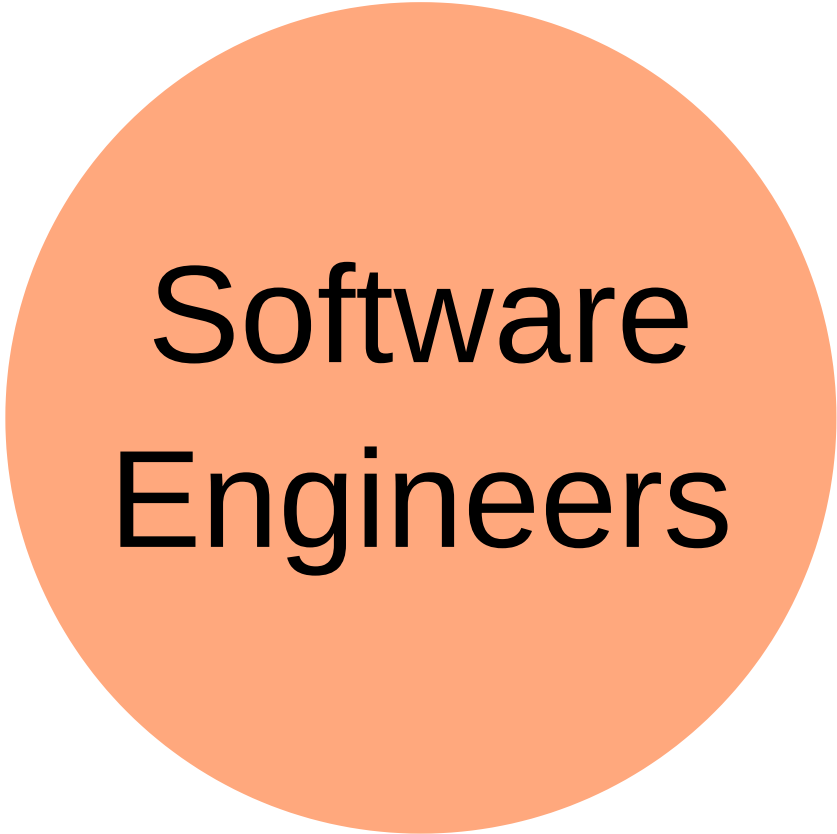
By Olivia Tambini 21 days ago Digital Home

A letter from Amazon reveals all





**Data  
Scientists**



**Software  
Engineers**

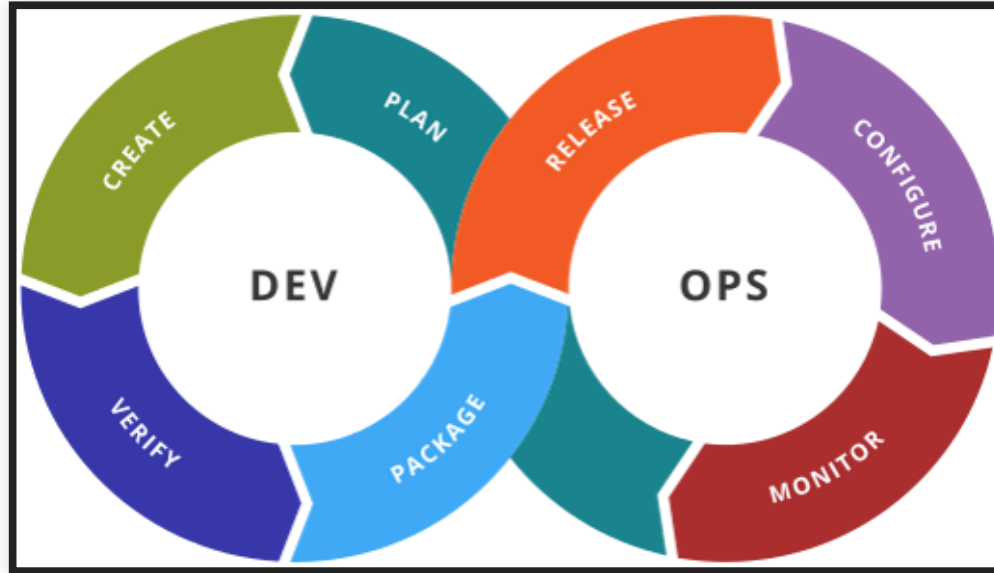


A Venn diagram consisting of two overlapping circles. The left circle is light green and contains the text 'Data Scientists'. The right circle is light orange and contains the text 'Software Engineers'. The overlapping area in the center is a darker shade of orange.

**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

Perform risk + hazard analysis





A Venn diagram consisting of two overlapping circles. The left circle is light green and contains the text 'Data Scientists'. The right circle is light orange and contains the text 'Software Engineers'. The overlapping area in the center is a darker shade of orange.

**Data  
Scientists**

**Software  
Engineers**

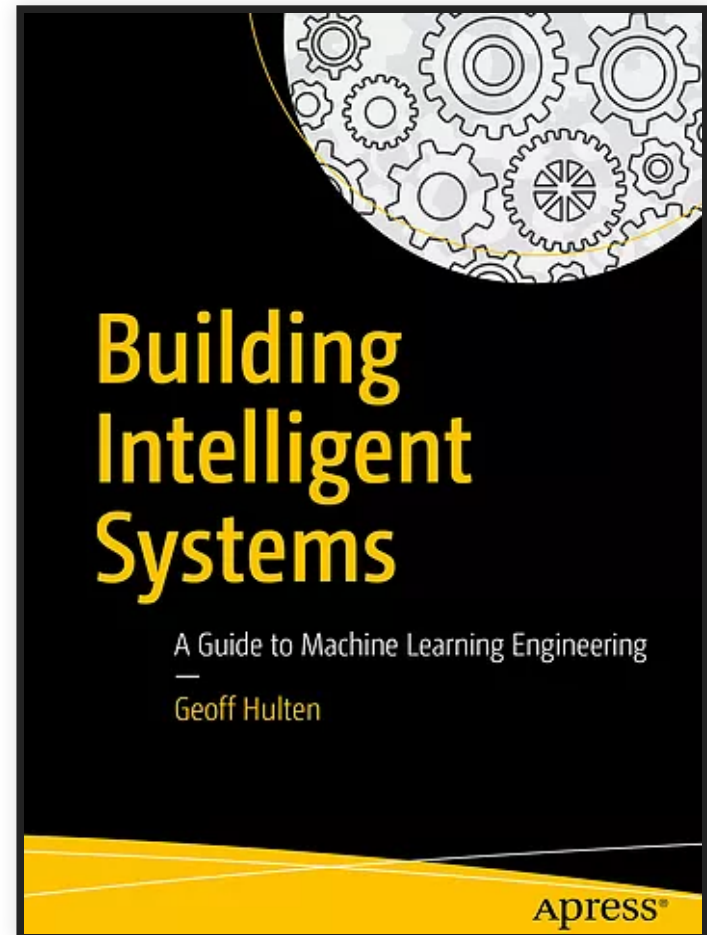
# READINGS

All lecture material:

<https://github.com/ckaestne/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
- Quality assurance beyond model accuracy
  - Blackbox testing, test automation
  - Testing the entire ML pipeline
  - Consider whole system
  - Testing in production with telemetry
- Interdisciplinary teams, joint vocabulary, and awareness

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