SOFTWARE ARCHITECTURE OF AI-ENABLED SYSTEMS

Christian Kaestner

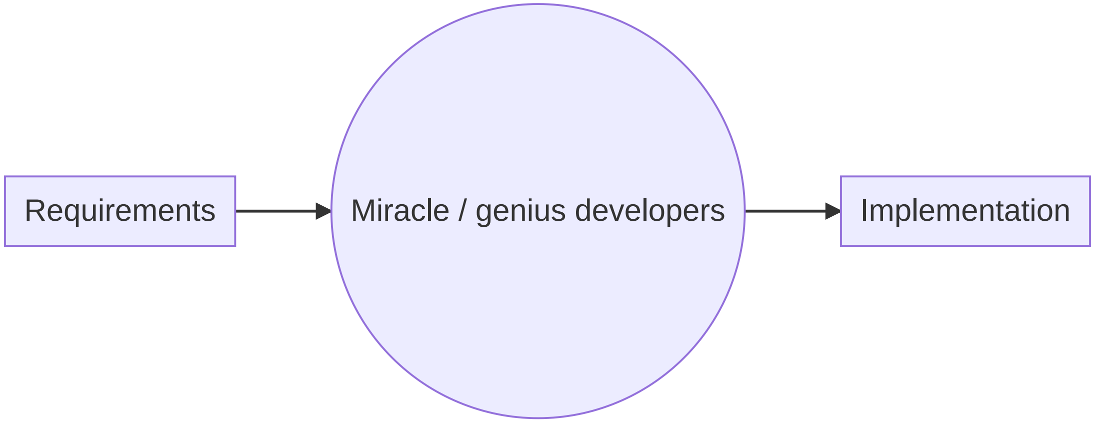
Required reading:

- Hulten, Geoff. "Building Intelligent Systems: A Guide to Machine Learning Engineering." Apress, 2018, Chapter 13 (Where Intelligence Lives).
- Daniel Smith. "Exploring Development Patterns in Data Science." TheoryLane Blog Post. 2017.

LEARNING GOALS

- Create architectural models to reason about relevant characteristics
- Critique the decision of where an AI model lives (e.g., cloud vs edge vs hybrid), considering the relevant tradeoffs
- Deliberate how and when to update models and how to collect telemetry

SOFTWARE ARCHITECTURE



SOFTWARE ARCHITECTURE

Focused on reasoning about tradeoffs and desired qualities

SOFTWARE ARCHITECTURE

> *The software architecture of a program or computing system is the **structure or structures** of the system, which comprise **software elements**, the **externally visible properties** of those elements, and the relationships among them. -- Kazman et al. 2012*

WHY ARCHITECTURE? (KAZMAN ET AL. 2012)

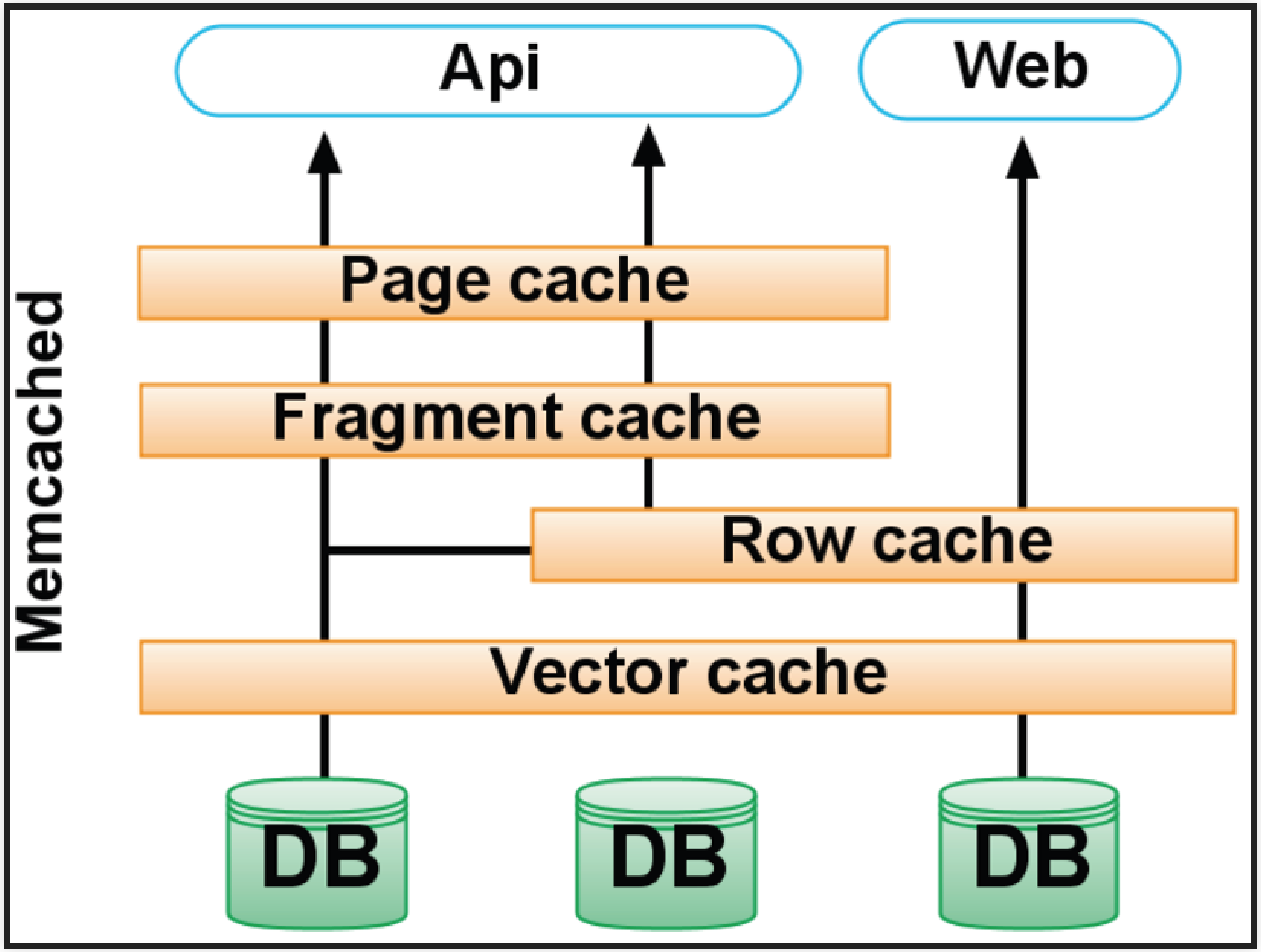
- Represents earliest design decisions.
- Aids in **communication** with stakeholders
    - Shows them “how” at a level they can understand, raising questions about whether it meets their needs
- Defines **constraints** on implementation
    - Design decisions form “load-bearing walls” of application
- Dictates **organizational structure**
    - Teams work on different components
- Inhibits or enables **quality attributes**
    - Similar to design patterns
- Supports **predicting** cost, quality, and schedule
    - Typically by predicting information for each component
- Aids in software **evolution**
    - Reason about cost, design, and effect of changes
- Aids in **prototyping**
    - Can implement architectural skeleton early

CASE STUDY: TWITTER

Speaker notes

Source and additional reading: Raffi. New Tweets per second record, and how! Twitter Blog, 2013

TWITTER - CACHING ARCHITECTURE



Speaker notes

- Running one of the world’s largest Ruby on Rails installations
- 200 engineers
- Monolithic: managing raw database, memcache, rendering the site, and * presenting the public APIs in one codebase
- Increasingly difficult to understand system; organizationally challenging to manage and parallelize engineering teams
- Reached the limit of throughput on our storage systems (MySQL); read and write hot spots throughout our databases
- Throwing machines at the problem; low throughput per machine (CPU + RAM limit, network not saturated)
- Optimization corner: trading off code readability vs performance

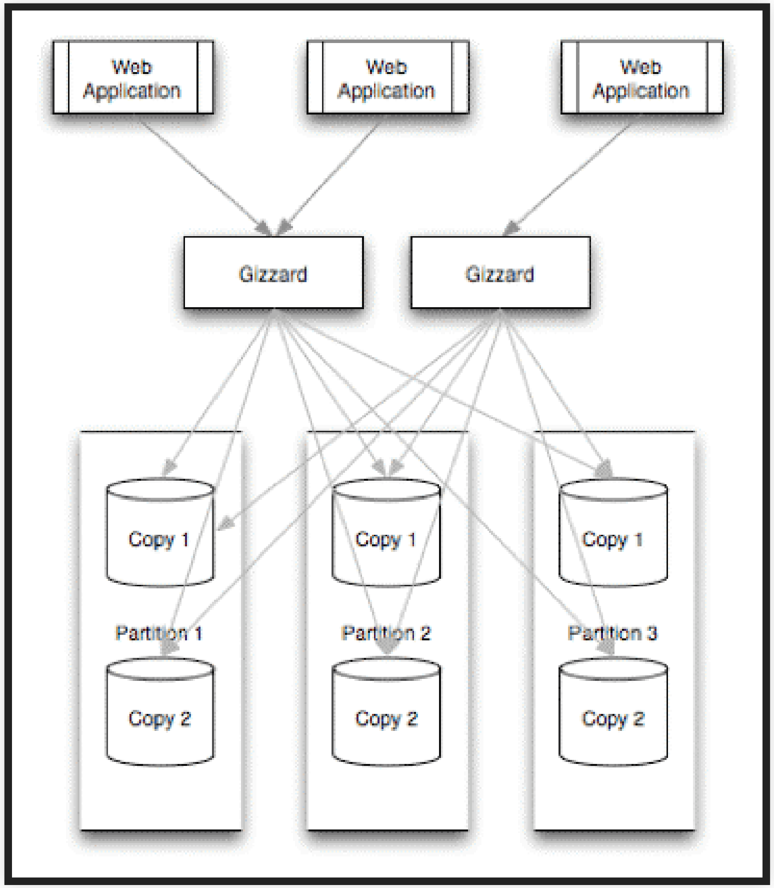
TWITTER'S REDESIGN GOALS

- Performance
  - Improve median latency; lower outliers
  - Reduce number of machines 10x
- Reliability
  - Isolate failures
- Maintainability
  - "We wanted cleaner boundaries with “related” logic being in one place": encapsulation and modularity at the systems level (rather than at the class, module, or package level)
- Modifiability
  - Quicker release of new features: "run small and empowered engineering teams that could make local decisions and ship user-facing changes, independent of other teams"

Raffi. New Tweets per second record, and how! Twitter Blog, 2013

TWITTER: REDESIGN DECISIONS

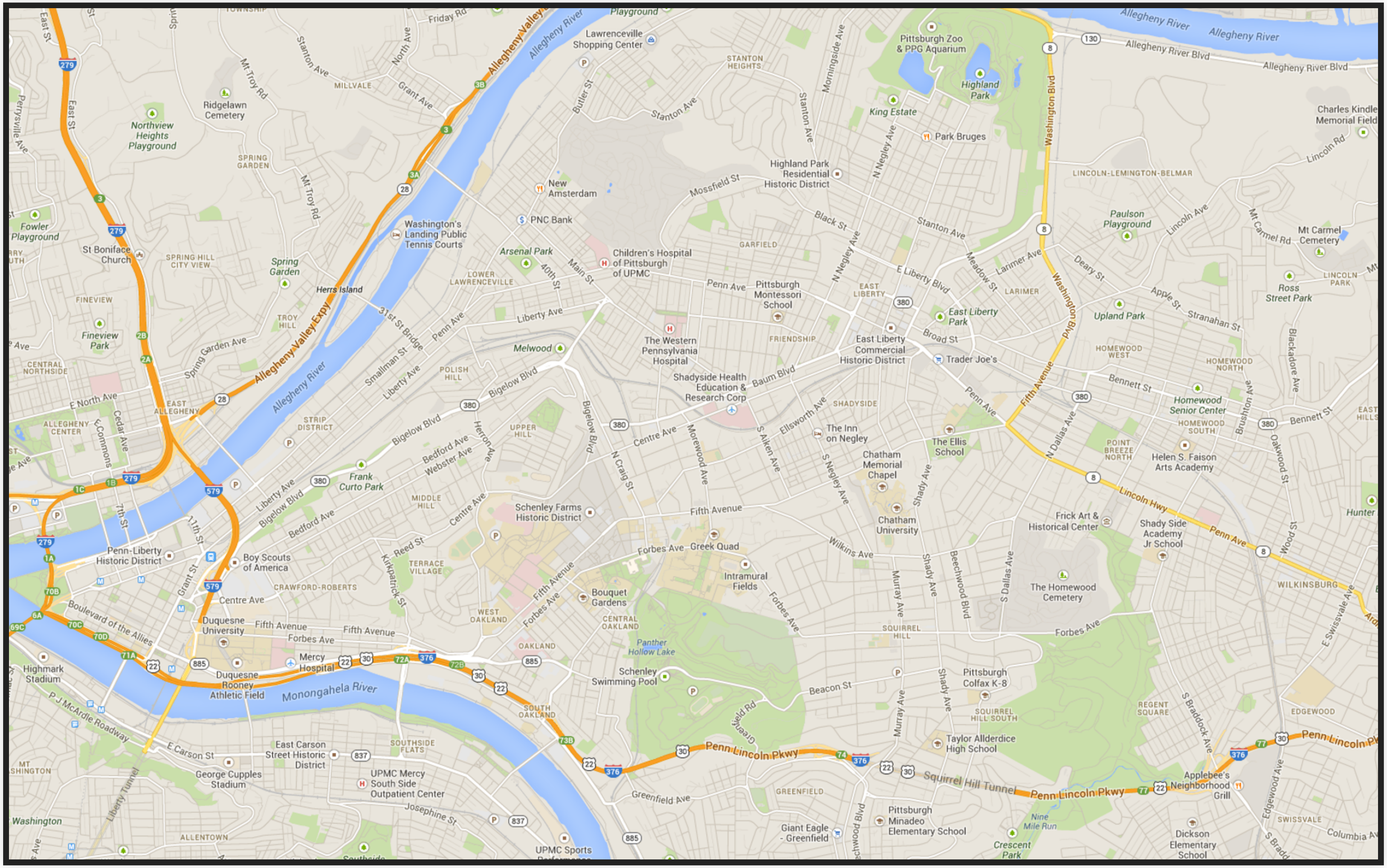
- Ruby on Rails -> JVM/Scala
- Monolith -> Microservices
- RPC framework with monitoring, connection pooling, failover strategies, loadbalancing, ... built in
- New storage solution, temporal clustering, "roughly sortable ids"
- Data driven decision making



TWITTER CASE STUDY: KEY INSIGHTS

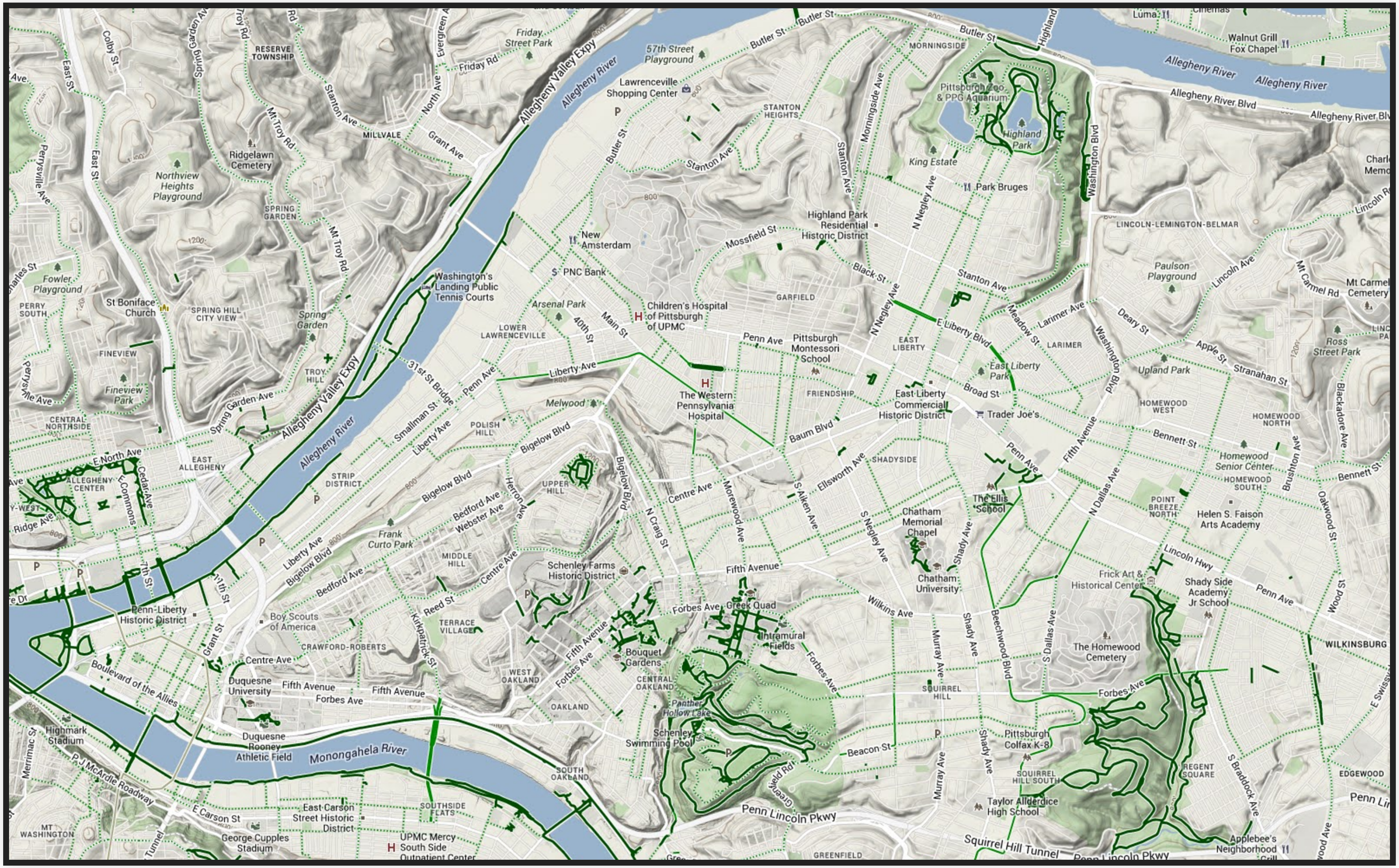
- Architectural decisions affect entire systems, not only individual modules
- Abstract, different abstractions for different scenarios
- Reason about quality attributes early
- Make architectural decisions explicit
- Question: **Did the original architect make poor decisions?**

ARCHITECTURAL MODELING AND REASONING


Allegheny River
Allegheny River Blvd
Lawrenceville Shopping Center
Pittsburgh Zoo & PPG Aquarium
Highland Park
King Estate
Park Bruges
Stanton Heights
Millvale
Friday Rd
Stanton Ave
North Ave
Grant Ave
Mt Troy Rd
Ridgelawn Cemetery
Northview Heights Playground
Spring Garden
Allegheny Valley Expy
Washington's Landing Public Tennis Courts
New Amsterdam
PNC Bank
Mossfield St
Highland Park Residential Historic District
Black St
Stanton Ave
Lincoln-Lemington-Belmar
Paulson Playground
Lincoln Ave
Mt Carmel Rd
Mt Carmel Cemetery
Charles Kindle Memorial Field
Lincoln Rd
Washington Blvd
Fowler Playground
St Boniface Church
Spring Hill City View
Spring Garden
Herrs Island
Arsenal Park
Children's Hospital of Pittsburgh of UPMC
Garfield
Penn Ave
Pittsburgh Montessori School
East Liberty
E Liberty Blvd
Larimer Ave
Larimer
Deary St
Apple St
Ross Street Park
Lincoln Park
Upland Park
Stranahan St
East Liberty Park
Broad St
Lower Lawrenceville
Fineview
Fineview Park
Troy Hill
31st St Bridge
Liberty Ave
Melwood
The Western Pennsylvania Hospital
Friendship
East Liberty Commercial Historic District
Trader Joe's
Homewood West
Homewood North
Bennett St
Homewood Senior Center
Homewood South
Central Northside
Spring Garden Ave
Smallman St
Polish Hill
Bigelow Blvd
Shadyside Health Education & Research Corp
Baum Blvd
Shadyside
Ellsworth Ave
The Inn on Negley
The Ellis School
Fifth Avenue
Point Breeze North
Helen S. Faison Arts Academy
E North Ave
Allegheny Center
East Allegheny
Strip District
Upper Hill
Centre Ave
Bedford Ave
Webster Ave
Frank Curto Park
Chatham Memorial Chapel
Chatham University
Lincoln Hwy
Frick Art & Historical Center
Shady Side Academy Jr School
Penn Ave
Hunter
Middle Hill
Schenley Farms Historic District
Wilkins Ave
Penn-Liberty Historic District
Boy Scouts of America
Reed St
Terrace Village
Forbes Ave
Greek Quad
Intramural Fields
The Homewood Cemetery
Wilkinsburg
Crawford-Roberts
Centre Ave
Bouquet Gardens
Duquesne University
West Oakland
Central Oakland
Squirrel Hill
Forbes Ave
Boulevard of the Allies
Oakland
Panther Hollow Lake
Mercy Hospital
Highmark Stadium
Duquesne Rooney Athletic Field
Monongahela River
Schenley Swimming Pool
Beacon St
Pittsburgh Colfax K-8
Regent Square
Edgewood
P J McArdle Roadway
South Oakland
Squirrel Hill South
Taylor Allderdice High School
E Carson St
East Carson Street Historic District
Southside Flats
Penn Lincoln Pkwy
Squirrel Hill Tunnel
Applebee's Neighborhood Grill
George Cupples Stadium
UPMC Mercy South Side Outpatient Center
Josephine St
Greenfield Ave
Greenfield
Giant Eagle - Greenfield
Pittsburgh Minadeo Elementary School
Nine Mile Run
Crescent Park
Dickson Elementary School
Swissvale
Columbia Ave
Washington
Allentown
Liberty Tunnel
UPMC Sports Performance

Speaker notes

Map of Pittsburgh. Abstraction for navigation with cars.



Allegheny River
Allegheny River Blvd
Monongahela River
Allegheny Valley Expy
MILLVALE
RESERVE TOWNSHIP
Friday Street Park
57th Street Playground
Lawrenceville Shopping Center
MORNINGSIDE
STANTON HEIGHTS
Pittsburgh Zoo & PPG Aquarium
Highland Park
King Estate
Park Bruges
Walnut Grill Fox Chapel
Ridgelawn Cemetery
Northview Heights Playground
SPRING GARDEN
New Amsterdam
PNC Bank
Highland Park Residential Historic District
LINCOLN-LEMINGTON-BELMAR
Paulson Playground
Mt Carmel Cemetery
Washington's Landing Public Tennis Courts
Fowler Playground
PERRY SOUTH
St Boniface Church
SPRING HILL CITY VIEW
Spring Garden
Arsenal Park
LOWER LAWRENCEVILLE
Children's Hospital of Pittsburgh of UPMC
GARFIELD
Pittsburgh Montessori School
EAST LIBERTY
LARIMER
Ross Street Park
FINEVIEW
Fineview Park
TROY HILL
Liberty Ave
Melwood
The Western Pennsylvania Hospital
FRIENDSHIP
East Liberty Park
East Liberty Commercial Historic District
Trader Joe's
Upland Park
HOMEWOOD WEST
HOMEWOOD NORTH
CENTRAL NORTHSIDE
EAST ALLEGHENY
ALLEGHENY CENTER
POLISH HILL
STRIP DISTRICT
UPPER HILL
SHADYSIDE
The Ellis School
Homewood Senior Center
HOMEWOOD SOUTH
POINT BREEZE NORTH
Helen S. Faison Arts Academy
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Boy Scouts of America
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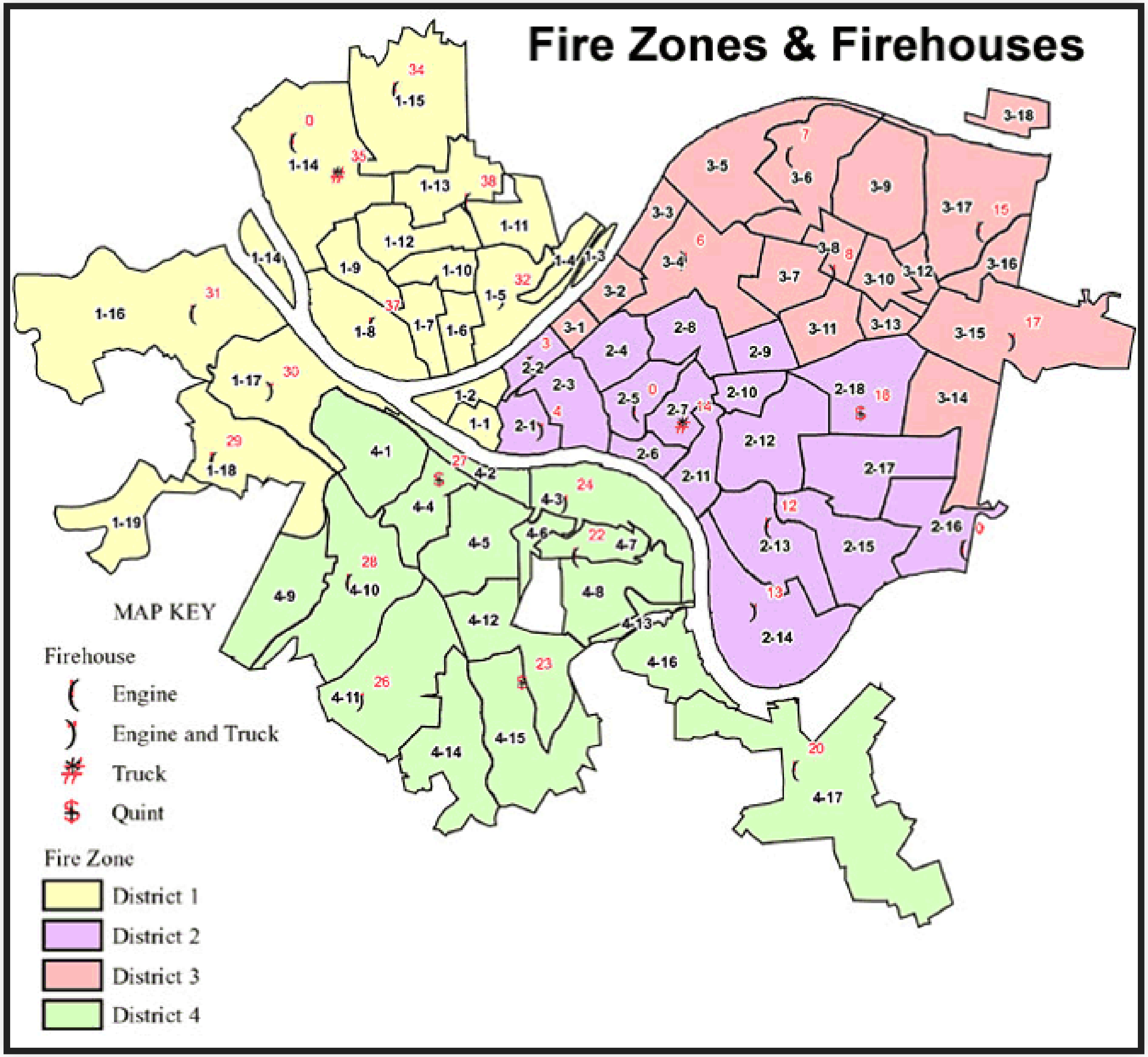
Washington Blvd
Lincoln Hwy
Beechwood Blvd
Murray Ave
Shady Ave
Wilkins Ave
E Carson St
Boulevard of the Allies
P J McArdle Roadway

Speaker notes

Cycling map of Pittsburgh. Abstraction for navigation with bikes and walking.


Fire Zones & Firehouses
MAP KEY
Firehouse
Engine
Engine and Truck
Truck
Quint
Fire Zone
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District 2
District 3
District 4
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Speaker notes

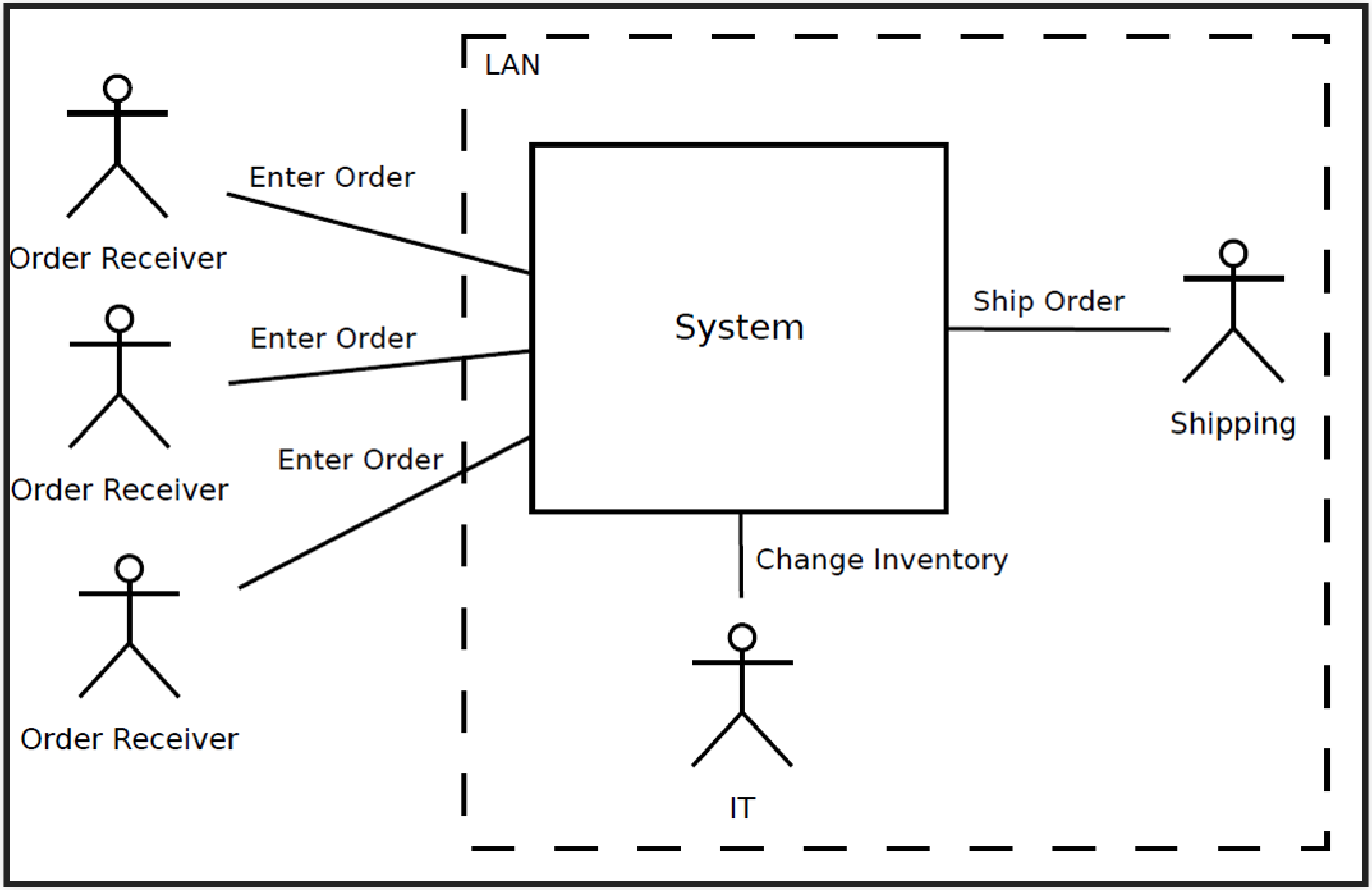
Fire zones of Pittsburgh. Various use cases, e.g., for city planners.

ANALYSIS-SPECIFIC ABSTRACTIONS

- All maps were abstractions of the same real-world construct
- All maps were created with different goals in mind
    - Different relevant abstractions
    - Different reasoning opportunities

- Architectural models are specific system abstractions, for reasoning about specific qualities
- No uniform notation

WHAT CAN WE REASON ABOUT?



WHAT CAN WE REASON ABOUT?

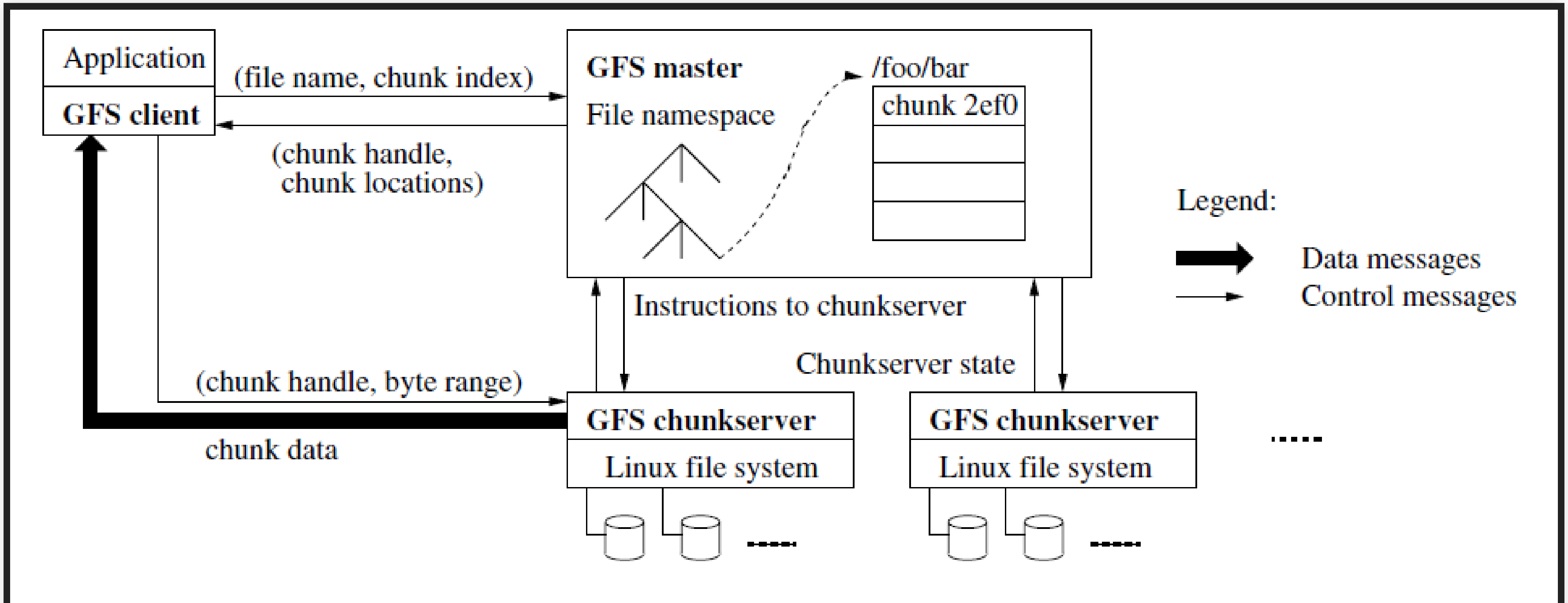


Figure 1: GFS Architecture

Ghemawat, Sanjay, Howard Gobioff, and Shun-Tak Leung. "The Google file system." ACM SIGOPS operating systems review. Vol. 37. No. 5. ACM, 2003.

Speaker notes

Scalability through redundancy and replication; reliability wrt to single points of failure; performance on edges; cost

MODELING RECOMMENDATIONS

- Use notation suitable for analysis
- Document meaning of boxes and edges in legend
- Graphical or textual both okay; whiteboard sketches often sufficient
- Formal notations available

CASE STUDY: AUGMENTED REALITY TRANSLATION

Speaker notes

Image: https://pixabay.com/photos/nightlife-republic-of-korea-jongno-2162772/

CASE STUDY: AUGMENTED REALITY TRANSLATION

CASE STUDY: AUGMENTED REALITY TRANSLATION

Speaker notes

Consider you want to implement an instant translation service similar toGoogle translate, but run it on embedded hardware in glasses as an augmented reality service.

QUALITIES OF INTEREST?

ARCHITECTURAL DECISION: SELECTING AI TECHNIQUES

What AI techniques to use and why? Tradeoffs?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Speaker notes

Relate back to previous lecture about AI technique tradeoffs, including for example Accuracy Capabilities (e.g. classification, recommendation, clustering…) Amount of training data needed Inference latency Learning latency; incremental learning? Model size Explainable? Robust?

ARCHITECTURAL DECISION: WHERE SHOULD THE MODEL LIVE?

WHERE SHOULD THE MODEL LIVE?

- Glasses
- Phone
- Cloud

What qualities are relevant for the decision?

Speaker notes

Trigger initial discussion

CONSIDERATIONS

- How much data is needed as input for the model?
- How much output data is produced by the model?
- How fast/energy consuming is model execution?
- What latency is needed for the application?
- How big is the model? How often does it need to be updated?
- Cost of operating the model? (distribution + execution)
- Opportunities for telemetry?
- What happens if users are offline?

EXERCISE: LATENCY AND BANDWIDTH ANALYSIS OF AR TRANSLATION

1. Identify key components of a solution and their interactions
2. Estimate latency and bandwidth requirements between components
3. Discuss tradeoffs among different deployment models

Speaker notes

Identify at least OCR and Translation service as two AI components in a larger system. Discuss which system components are worth modeling (e.g., rendering, database, support forum). Discuss how to get good estimates for latency and bandwidth.

WHEN WOULD ONE USE THE FOLLOWING DESIGNS?

- Static intelligence in the product
- Client-side intelligence
- Server-centric intelligence
- Back-end cached intelligence
- Hybrid models

Speaker notes

From the reading:

- Static intelligence in the product
  - difficult to update
  - good execution latency
  - cheap operation
  - offline operation
  - no telemetry to evaluate and improve
- Client-side intelligence
  - updates costly/slow, out of sync problems
  - complexity in clients
  - offline operation, low execution latency
- Server-centric intelligence
  - latency in model execution (remote calls)
  - easy to update and experiment
  - operation cost
  - no offline operation
- Back-end cached intelligence
  - precomputed common results
  - fast execution, partial offline
  - saves bandwidth, complicated updates
- Hybrid models

MORE CONSIDERATIONS

- Coupling of ML pipeline parts
- Coupling with other parts of the system
- Ability for different developers and analysts to collaborate
- Support online experiments
- Ability to monitor

ARCHITECTURAL DECISION: TELEMETRY REQUIREMENTS

TELEMETRY DESIGN

How to evaluate mistakes in production?

Speaker notes

Discuss strategies to determine accuracy in production. What kind of telemetry needs to be collected?

THE RIGHT AND RIGHT AMOUNT OF TELEMETRY

Purpose:

- Monitor operation
- Monitor mistakes (e.g., accuracy)
- Improve models over time (e.g., detect new features)

Challenges:

- too much data
- no/not enough data
- hard to measure, poor proxy measures
- rare events
- cost
- privacy

TELEMETRY TRADEOFFS

What data to collect? How much? When?

Estimate data volume and possible bottlenecks in system.


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Speaker notes

Discuss alternatives and their tradeoffs. Draw models as suitable.

RELATED: COST OF DATA AND FEATURE ENGINEERING

- How much data do we acquire for training and evaluating models?
- What data sources at what scale and latency (considering engineering cost, storage cost, processing cost, license cost, ...)
- Is it worth investing more time in feature engineering? What if additional data sources are needed?
- What is the cost for cleaning, preprocessing the data and the value of the additional accuracy?

ARCHITECTURAL DECISION: INDEPENDENT MODEL SERVICE

Microservice architecture:

Model Inference and Model Learning as a RESTful Service?

COUPLING AND CHANGEABILITY

What's the interface between the AI component and the rest of the system?

- Learning data and process
- Inference API
    - Where does feature extraction happen?
    - Provide raw data (images, user profile, all past purchases) to service, grant access to shared database, or provide feature vector?
    - Cost of feature extraction? Who bears the cost?
    - Versioned interface?
- Coupling to other models? Direct coupling to data sources (e.g., files, databases)? Expected formats for raw data (e.g., image resolution)?
- Coupling to telemetry?

MODEL SERVICE API

Consider encapsulating the model as a microservice. Sketch a (REST) API.

FUTURE-PROOFING AN API

- Anticipating and encapsulating change
    - What parts around the model service are likely to change?
    - Rigid vs flexible data formats?
- Versioning of APIs
    - Version numbers vs immutable services?
    - Expecting to run multiple versions in parallel? Implications for learning and evolution?

ROBUSTNESS

- Redundancy for availability?
- Load balancer for scalability?
- Can mistakes be isolated?
    - Local error handling?
    - Telemetry to isolate errors to component?
- Logging and log analysis for what qualities?

ARCHITECTURAL DECISION: UPDATING MODELS

- Design for change!
- Models are rarely static outside the lab
- Data drift, feedback loops, new features, new requirements
- When and how to update models?
- How to version? How to avoid mistakes?

RISK OF STALE MODELS

What could happen if models become stale?

Risk: Discuss drift, adversarial interactions, feedback loops

UPDATE REQUIREMENTS OR GOALS

Estimate the required update frequency and the related cost regarding training, data transfer, etc.


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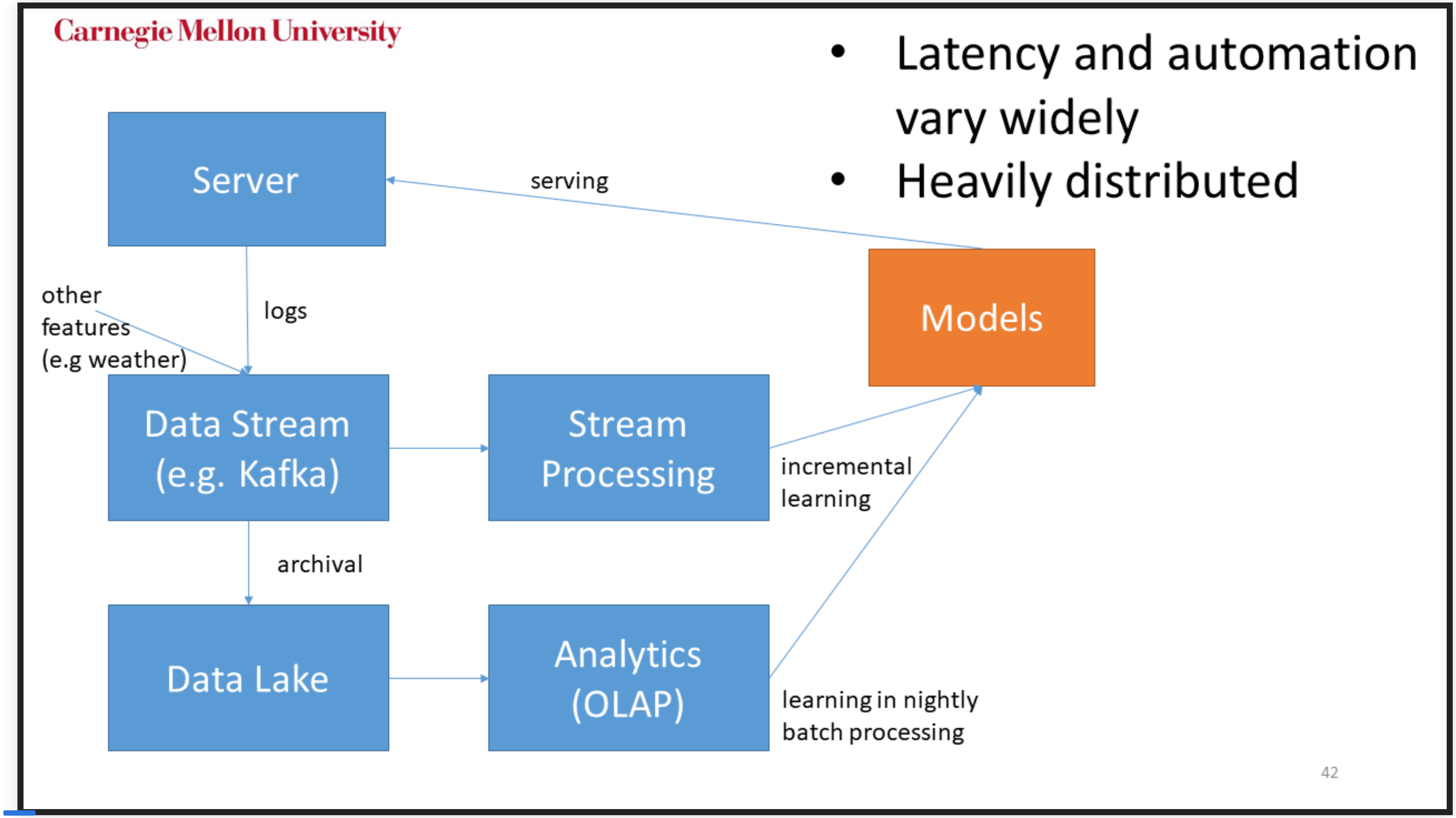
Speaker notes

Discuss how frequently the involved models need to be updated. Are static models acceptable? Identify what information to collect and estimate the relevant values.

OUTLOOK: BIG DATA DESIGNS

Stream + Batch Processing



ARCHITECTURAL STYLES / TACTICS / DESIGN PATTERNS FOR AI ENABLED SYSTEMS

(no standardization, *yet*)

ARCHITECTURES AND PATTERNS

- The Big Ass Script Architecture
- Decoupled multi-tiered architecture (data vs data analysis vs reporting; separate business logic from ML)
- Microservice architecture (multiple learning and inference services)
- Gateway Routing Architecture

- Pipelines
- Data lake, lambda architecture
- Reuse between training and serving pipelines
- Continuous deployment, ML versioning, pipeline testing

- Daniel Smith. "Exploring Development Patterns in Data Science." TheoryLane Blog Post. 2017.
- Washizaki, Hironori, Hiromu Uchida, Foutse Khomh, and Yann-Gaël Guéhéneuc. "Machine Learning Architecture and Design Patterns." Draft, 2019

ANTI-PATTERNS

- Big Ass Script Architecture
- Dead Experimental Code Paths
- Glue code
- Multiple Language Smell
- Pipeline Jungles
- Plain-Old Datatype Smell
- Undeclared Consumers

- Washizaki, Hironori, Hiromu Uchida, Foutse Khomh, and Yann-Gaël Guéhéneuc. "Machine Learning Architecture and Design Patterns." Draft, 2019
- 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.

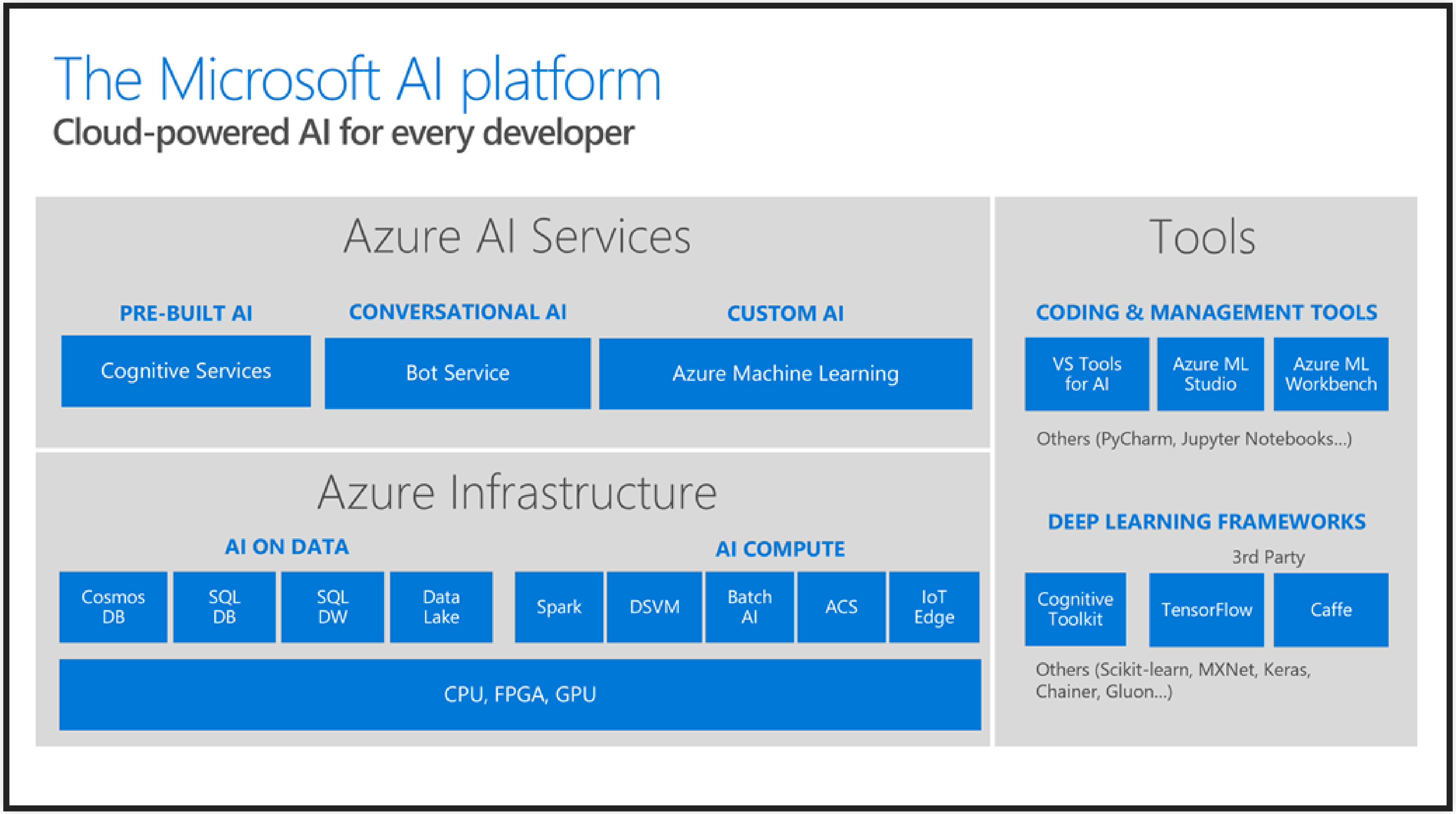
AI AS A SERVICE

Third-Party AI Components in the Cloud

AI Components as Microservices

READYMADE AI COMPONENTS IN THE CLOUD

- Data Infrastructure
  - Large scale data storage, databases, stream (MongoDB, Bigtable, Kafka)
- Data Processing
  - Massively parallel stream and batch processing (Sparks, Hadoop, ...)
  - Elastic containers, virtual machines (docker, AWS lambda, ...)
- AI Tools
  - Notebooks, IDEs, Visualization
  - Learning Libraries, Frameworks (tensorflow, torch, keras, ...)
- Models
  - Image, face, and speech recognition, translation
  - Chatbots, spell checking, text analytics
  - Recommendations, knowledge bases



The Microsoft AI platform
Cloud-powered AI for every developer
Azure AI Services
PRE-BUILT AI
Cognitive Services
CONVERSATIONAL AI
Bot Service
CUSTOM AI
Azure Machine Learning
Azure Infrastructure
AI ON DATA
Cosmos DB
SQL DB
SQL DW
Data Lake
AI COMPUTE
Spark
DSVM
Batch AI
ACS
IoT Edge
CPU, FPGA, GPU
Tools
CODING & MANAGEMENT TOOLS
VS Tools for AI
Azure ML Studio
Azure ML Workbench
Others (PyCharm, Jupyter Notebooks...)
DEEP LEARNING FRAMEWORKS
3rd Party
Cognitive Toolkit
TensorFlow
Caffe
Others (Scikit-learn, MXNet, Keras, Chainer, Gluon...)

BUILD VS BUY

Hardware, software, models?

Speaker notes

Discuss privacy implications

REFLECTION

Qualities of interest? Important design tradeoffs? Decisions?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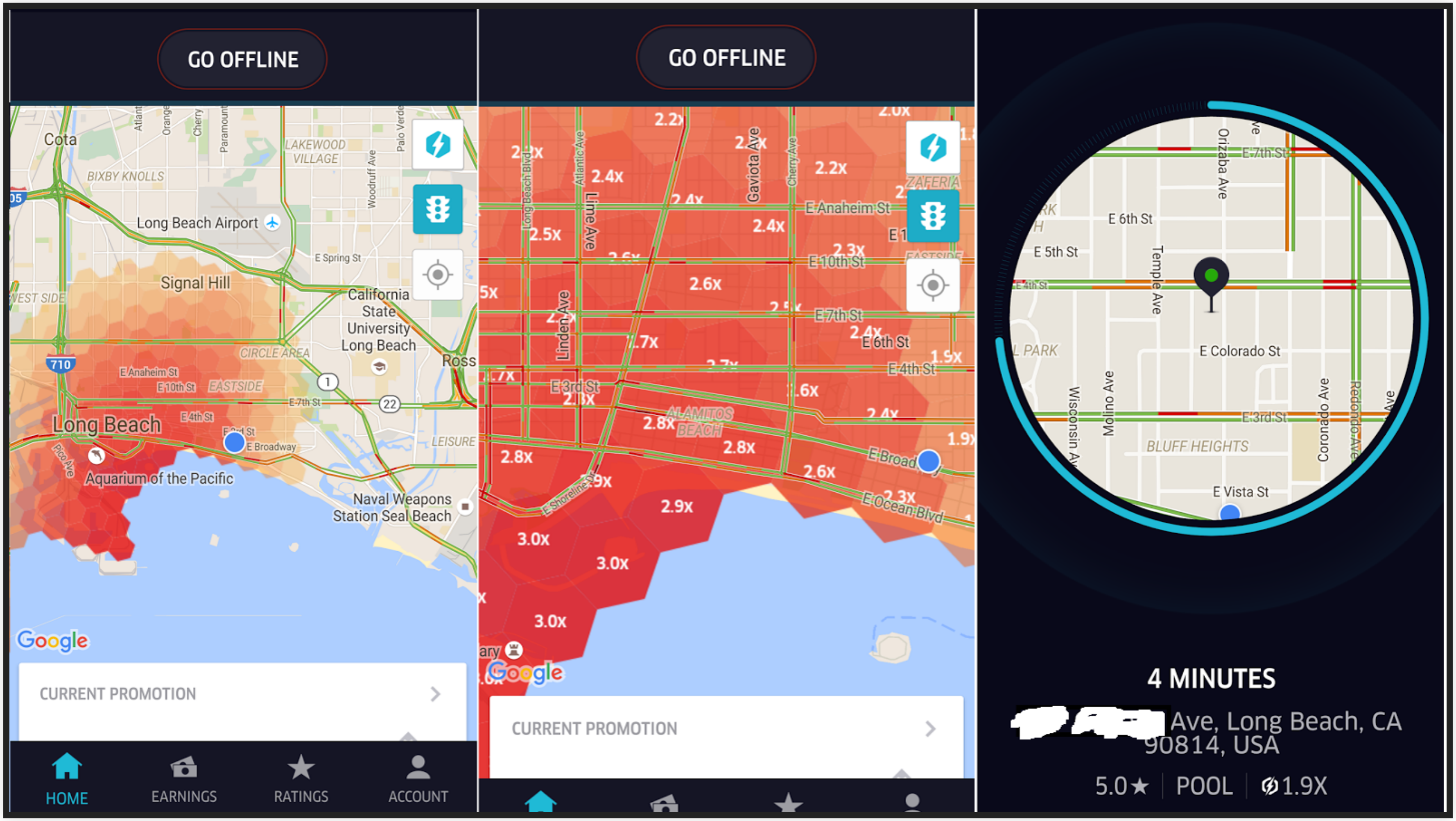
SUMMARY

- Software architecture is an established discipline to reason about design alternatives
- Understand relevant quality goals
- Problem-specific modeling and analysis: Gather estimates, consider design alternatives, make tradeoffs explicit
- Examples of important design decision:
    - modeling technique to use
    - where to deploy the model
    - how and how much telemetry to collect
    - whether and how to modularize the model service
    - when and how to update models
    - build vs buy, cloud resources

CASE STUDY 2: UBER SURGE PREDICTION


GO OFFLINE
Cota
LAKEWOOD VILLAGE
BIXBY KNOLLS
Long Beach Airport
E Spring St
Signal Hill
California State University Long Beach
CIRCLE AREA
E Anaheim St
E 10th St
EASTSIDE
E 7th St
Long Beach
E 4th St
E 3rd St
E Broadway
LEISURE
Aquarium of the Pacific
Naval Weapons Station Seal Beach
Google
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E 4th St
E 3rd St
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E 5th St
E Colorado St
E 3rd St
BLUFF HEIGHTS
E Vista St
4 MINUTES
[redacted] Ave, Long Beach, CA 90814, USA
5.0★ | POOL | 1.9X

Speaker notes

Consider you work at Uber and want to predict where rider demand is going to be high.

QUALITIES OF INTEREST?


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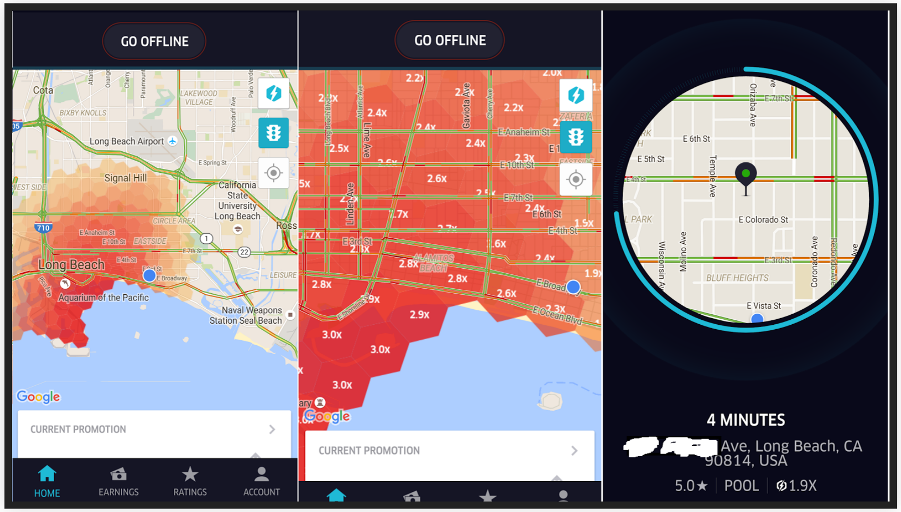
GO OFFLINE
GO OFFLINE
Long Beach Airport
Signal Hill
California State University Long Beach
Long Beach
Aquarium of the Pacific
Naval Weapons Station Seal Beach
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Ave, Long Beach, CA 90814, USA
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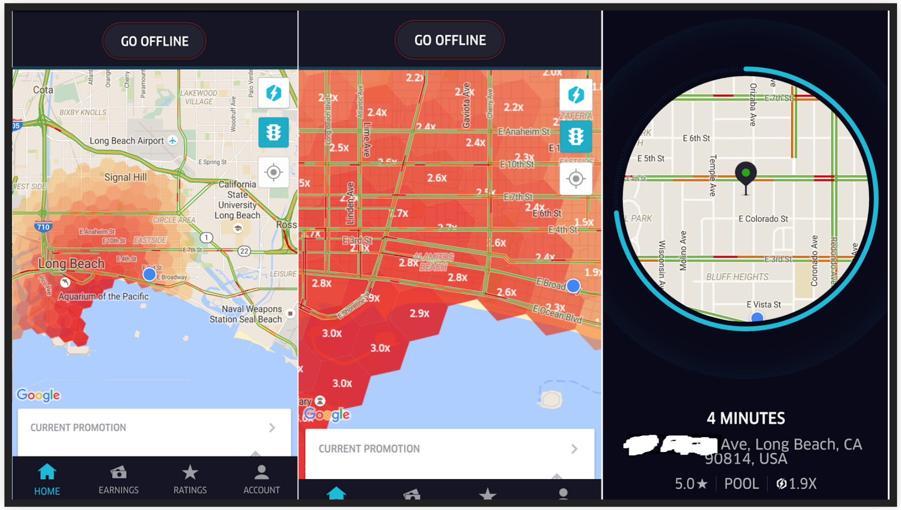
WHERE SHOULD THE MODEL LIVE?

- Car
- Phone
- Cloud

What qualities are relevant for the decision?



Speaker notes

Trigger initial discussion

TELEMETRY DESIGN

How to evaluate mistakes in production?