



Machine Learning in Production From Models to Systems

Administrativa

- Follow up on syllabus discussion:
 - When not feeling well -- please stay home and get well, and email us for accommodation
 - When using generative AI to generate responses (or email/slack messages) -- please ask it to be brief and to the point!
- Remember to post introduction to #social if you haven't yet

Learning goals

- Understand how ML components are a (small or large) part of a larger system
- Explain how machine learning fits into the larger picture of building and maintaining production systems
- Define system goals and map them to goals for ML components
- Describe the typical components relating to AI in an AI-enabled system and typical design decisions to be made

Required Readings

- Chapters 4 (Goals), 5 (Components), and 7 (Experiences) from the book "Building Intelligent Systems: A Guide to Machine Learning Engineering" by Hulten

ML Models as Part of a System

Example: Image Captioning Problem



Example: Image Captioning Problem



Why do we care about image captioning?



Machine learning as (small) component in a system

Your Audit Risk Results

YOUR AUDIT RISK IS LOW

A horizontal color scale representing audit risk. The scale is a gradient from green on the left to red on the right. A vertical slider bar is positioned on the left side of the scale, pointing towards the green end. The words "LOW" are on the far left and "HIGH" are on the far right. The text "YOUR AUDIT RISK IS LOW" is centered above the scale.

LOW HIGH

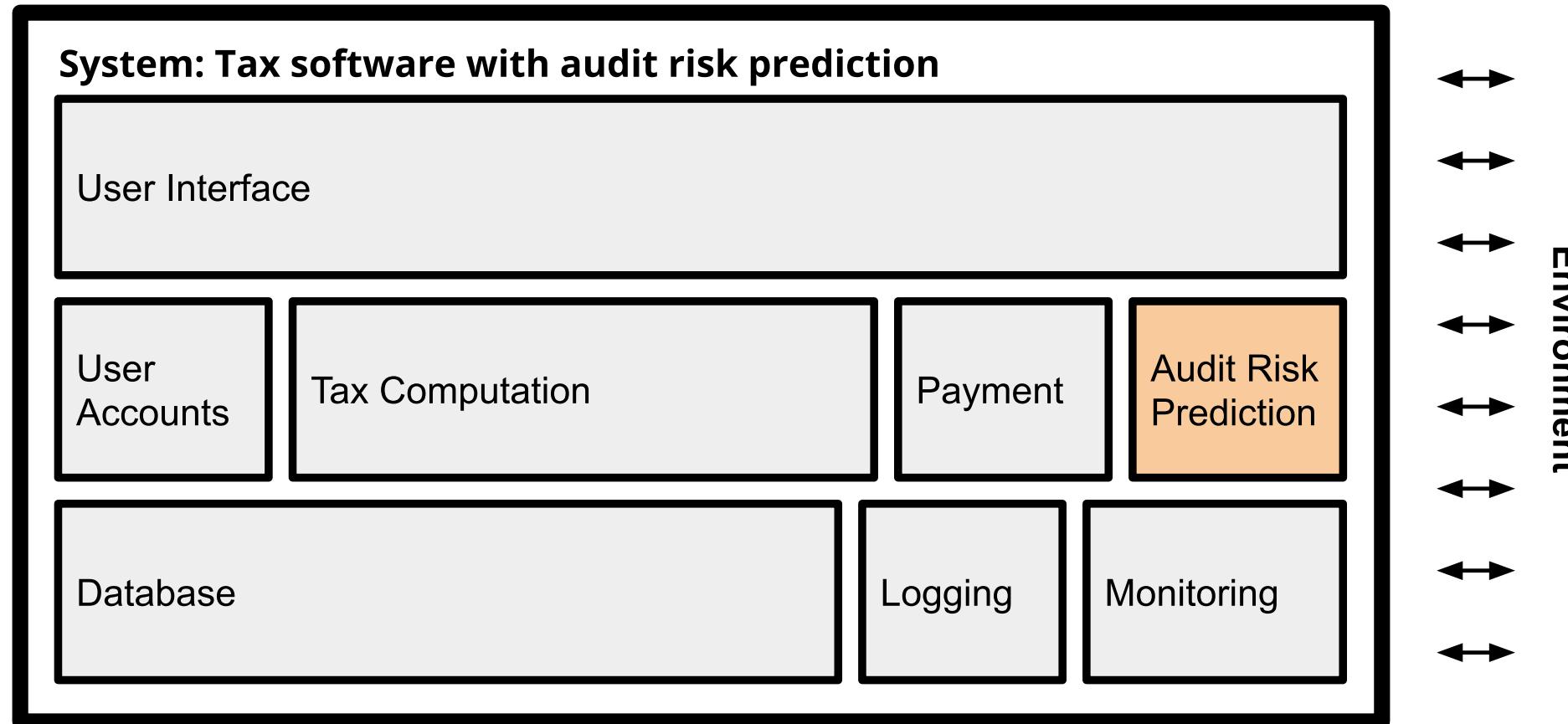
Great news! There's nothing to worry about. We didn't find anything in your return that we consider a typical audit trigger, which means you're in good shape. Plus, we've also got you covered with our [free Audit Support Guarantee](#).

Speaker notes

Traditional non-ML tax software, with an added ML component for audit risk estimation



Machine learning as (small) component in a system



Legend: Non-ML component, ML component, system boundary

Machine learning as (core) component in a system

The screenshot displays the SUNO app's user interface. At the top left is the SUNO logo. Below it, the "Suno Showcase" section features a grid of six video thumbnails, each with a play button, duration, and like count. The first thumbnail shows a silhouette of a person dancing. The second shows a man's face. The third is a colorful abstract scene. The fourth shows a person DJing. The fifth shows butterflies. The sixth shows a woman in a historical-style dress. Below each thumbnail is the song title, artist, and genre. The "Trending Songs" section follows, displaying a grid of six more video thumbnails. The first thumbnail for "Just A Fling" features a woman with pink hair. The second thumbnail for "| Click! Click! Click! |" features a woman's face. The third thumbnail for "Lightheadedness" features a person in a dynamic pose. The fourth thumbnail for "Why No Pineapples o..." shows a slice of pizza. The fifth thumbnail for "The Only Way Out Is..." shows a person in a dark setting. The sixth thumbnail for "I Wish - Ft." shows a woman in a white dress. Each thumbnail includes its duration, title, and like count.

SUNO

Suno Showcase

Home Create Library Explore Search

2:33 Suno yolkhead, 3dalsy, Bru...
Ain't Got a Nickel Ain't... up tempo Memphis soul ...
2:47 Vapor of Feelings ~... Italo disco, Italo-disco, 19...
2:48 Give it to me (Suno) MrTree
Butterflies Winding, introspective, m...
3:15 Butterflies
3:23 I Can Wait haunted ma...
4:24 I Can Wait

2:33 Suno yolkhead, 3dalsy, Bru...
Ain't Got a Nickel Ain't... up tempo Memphis soul ...
2:47 Vapor of Feelings ~... Italo disco, Italo-disco, 19...
2:48 Give it to me (Suno) MrTree
Butterflies Winding, introspective, m...
3:15 Butterflies
3:23 I Can Wait

3:08 FOGGY JUST A FLING Foggy emotional female vocal, ...
| Click! Click! Click! | GIANLUCA_... Pop, Dance Pop, Etherea...
4:26 Lightheadedness Teemuth surf rock punk rock skat...
4:26 Why No Pineapples o... Zero Nanash... Catchy Instrumental intr...
3:06 The Only Way Out Is... Delta Studio Alternative Metal, 2010 ...
4:57 I Wish - Ft. Alikar Femme-Fatale

0 Credits

Subscribe

Speaker notes

Transcription service, where interface is all built around an ML component



Machine learning as (core) component in a system



Products using Object Detection?



Products using Object Detection



What if Object Detection makes a Mistake?

Products using Object Detection



What if Object Detection makes a Mistake?

Products using Image Synthesis?

an armchair in the shape of an avocado. an armchair imitating an avocado.



From <https://openai.com/blog/dall-e/>

Products using ... a Juggling Robot?



Many more examples of ML in products:

- Product recommendations on Amazon
- Surge price calculation for Uber
- Inventory planning in Walmart
- Search for new oil fields by Shell
- Adaptive cruise control in a car
- Smart app suggestion in Android
- Fashion trends prediction with social media data
- Suggesting whom to talk to in a presidential campaign
- Tracking and predicting infections in a pandemic
- Adaptively reacting to network issues by a cell phone provider
- Matching players in a computer game by skill
- ...
- Some for end users, some for employees, some for expert users
- Big and small components of a larger system
- More or less non-ML code around the model

Model-Centric vs System-Wide Focus

Traditional Model Focus (Data Science)



Focus: building models from given data, evaluating accuracy

Automating Pipelines and MLOps (ML Engineering)



Focus: experimenting, deploying, scaling training and serving, model monitoring and updating

MLOps Infrastructure



From: Sculley, David, et al. "Hidden technical debt in machine learning systems." NIPS 28 (2015).

Speaker notes

Figure from Google's 2015 technical debt paper, indicating that the amount of code for actual model training is comparably small compared to lots of infrastructure code needed to automate model training, serving, and monitoring. These days, much of this infrastructure is readily available through competing MLOps tools (e.g., serving infrastructure, feature stores, cloud resource management, monitoring).



ML-Enabled Systems (ML in Production)



Interaction of ML and non-ML components, system requirements,
user interactions, safety, collaboration, delivering products

Model vs System Goals

Case Study: Self-help legal chatbot



The image shows a screenshot of a web-based legal chatbot service. At the top left is a blue square logo containing the white text '1LAW'. Below the logo, a large blue banner displays the text 'Welcome to the future of legal services. Always available and ready to help.' in white. Underneath the banner, there is a dark grey rectangular area containing the text 'Get legal assistance online. Chat with a lawyer for free!' in white. At the bottom of this area is a blue button with the white text 'Start Free Chat'.

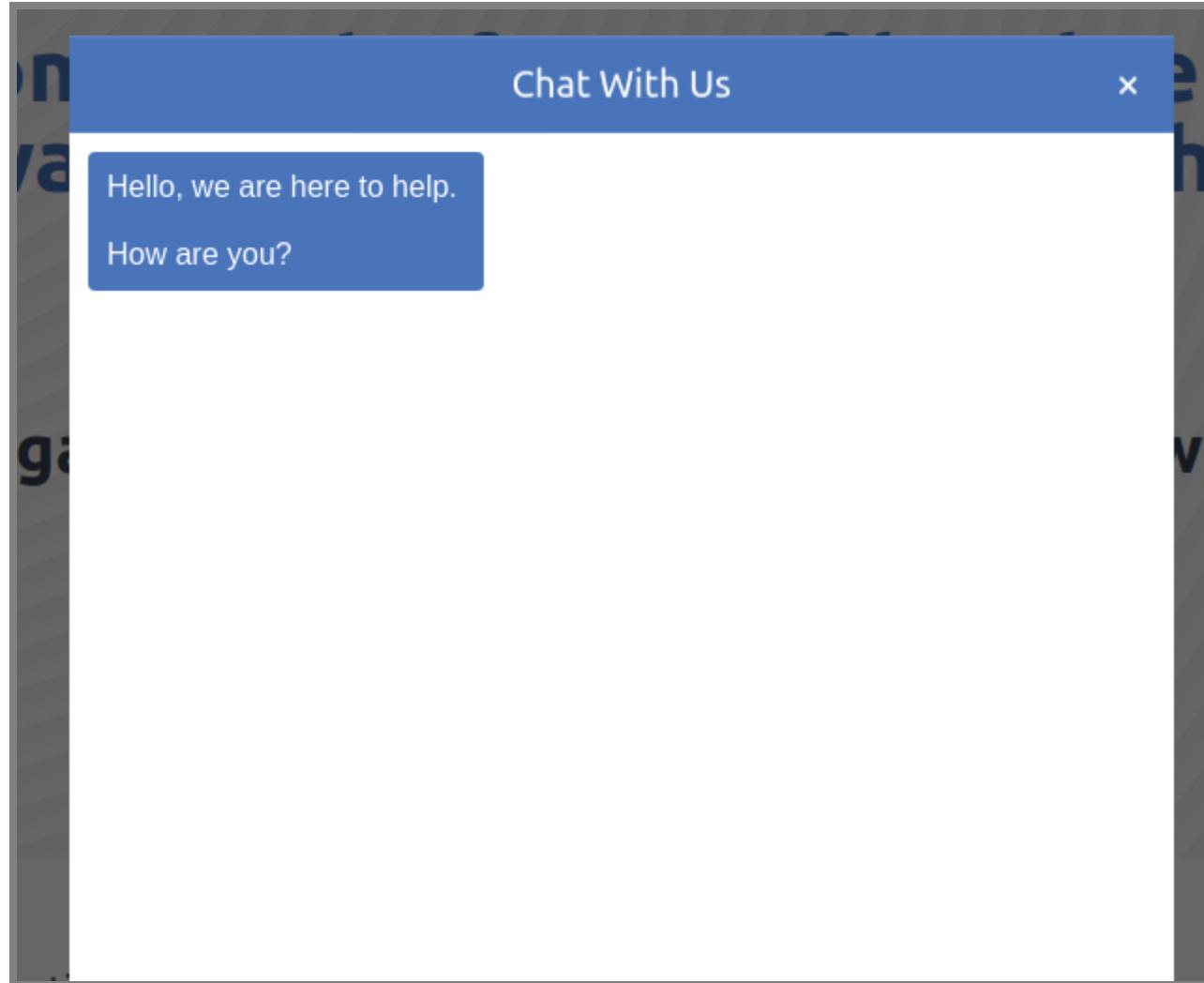
Based on the excellent paper: Passi, S., & Sengers, P. (2020). Making data science systems work. *Big Data & Society*, 7(2).

Speaker notes

Screenshots for illustration purposes, not the actual system studied



Case Study: Self-help legal chatbot



Previous System: Guided Chat

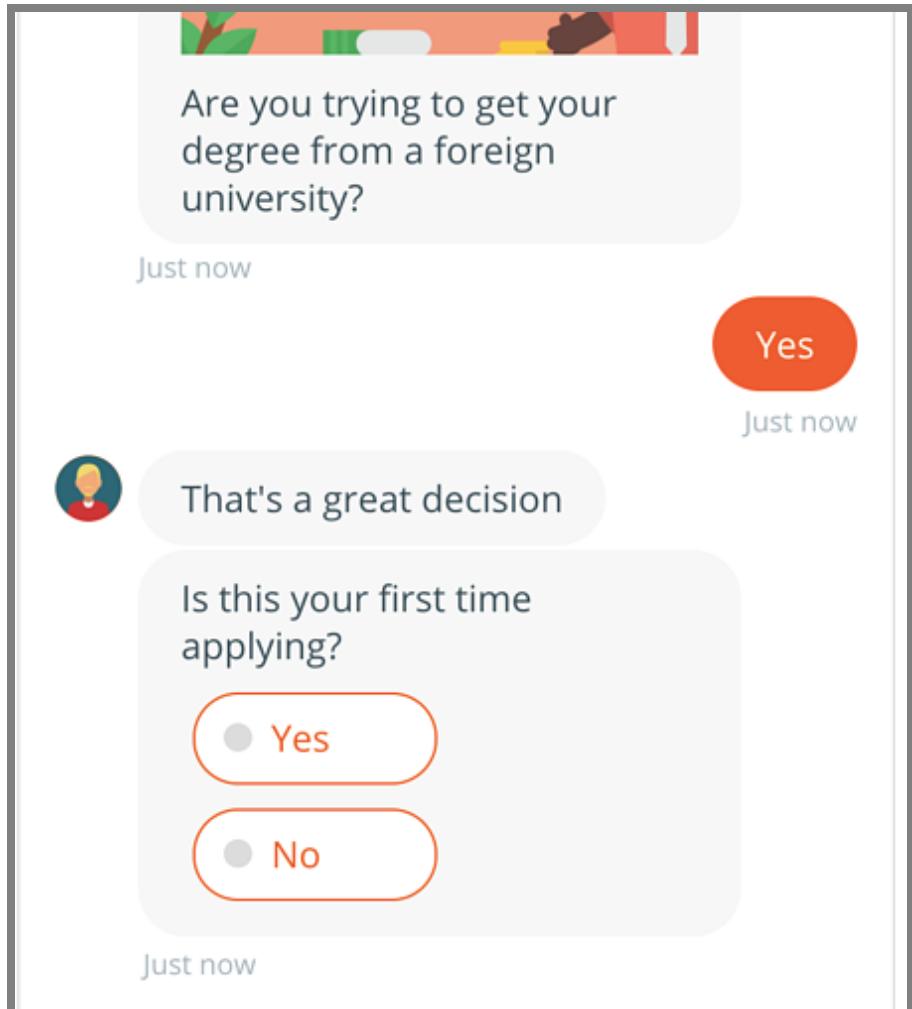


Image source: <https://www.streamcreative.com/chatbot-scripts-examples-templates>

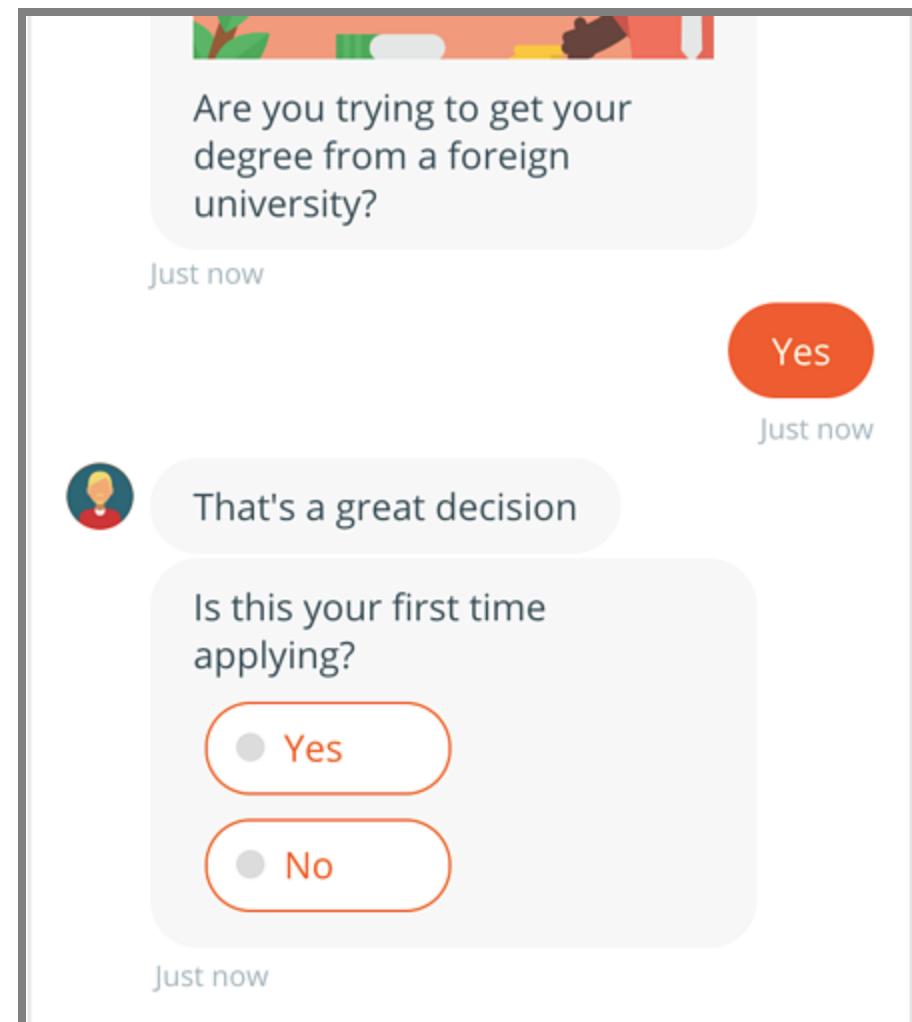
Problems with Guided Chats

Non-AI guided chat was too limited

- Cannot enumerate problems
- Hard to match against open entries
("I want to file for bankruptcy" vs "I have no money")

Involving human operators very expensive

Old-fashioned



Initial Goal: Better Chatbot

Help users with simple task

Connect them with lawyers when needed

Modernize appearance; "future of digital marketing"

Buy or Build?

The screenshot shows the Botsify homepage. At the top, there's a purple header with the Botsify logo, a navigation bar with 'Products', 'Partner', 'Resources', 'Pricing', 'Features', 'Sign in', and a green 'Signup' button. A red 'Update' button with the text 'Instagram Chatbots are available on Botsify now' is visible. Below the header, a large white section features the text 'Premium Chatbot Platform For Everyone' in bold black font. To the right of this text is a circular graphic divided into three segments: blue (top), green (bottom), and yellow (middle). The yellow segment contains the numbers '1K Chatbots', '20K Bot Responses', and '9K Hours Saved'. To the right of the graphic is a smartphone displaying a WhatsApp-like chat interface with a message from 'TamimiMarkets' asking for language preference between Arabic and English. Below the phone is a call-to-action section with two buttons: 'Get Free Trial' and 'Book Demo Now', each with a small icon.

Botsify

Products ▾ Partner ▾ Resources ▾ Pricing Features Sign in Signup

Update Instagram Chatbots are available on Botsify now

Premium Chatbot Platform For Everyone

Botsify is a managed chatbot platform that provide unified chat automation for your business. Get omnichannel live-chat service connected with multiple platforms to set autoresponses

1K Chatbots
20K Bot Responses
9K Hours Saved

Get Free Trial Book Demo Now

+307 trials started in last 7 days

Explore Platform Now

Free 1-1 Product Tour

Hi

Hello 😊, This is Tamimi Market's chatbot, please choose your preferred language to use the services.

1 Arabic
2 English

Select your country by replying number:

1 Saudi Arabia
2 Bahrain

Select the required service by replying number:

1 Weekly Offers
2 Rewards Program
3 Store locations and timings
4 Complaints / Feedback

We're open 7 AM – 11 PM, Everyday. Click Here - <https://tinyurl.com/yjnu7vhd>

Type a message

Speaker notes

One of many commercial frameworks for building AI chatbots



Data scientists' challenges

Infrastructure: Understand chat bot infrastructure and its capabilities

Knowing topics: Identify what users talk about, train/test concepts with past chat logs

- "We fed VocabX a line deliberately trying to confuse it. We wrote, 'I am thinking about chapter 13 in Boston divorce filing.' VocabX figured out the two topics: (1) business and industrial/company/bankruptcy (2) society/social institution/divorce."

Guiding conversations: Supporting open-ended conversations requires detecting what's on topic and finding a good response; intent-topic modeling

- *Is talk about parents and children on topic when discussing divorce?*
- Data gathering/labeling very challenging -- too many corner cases

Stepping Back: What are the goals of the system?



Status meeting with (inhouse) Customer

The chatbot performed better than before but was far from ready for deployment. There were “too many edge cases” in which conversations did not go as planned.

Customer: "Maybe we need to think about it like an 80/20 rule. In some cases, it works well, but for some, it is harder. 80% everything is fine, and in the remaining 20%, we try to do our best."

Data science lead: The trouble is how to automatically recognize what is 80 and what is 20.

Data scientist: It is harder than it sounds. One of the models is a matching model trained on pairs of legal questions and answers. 60,000 of them. It seems large but is small for ML.

Customer: That's a lot. Can it answer a question about say visa renewal?

Data scientist: If there exists a question like that in training data, then yes. But with just 60,000, the model can easily overfit, and then for anything outside, it would just fail.

Customer: I see what you are saying. Edge cases are interesting from an academic perspective, but for a business the first and foremost thing is value. You are trying to solve an interesting problem. I get it. But I feel that you may have already solved it enough to gain business value.

Speaker notes

Adapted from Passi, S., & Sengers, P. (2020). [Making data science systems work](#). Big Data & Society, 7(2).



System Goal for Chatbot

- Collect user data to sell to lawyers
- Signal technical competency to lawyers
- Acceptable to fail: Too complicated for self-help, connect with lawyer
- Solving edge cases not important

"Edge cases are important, but the end goal is user information, monetizing user data. We are building a legal self-help chatbot, but a major business use case is to tell people: 'here, talk to this lawyer.' We do want to connect them with a lawyer. Even for 20%, when our bot fails, we tell users that the problem cannot be done through self-help. Let us get you a lawyer, right? That is what we wanted in the first place."

Speaker notes

See Passi, S., & Sengers, P. (2020). [Making data science systems work](#). Big Data & Society, 7(2).



Model vs System Goal?



Model vs System Goal?

Your Audit Risk Results



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Model vs System Goal?

the-changelog-318

Last saved a few seconds ago

Share

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

Play Back 5s 1x 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? ☆☆☆☆☆

Model vs System Goal?



Model vs System Goal?



Model vs System Goal?

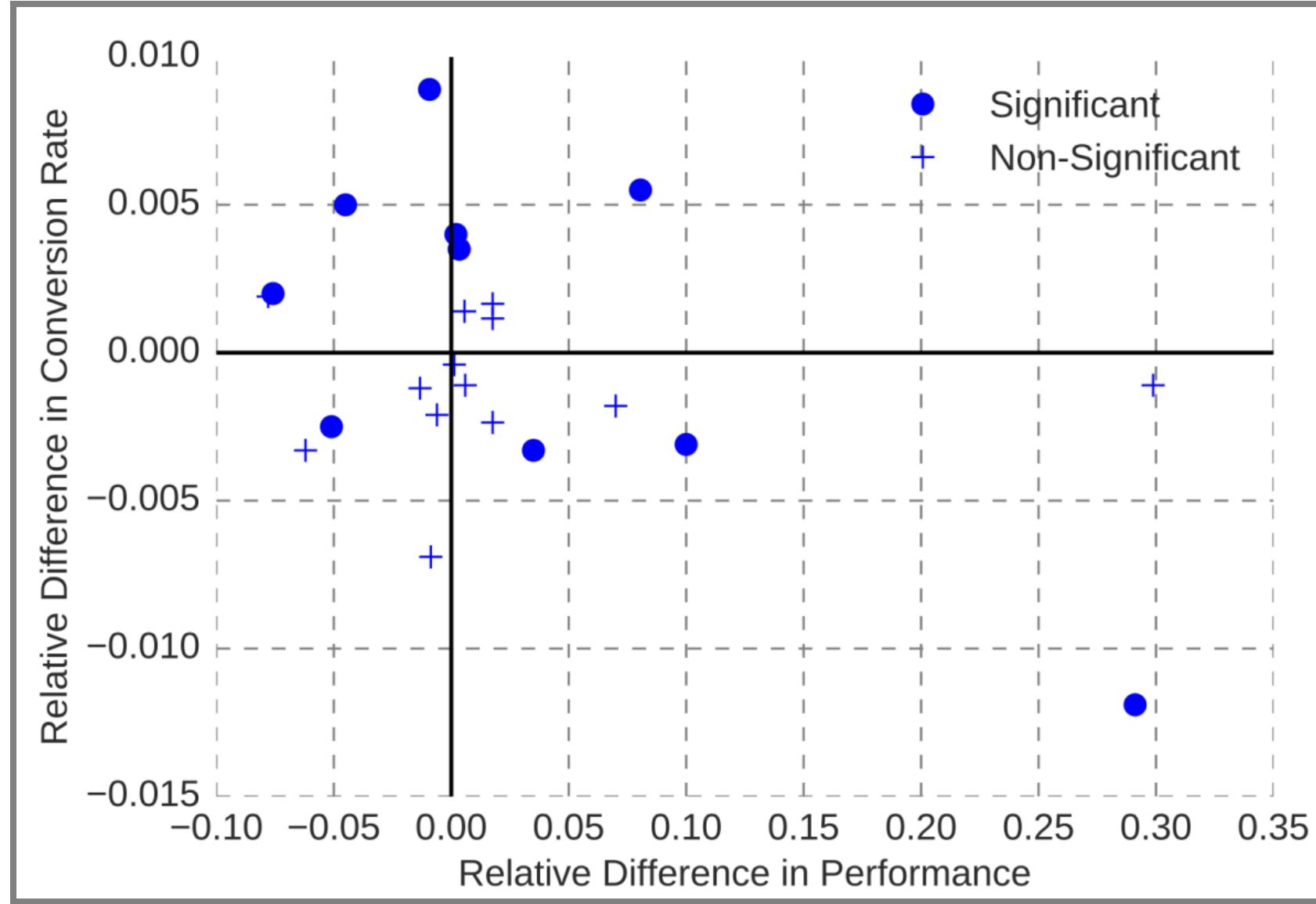
an armchair in the shape of an avocado. an armchair imitating an avocado.



Model vs System Goal?



Model vs System Goal?



More Accurate Predictions may not be THAT Important

- "Good enough" may be good enough
- Prediction critical for system success or just an gimmick?
- Better predictions may come at excessive costs
 - need way more data, much longer training times
 - privacy concerns
- Better user interface ("experience") may mitigate many problems
 - e.g. explain decisions to users
- Use only high-confidence predictions?

Machine learning that matters

- 2012(!) essay lamenting focus on algorithmic improvements and benchmarks
 - focus on standard benchmark sets, not engaging with problem: Iris classification, digit recognition, ...
 - focus on abstract metrics, not measuring real-world impact: accuracy, ROC
 - distant from real-world concerns
 - lack of follow-through, no deployment, no impact
- Failure to *reproduce* and *productionize* paper contributions common
- Ignoring design choices in how to collect data, what problem to solve, how to design human-AI interface, measuring impact, ...
- Argues: *Should focus on making impact -- requires building systems*

Wagstaff, Kiri. "Machine learning that matters." In Proceedings of the 29 th International Conference on Machine Learning, (2012).

On Terminology



- There is no standard term for referring to building systems with AI components
- **ML-Enabled Systems**, *Production ML Systems*, **AI-Enabled Systems**, or **ML-Infused Systems**; *SE4AI*, *SE4ML*
- sometimes **AI Engineering / ML Engineering** -- but usually used with a ML-pipeline focus
- **MLOps** ~ technical infrastructure automating ML pipelines
- sometimes **ML Systems Engineering** -- but often this refers to building distributed and scalable ML and data storage platforms
- "AIOps" ~ using AI to make automated decisions in operations; "DataOps" ~ use of agile methods and automation in business data analytics
- My preference: **Software Products with Machine-Learning Components**

Setting and Untangling Goals

Step 1 of Requirements...

Fundamentals of Engineering AI-Enabled Systems

Holistic system view: AI and non-AI components, pipelines, stakeholders, environment interactions, feedback loops

Requirements:

- System and model goals
- User requirements
- Environment assumptions
- Quality beyond accuracy
- Measurement
- Risk analysis
- Planning for mistakes

Architecture + design:

- Modeling tradeoffs
- Deployment architecture
- Data science pipelines
- Telemetry, monitoring
- Anticipating evolution
- Big data processing
- Human-AI design

Quality assurance:

- Model testing
- Data quality
- QA automation
- Testing in production
- Infrastructure quality
- Debugging

Operations:

- Continuous deployment
- Contin. experimentation
- Configuration mgmt.
- Monitoring
- Versioning
- Big data
- DevOps, MLOps

Teams and process: Data science vs software eng. workflows, interdisciplinary teams, collaboration points, technical debt

Responsible AI Engineering

Provenance,
versioning,
reproducibility

Safety

Security and
privacy

Fairness

Interpretability
and explainability

Transparency
and trust

Ethics, governance, regulation, compliance, organizational culture

Layers of Success Measures

- **Organizational objectives:** Innate/overall goals of the organization
- **System goals:** Goals of the software system/product/feature to be built
- **User outcomes:** How well the system is serving its users, from the user's perspective
- **Model properties:** Quality of the model used in a system, from the model's perspective
- **Leading indicators:** Short-term proxies for long-term measures, typically for organizational objectives



Ideally, these goals should be aligned with each other

Organizational Goals

Innate/overall goals of the organization

- Business
 - Current/future revenue, profit
 - Reduce business risks
- Non-Profits
 - Lives saved, animal welfare increased, CO2 reduced, fires averted
 - Social justice improved, well-being elevated, fairness improved
- Often not directly measurable from system output; slow indicators

Implication: Accurate ML models themselves are not the ultimate goal!

ML may only indirectly influence such organizational objectives; influence is often hard to quantify; lagging measures

Leading Indicators

Short-term proxies for long-term measures

Typically measures correlating with future success, from the business perspective

Examples:

- Customers sentiment: Do they like the product? (e.g., surveys, ratings)
- Customer engagement: How often do they use the product?
 - Regular use, time spent on site, messages posted
 - Growing user numbers, recommendations

Caveats

- Often indirect, proxy measures
- Can be misleading (e.g., more daily active users => higher profits?)

System/Feature Goals

Concrete outputs the system (or a feature of the system) should produce

Relates to system requirements

Examples:

- Detect cancer in radiology scans
- Provide and recommend music to stream
- Make personalized music recommendations
- Transcribe audio files
- Provide legal help with a self-service chatbot

User Goals

How well the system is serving its users, from the user's perspective

Examples:

- Users choosing recommended items and enjoying them
- Users making better decisions
- Users saving time thanks to the system
- Users achieving their goals

Easier and more granular to measure, but possibly only indirect relation to organization/system objectives

Model Goals

Quality of the model used in a system, from the model's perspective

- Model accuracy
- Rate and kinds of mistakes
- Successful user interactions
- Inference time
- Training cost

Often not directly linked to organizational/system/user goals

Success Measures in the Music Gen. Scenario?



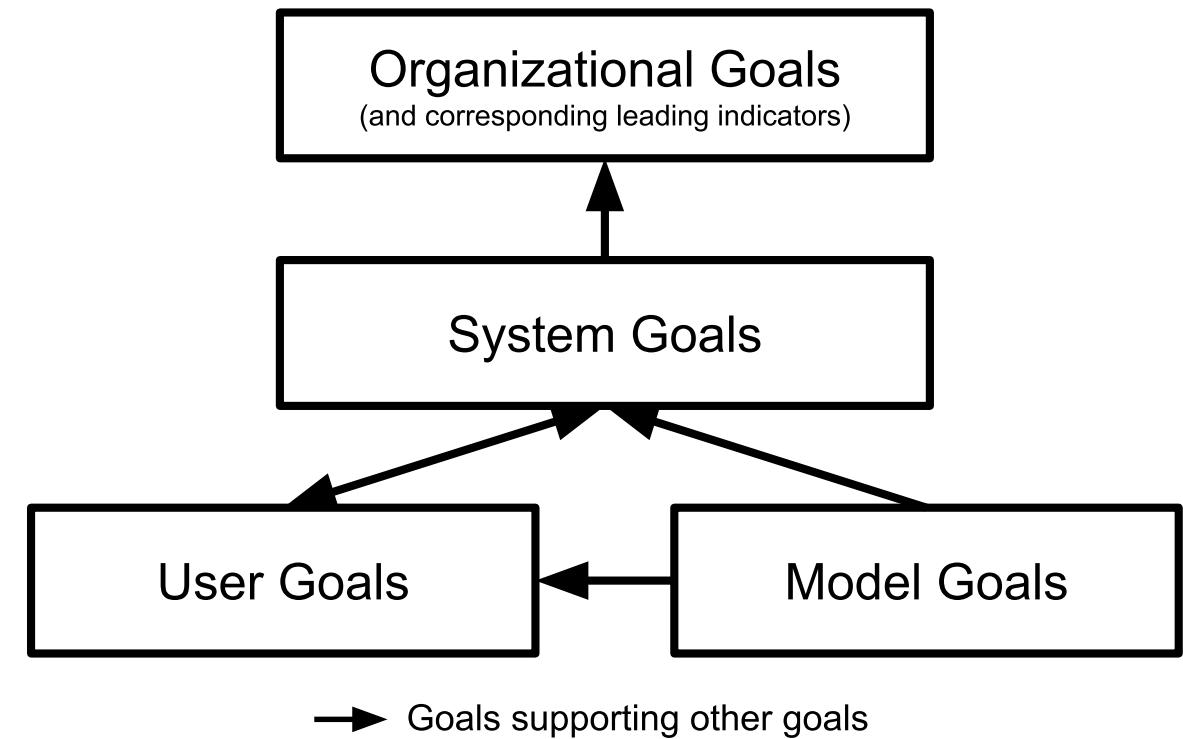
Organizational goals? Leading indicators? System goals? User
≡ goals? Model goals?

→ Goals supporting other goals

Success Measures in the Audit Risk Scenario?



Organizational goals? Leading indicators? System goals? User goals? Model goals?



Breakout: Automating Admission Decisions

What are different types of goals behind automating admissions decisions to a Master's program?

As a group post answer to #lecture tagging all group members using template:

Organizational goals: ...

Leading indicators: ...

System goals: ...

User goals: ...

Model goals: ...

Academic Integrity Issue

- Please do not cover for people not participating in discussion
- Easy to detect discrepancy between # answers and # people in classroom
- Please let's not have to have unpleasant meetings.

Breakout: Automating Admission Decisions

What are different types of goals behind automating admissions decisions to a Master's program?

As a group post answer to #lecture tagging all group members using template:

Organizational goals: ...

Leading indicators: ...

System goals: ...

User goals: ...

Model goals: ...

Systems Thinking



Repeat: Machine learning as component in a system



The System Interacts with Users

Your Audit Risk Results



Great news! There's nothing to worry about. We didn't find anything in your return that we consider a typical audit trigger, which means you're in good shape. Plus, we've also got you covered with our [free Audit Support Guarantee](#).

Speaker notes

Audit risk meter from Turbo-Tax

The System Interacts with the World



The System Interacts with the World



- Model: Use historical data to predict crime rates by neighborhoods
- Used for predictive policing: Decide where to allocate police patrol

User Interaction Design

Often: System interact with the world through *by influencing people* ("human in the loop")

Automate: Take action on user's behalf

Prompt: Ask the user if an action should be taken

Organize/Annotate/Augment: Add information to a display

Hybrids of these

Factors to Consider (from Reading)

Forcefulness: How strongly to encourage taking an action (or even automate it)?

Frequency: How often to interact with the user?

Value: How much does a user (think to) benefit from the prediction?

Cost: What is the damage of a wrong prediction?

Discussion: Safe Browsing



- (1) How do we present the intelligence to the user?
- (2) Justify in terms of system goals, forcefulness, frequency, value of correct and cost of wrong predictions

Speaker notes

Devices for older adults to detect falls and alert caretaker or emergency responders automatically or after interaction. Uses various inputs to detect falls. Read more: [How fall detection is moving beyond the pendant](#), MobiHealthNews, 2019



Collecting Feedback

Report Incorrect Phishing Warning

If you received a phishing warning but believe that this is actually a legitimate page, please complete the form below to report the error to Google. Information about your report will be maintained in accordance with Google's [privacy policy](#).

URL:



I'm not a robot



reCAPTCHA
Privacy - Terms

Comments:
(Optional)

Submit Report

Google

Feedback Loops



The System Interacts with the World

The screenshot shows a news article from MIT Technology Review. The header includes the MIT Technology Review logo and a 'Topics' section. Below the header, the word 'Artificial intelligence' is listed in purple. The main title of the article is 'Predictive policing algorithms are racist. They need to be dismantled.' A subtitle below the title states: 'Lack of transparency and biased training data mean these tools are not fit for purpose. If we can't fix them, we should ditch them.' The author's name, 'Will Douglas Heaven', is mentioned at the bottom left, along with the date 'July 17, 2020'.

MIT Technology Review

Topics

Artificial intelligence

Predictive policing algorithms are racist. They need to be dismantled.

Lack of transparency and biased training data mean these tools are not fit for purpose. If we can't fix them, we should ditch them.

by **Will Douglas Heaven**

July 17, 2020

ML Predictions have Consequences

Assistance, productivity, creativity

Manipulation, polarization, discrimination

Feedback loops

- Need for **responsible engineering**

Safety is a System Property

- Code/models are not unsafe, cannot harm people
- Systems can interact with the environment in ways that are unsafe



Safety Assurance in/outside the Model

Goal: Ensure smart toaster does not burn the kitchen



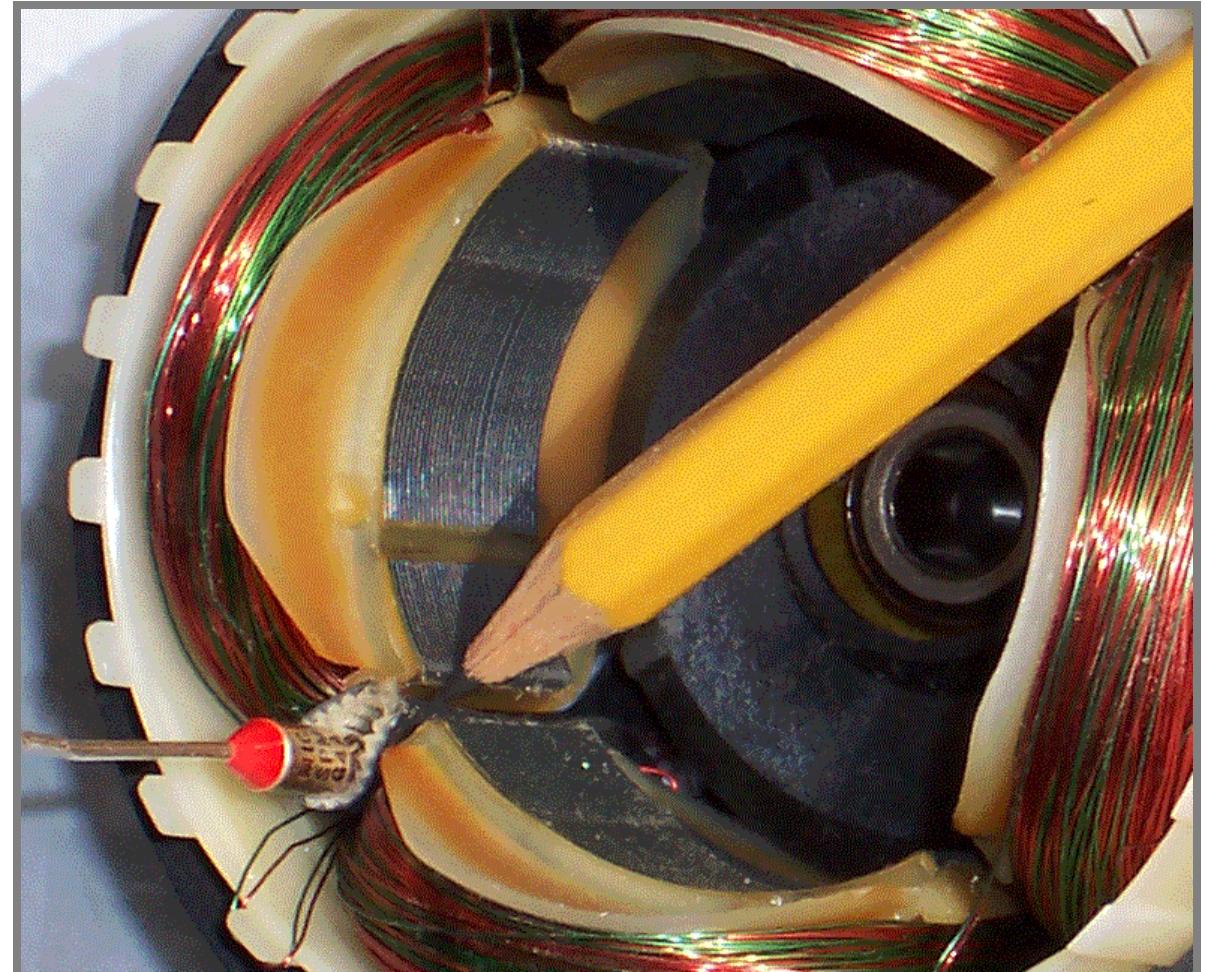
Safety Assurance in/outside the Model

In the model

- Ensure maximum toasting time
- Use heat sensor and past outputs for prediction
- Hard to make guarantees

Outside the model (e.g., "guardrails")

- Simple code check for max toasting time
- Non-ML rule to shut down if too hot
- Hardware solution: thermal fuse



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

Model vs System Properties

Similar to safety, many other qualities should be discussed at model and system level

- Fairness
- Security
- Privacy
- Transparency, accountability
- Maintainability
- Scalability, energy consumption
- Impact on system goals
- ...

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

System-Level Challenges for AI-Enabled Systems

- Getting and updating data, concept drift, changing requirements
- Handling massive amounts of data
- Interactions with the real world, feedback loops
- Lack of modularity, lack of specifications, nonlocal effects
- Deployment and maintenance
- Versioning, debugging and incremental improvement
- Keeping training and operating cost manageable
- Interdisciplinary teams
- Setting system goals, balancing stakeholders and requirements
- ...

Operating Production ML Systems

(deployment, updates)

Things change...

Newer better models released
(better model architectures, more
training data, ...)

Goals and scope change (more
domains, handling dialects, ...)

The world changes (new
products, names, slang, ...)

Online experimentation



Things change...

Reasons for change in audit risk prediction model?

Your Audit Risk Results



Great news! There's nothing to worry about. We didn't find anything in your return that we consider a typical audit trigger, which means you're in good shape. Plus, we've also got you covered with our [free Audit Support Guarantee](#).

Monitoring in Production

Design for telemetry

Report Incorrect Phishing Warning

If you received a phishing warning but believe that this is actually a legitimate page, please complete the form below to report the error to Google. Information about your report will be maintained in accordance with Google's [privacy policy](#).

URL:

I'm not a robot  reCAPTCHA
Privacy - Terms

Comments: (Optional)





Monitoring in Production

What and how to monitor in audit risk prediction?

Your Audit Risk Results



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Pipeline Thinking



Design with Pipeline and Monitoring



Pipelines Thinking is Challenging

In enterprise ML teams:

- Data scientists often focus on modeling in local environment, model-centric workflow
- Rarely robust infrastructure, often monolithic and tangled
- Challenges in deploying systems and integration with monitoring, streams etc

Shifting to pipeline-centric workflow challenging

- Requires writing robust programs, slower, less exploratory
- Standardized, modular infrastructure
- Big conceptual leap, major hurdle to adoption

Summary

Production AI-enabled systems require a *whole system perspective*, beyond just the model or the pipeline

Distinguish goals: organization, system, user, model goals

Quality at a *system level*: safety beyond the model, beyond accuracy

Large design space for user interface (intelligent experience):
forcefulness, frequency, telemetry

Plan for operations (telemetry, updates)

Recommended Readings

- Passi, S., & Sengers, P. (2020). [Making data science systems work](#). Big Data & Society, 7(2).
- Wagstaff, Kiri. "[Machine learning that matters](#)." In Proceedings of the 29th International Conference on Machine Learning, (2012).
- Sculley, David, Gary Holt, Daniel Golovin, Eugene Davydov, Todd Phillips, Dietmar Ebner, Vinay Chaudhary, Michael Young, Jean-Francois Crespo, and Dan Dennison. "[Hidden technical debt in machine learning systems](#)." In Advances in neural information processing systems, pp. 2503-2511. 2015.
- O'Leary, Katie, and Makoto Uchida. "[Common problems with Creating Machine Learning Pipelines from Existing Code](#)." Proc. Third Conference on Machine Learning and Systems (MLSys) (2020).
- Nushi, Besmira, Ece Kamar, Eric Horvitz, and Donald Kossmann. "[On human intellect and machine failures: troubleshooting integrative machine learning systems](#)." In *Proceedings of the Thirty-First AAAI Conference on Artificial Intelligence*, pp. 1017-1025. 2017.
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