17-423/723: Software System Design

Quality Attributes & Trade-offs

Jan 26, 2026

Learning Goals

- Describe different types of quality attributes (QAs)
- Determine QAs that are relevant for a system
- Determine metrics for measuring QAs
- Specify quality attribute requirements using scenarios
- Identify trade-offs among different QAs and compare design options with respect to those trade-offs

Course Roadmap

- Foundational concepts & techniques for design
  - Problem vs. solution space, design modeling, **quality attributes & trade-offs**, design review, design processes
- Designing for quality attributes
  - Design for change, testability, interoperability, reuse, scalability, robustness, security, usability, AI

Today's Questions

- What are quality attributes (QAs), and why should I care?
- How do I determine what QAs are relevant for my system?
- How do I measure and specify QAs?
- What are trade-offs among different QAs, and how do I make the right trade-offs?

Quality Attributes (QAs)

- **Measurable** and **testable** properties of a product that are used to indicate how well it functions
- **Examples**
  - Reliability
  - Availability
  - Performance
  - Scalability
  - Robustness
  - Safety
  - Security
  - Extensibility
  - Maintainability
  - Usability, and many others...

Where do QAs come from?

- Stakeholder needs & incentives!
- **Guiding question**: Who are the most important stakeholders, and what qualities of my product do they care most about?
  - **Stakeholders**: End users, customers, investors, government regulators, integrators, developers, etc.,

Stakeholders? Relevant QAs?

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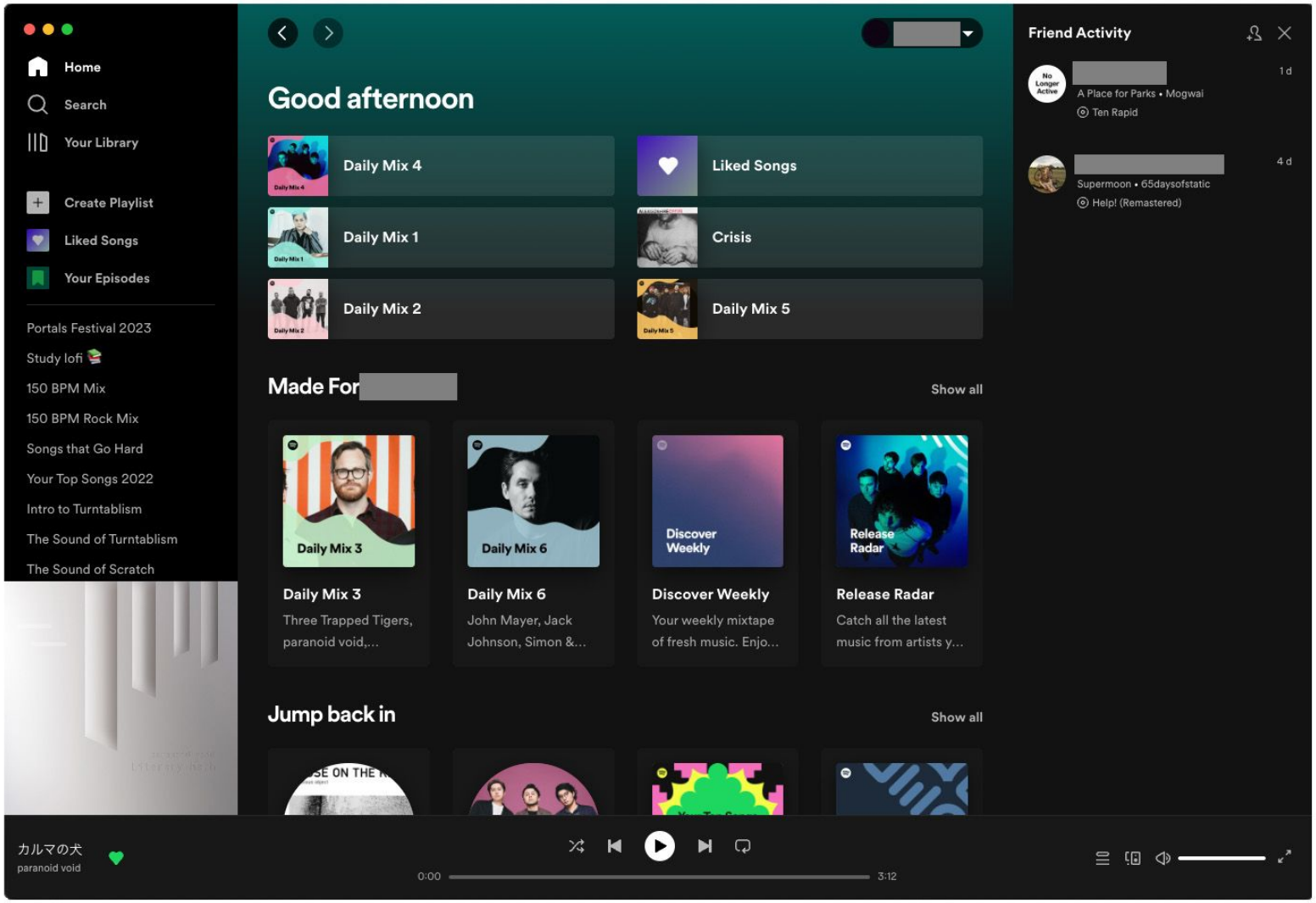
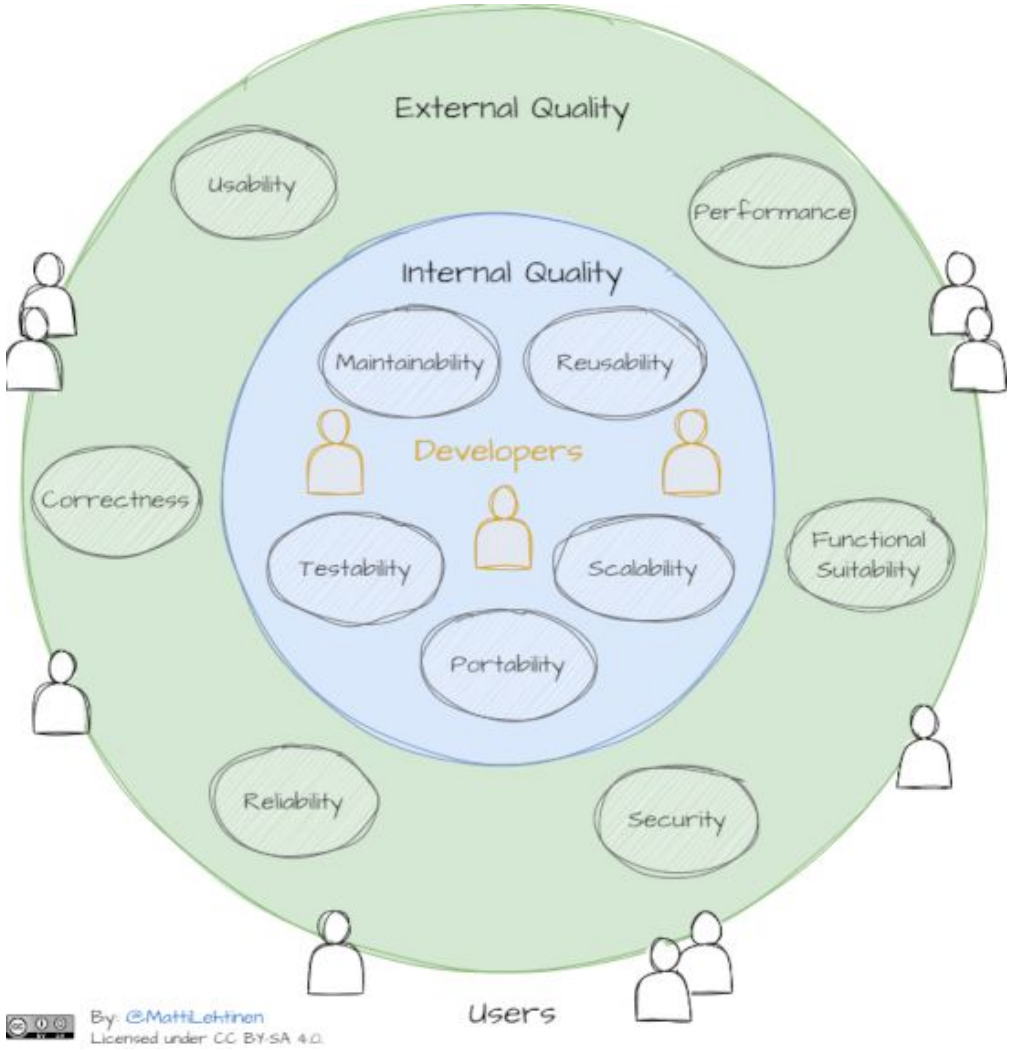


Stakeholders? Relevant QAs?

External vs. Internal Quality Attributes

- **External QAs**: Qualities that are visible to the stakeholders
- Common tendency is to focus on external QAs only
- But **internal QAs** also matter! When neglected:
  - Increase in developer effort
  - Increase in development costs & time
  - Decrease in code quality, which also likely leads to decrease in external QAs
  - Remember: **Developers are also stakeholders of the software that you create!**



QAs are “Load-Bearing Walls”

- QAs are very hard to “add in later”
- Early design decisions strongly impact the qualities of a system
- QAs are often cross-cutting concerns and spread throughout a system, not localized in one part
- Improving a QA typically involves significant changes or even redesign of the system

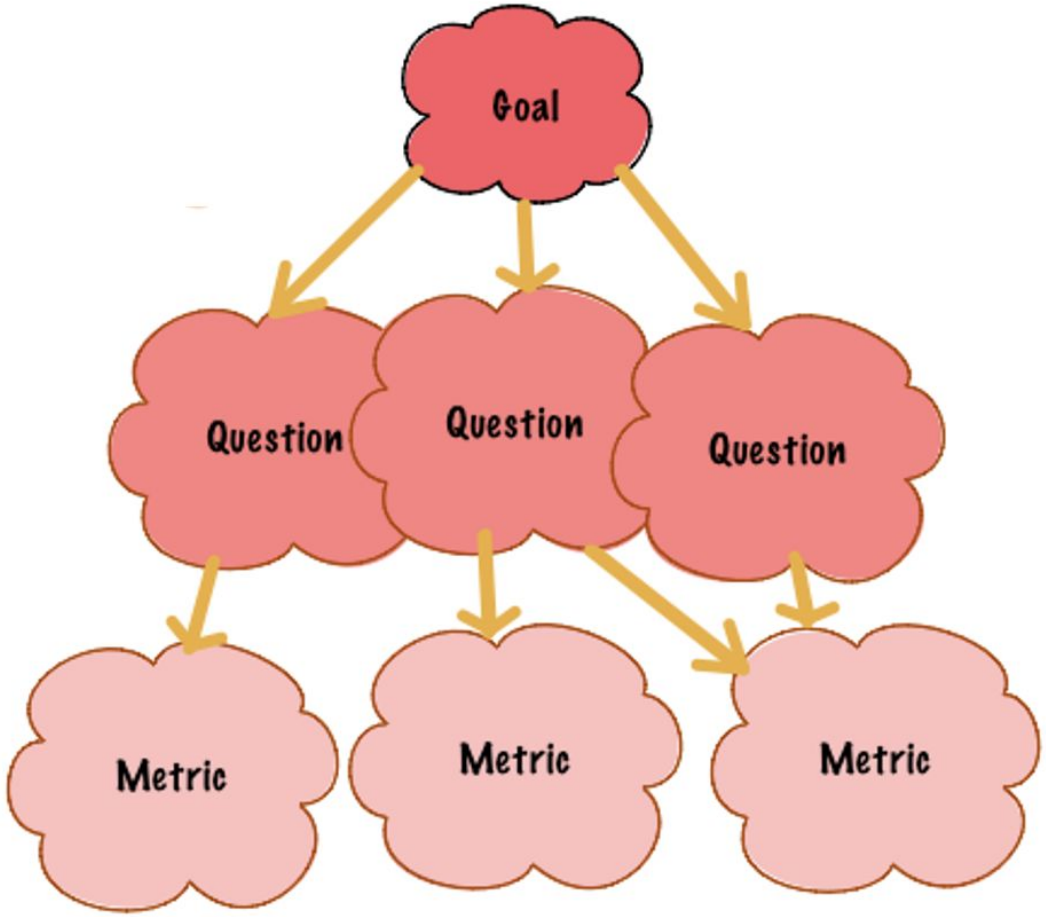
How do I measure quality attributes?

Measuring Quality Attributes

- To test and improve desired qualities of a software product, we must be able to **measure** them
- Some QAs seem less measurable than others (security, usability vs. performance, reliability)
- Even for a single QA, different metrics make sense for different applications
  - e.g., “Performance” has different meanings for different apps
- How do we come up with suitable metrics for a QA?

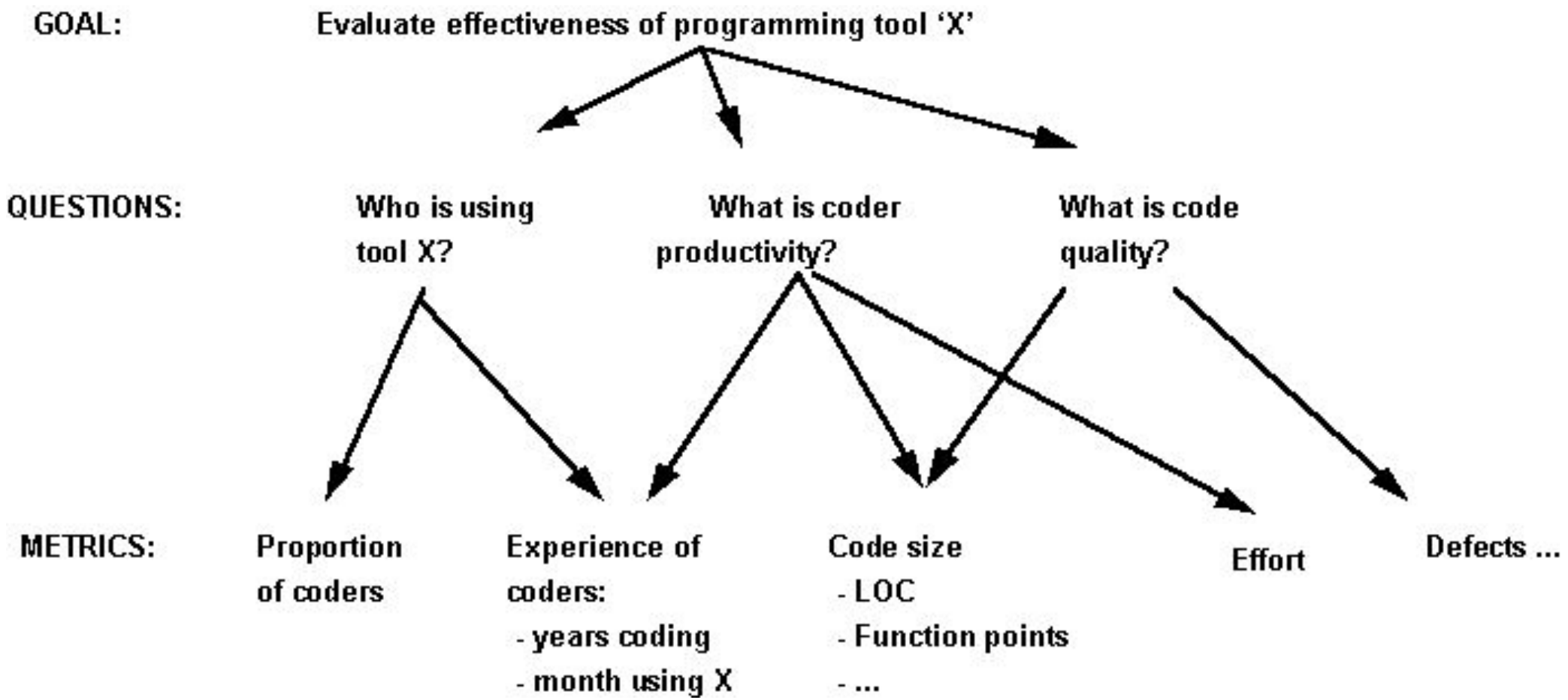
Goal-Question-Metric (GQM)

- A method for identifying metrics for software quality
- **Goal**: A high-level goal for evaluating a quality of a software artifact
- **Questions** to determine whether the goal is being achieved
- **Metrics** for answering the above questions

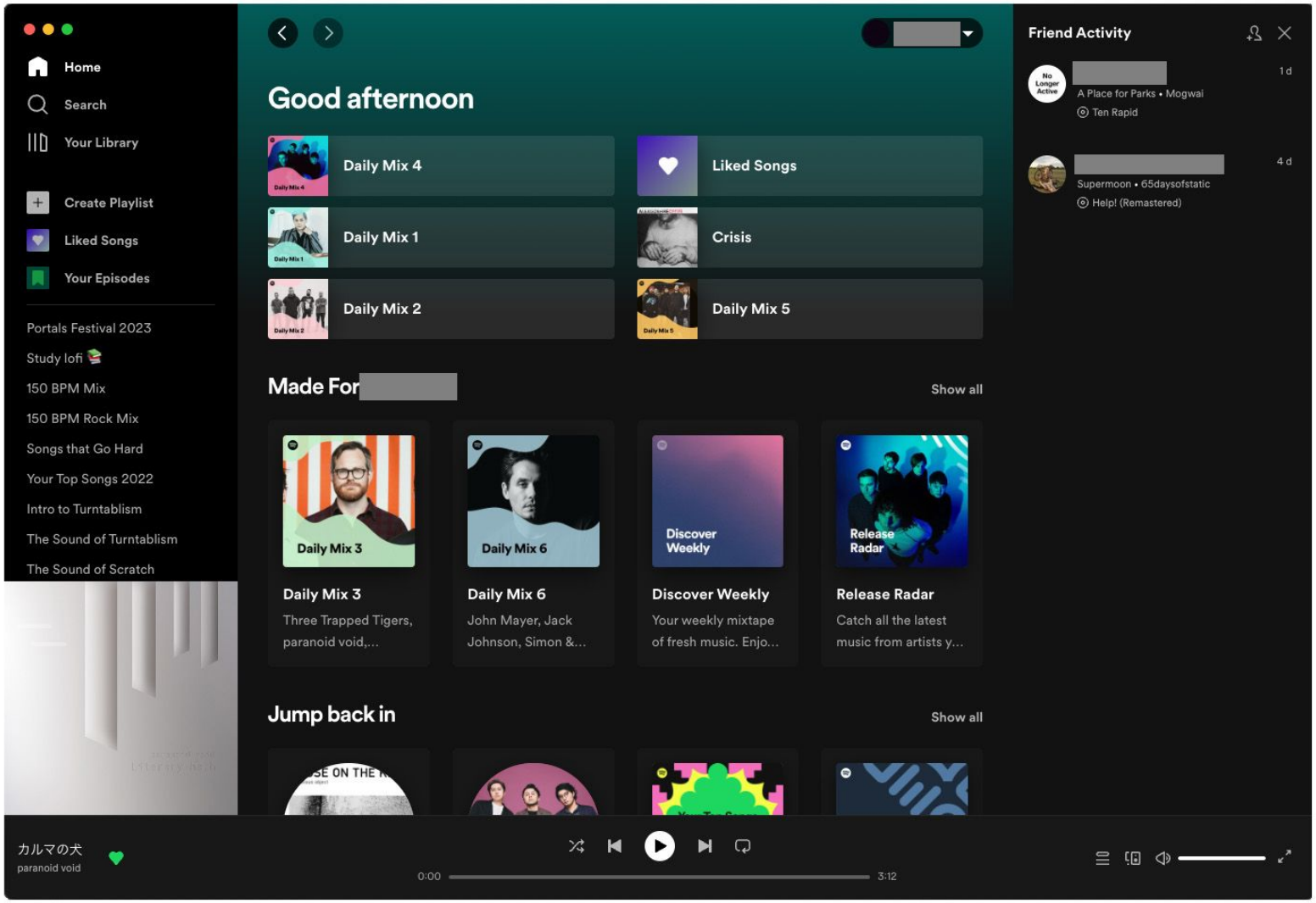


The goal question metric approach. Basilii, Caldiera & Rombach (1994)

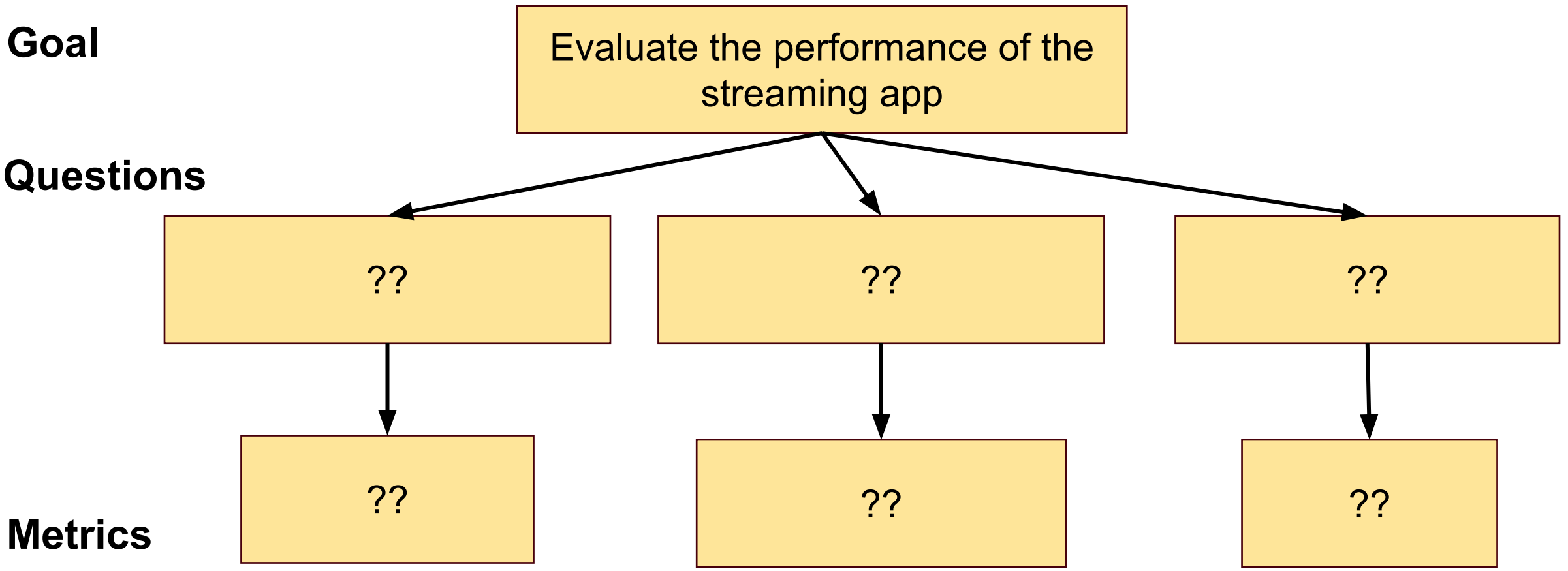
GQM Example


GOAL:
Evaluate effectiveness of programming tool 'X'
QUESTIONS:
Who is using tool X?
What is coder productivity?
What is code quality?
METRICS:
Proportion of coders
Experience of coders:
- years coding
- month using X
Code size
- LOC
- Function points
- ...
Effort
Defects ...

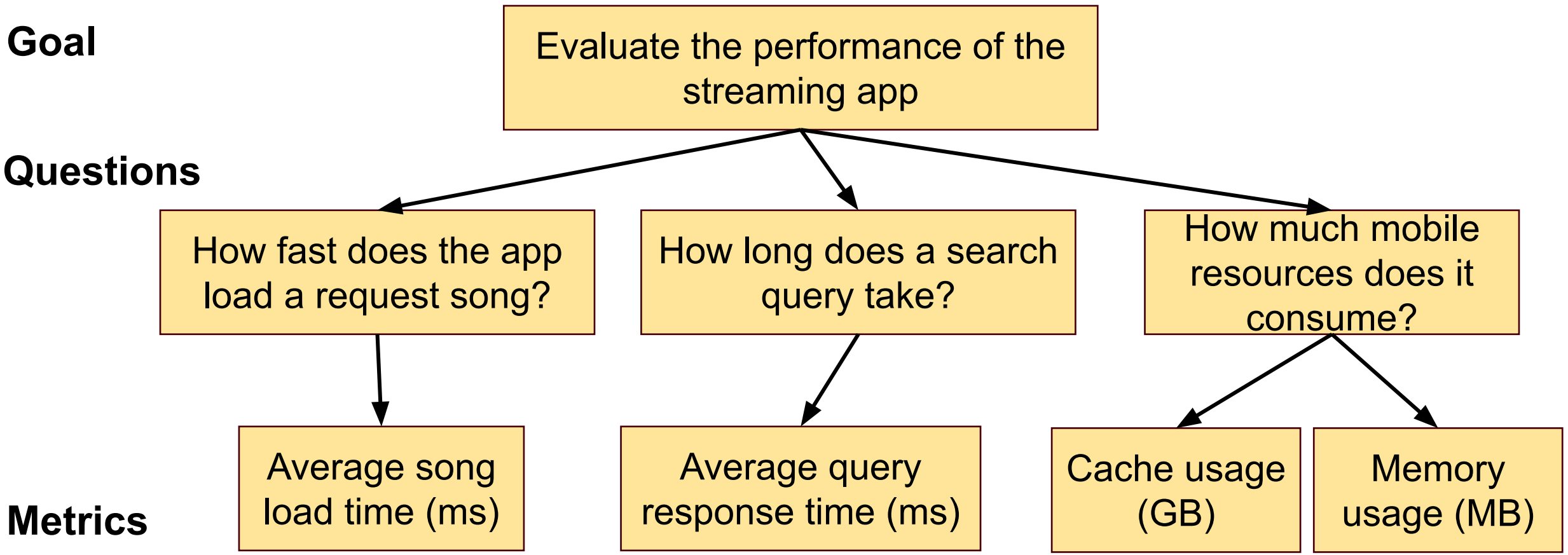
Today’s Case Study: Music Streaming App



GQM Example: Performance



GQM Example: Performance

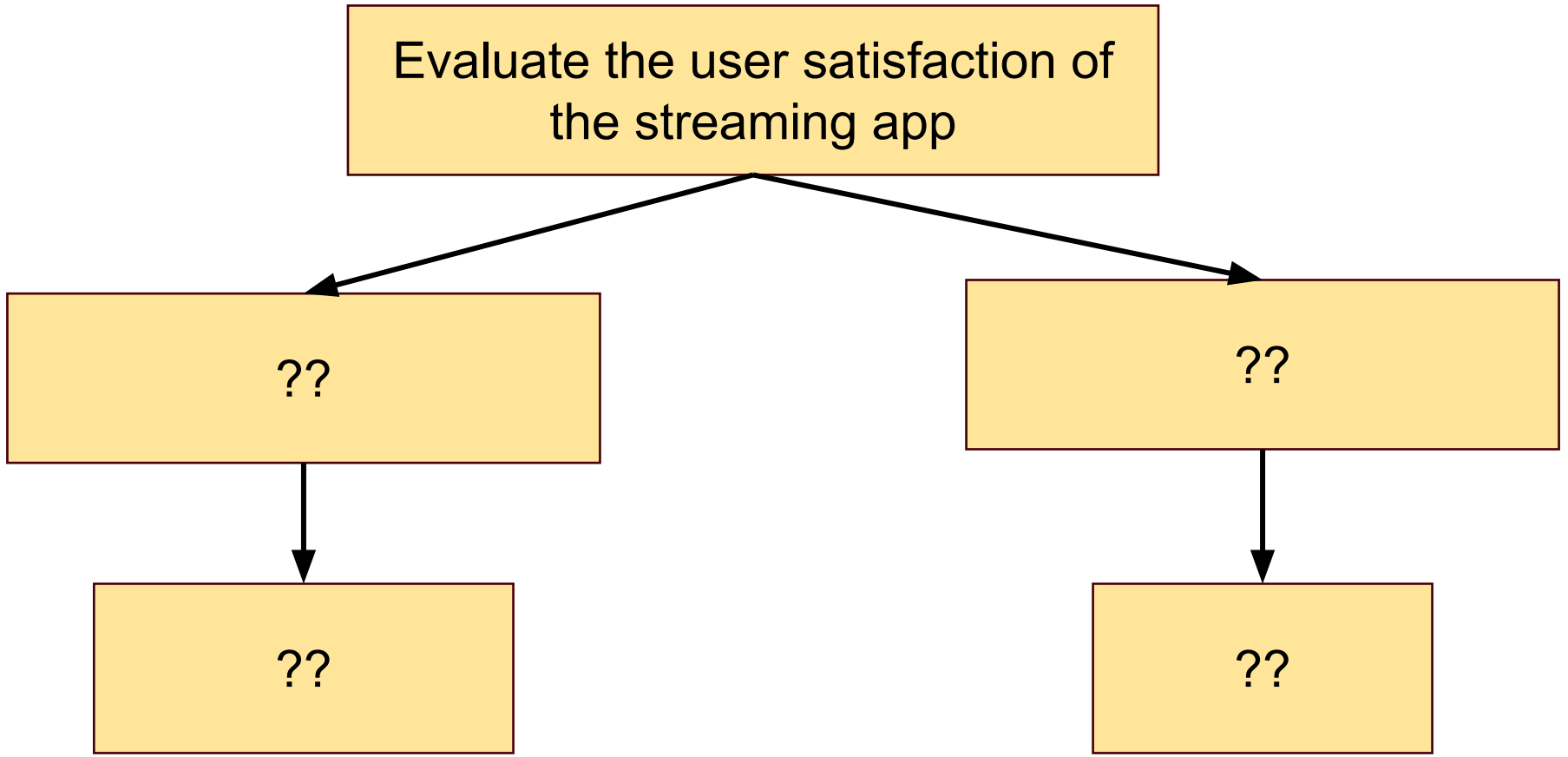


GQM Example: User Satisfaction

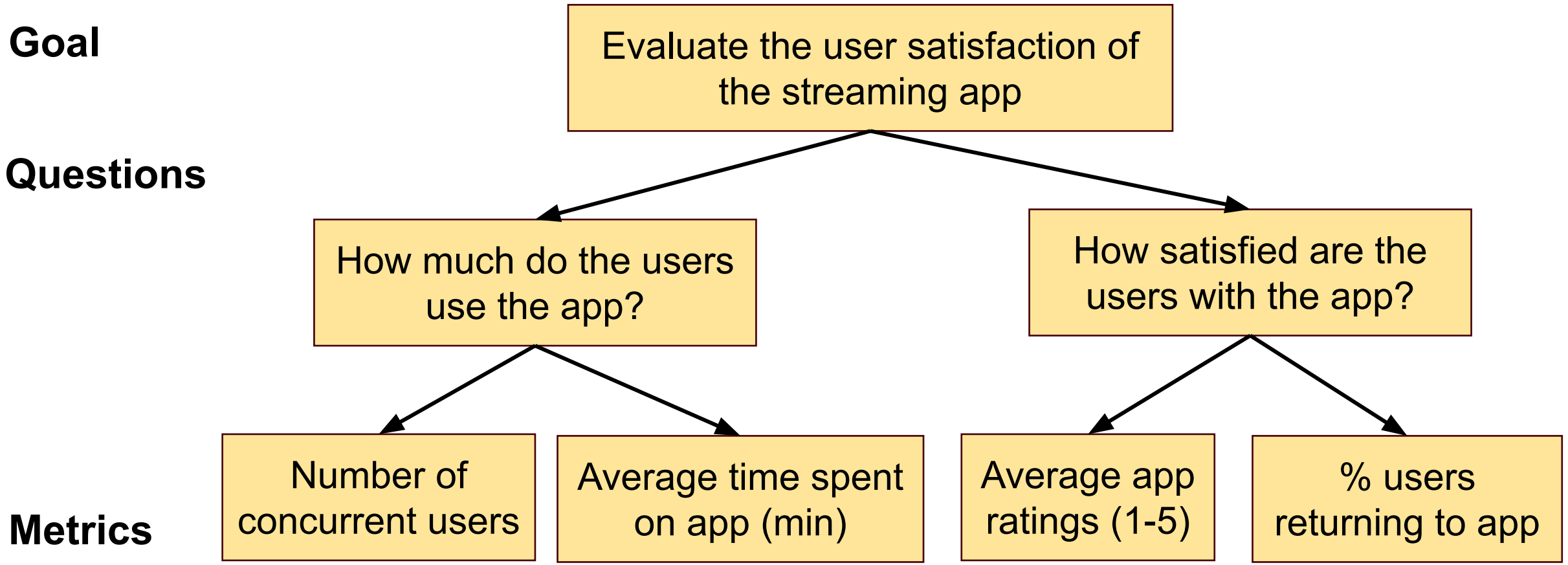
Goal

Questions

Metrics



GQM Example: User Satisfaction



QA Metrics: Tips and Caveats

- Choose metrics that are observable & testable
  - “Likelihood of a security attack: Impossible to observe in general
  - “Development time”: Too difficult to estimate accurately, even for repeated projects
- Reuse existing metrics where possible; don’t invent your own
  - We will cover these in the following lectures
- Metrics are often *proxies* for the underlying concept being measured, and can sometimes be misleading
  - High “User rating” or “number of user accounts” does not necessarily mean “usable”
  - “Lines of code” does not necessarily indicate “programmer productivity”

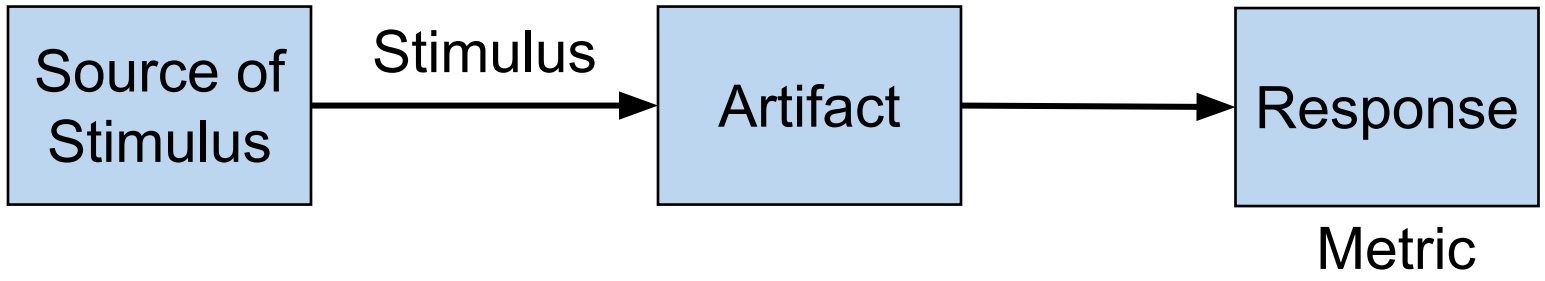
How do I specify quality attributes requirements?

Specifying QAs

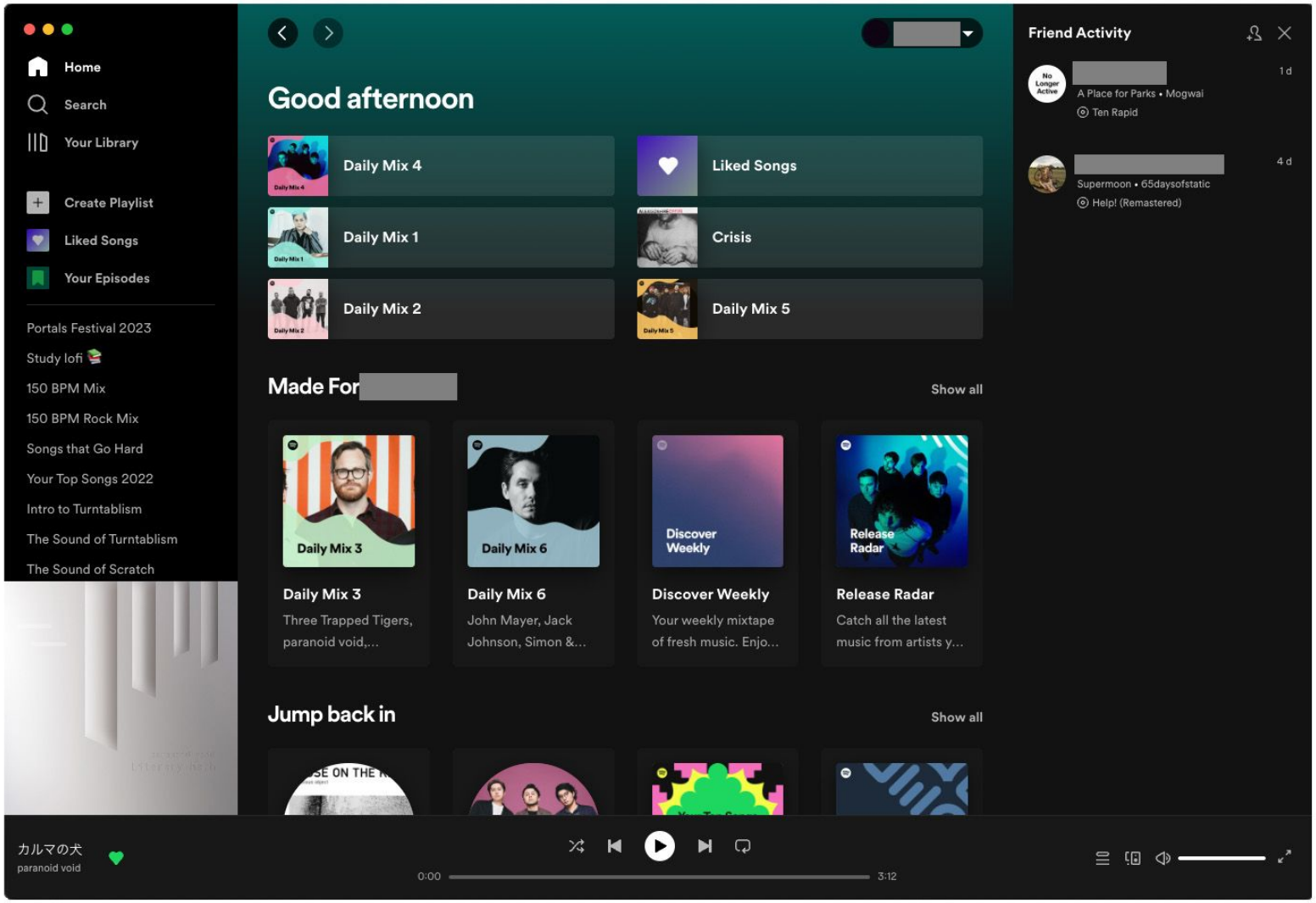
- A **QA specification** describes the level of QA that the system is expected to achieve
- Metrics alone are often not enough for specifying QAs precisely
- For a specific QA & a metric, the system may be required to achieve different levels of quality depending on the **context**
  - **Context:** Specific environmental conditions, system state, user inputs, or use cases
- **Scenarios** are one way to describe different contexts

Specifying QAs with Scenarios

- What does a **QA scenario** consist of?
  - **Artifact**: Software artifact (an app, a module, an API function...)
  - **Stimulus**: An input event or condition that causes the artifact to produce a response
  - **Source of stimulus**: The entity that generates the stimulus (e.g., user, another application, the API client…)
  - **Response**: What artifact does, given the stimulus, with a **metric** to define what a successful response is (e.g., time)



QA Scenarios: Examples



QA Scenarios: Examples

- *When the user requests to play a song, the app must load and play the song within the next 1000 ms.*
  - **Artifact**: Music streaming app
  - **Source of stimulus**: The app user
  - **Stimulus**: Request to play a song
  - **Response**: Load & play the song on the user's phone
  - **Metric**: Song latency (1000 ms)

QA Scenarios: Good or bad examples?

- (**Performance**) *When the user requests to play a song, the app must load and play the song within the next 1000 ms.*
- (**Performance**) *When the user requests to play one of the current top 100 songs, the app must load and play the song within next 500 ms.*
- (**Availability**) *If the user's phone loses the Internet connection, the app must continue to play the current song.*
- (**Scalability**) *The system must be able to handle 200 million active users at the same time.*
- (**Usability**) *The next released version of the app must maintain or increase the user satisfaction rating on the Google Play store.*

QA Scenarios: Tips and Caveats

- In general, there are too many system scenarios to enumerate
- Focus on scenarios that represent the most common use cases
- For certain qualities like robustness, security, and reliability, also consider edge cases
  - Unexpected/malicious user inputs, server failures as stimulus
  - In later lectures, we will discuss methods for coming up with some of these scenarios
- Even if the stimulus/source/response may seem obvious, be explicit about them
  - There's always a risk of ambiguity/misinterpretation (e.g., what does the "user" mean?)

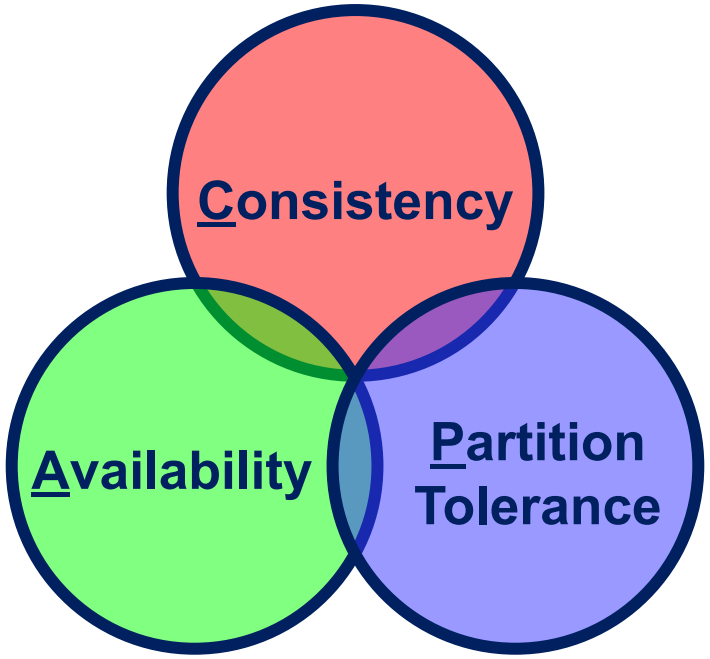
How do I make trade-offs among QAs?

QA Trade-offs

- In a typical problem domain, there are multiple desirable QAs
- In most cases, it is difficult to design & implement a software solution that achieves all of these QAs
  - Constraints and assumptions imposed by the problem space
  - Conflicts among different stakeholders' needs
  - Limited resources and time for development
  - Inherent conflicts among certain types of QAs
- Often, **trade-offs** need to be made among QAs, to obtain certain qualities while sacrificing others

QA Trade-off Example: Distributed Systems

- **Consistency:** Every client request returns the latest version of data
- **Availability:** Every client request is served with some response
- **Partition tolerance:** System continues to operate despite network failures
- **CAP theorem**: Choose two out of three
  - e.g., if a network failure occurs (and system tolerates it), choose consistency or availability
  - (Generally agreed to hold in practice, although not without some controversies)



"Towards robust distributed systems", Eric Brewer (2000)

QA Trade-offs: Other Examples

- **Security vs. usability**
  - Two-factor authentications is more secure but harder to use
  - Remembering a long password is harder, but also more secure
- **Security vs. performance**
  - Encrypting and decrypting data slows down the system while making it more secure
- **Performance vs. reliability**
  - TCP (slow but reliable) vs. UDP (fast but unreliable)
  - Use of redundancy (backup servers) increase reliability, but also introduces performance overhead (must keep the servers consistent)

QA Synergies: Examples

- Not all QA interactions are negative! QAs can also amplify each other under certain scenarios
- **Performance & usability**
  - Faster response times make it easier to use interactive systems
- **Performance & security**
  - Faster intrusion detection can keep the system more secure
- **Performance & reliability**
  - Components with message queues lose fewer messages if they process messages faster
  - Highly reliable connections do not require many retries, resulting in faster average case delivery

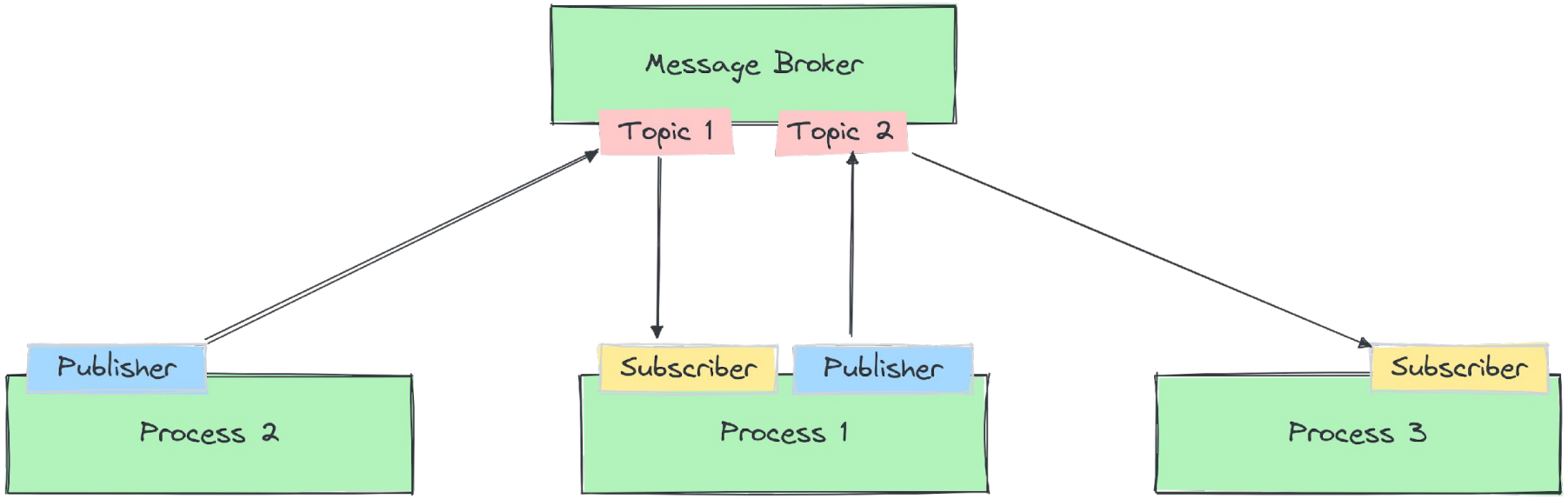
Trade-off Analysis: Example

- Consider two alternative options for message communication between processes: **Point-to-point** and **publish-subscribe**

Point-to-Point Communication

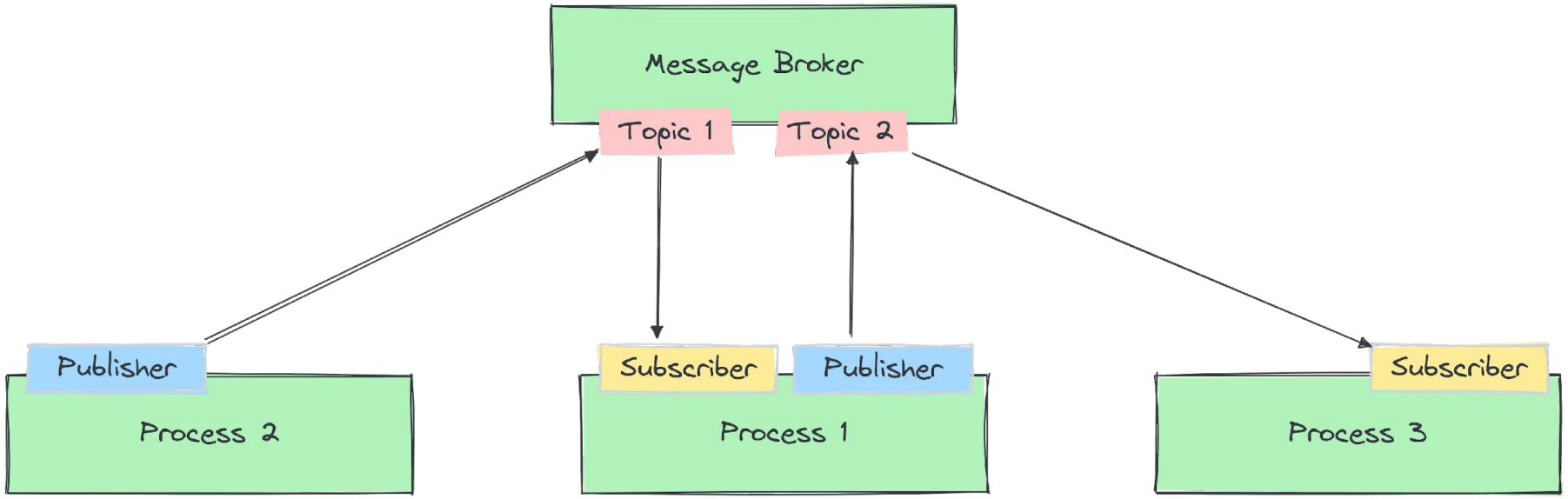
- A process directly communicates to another process
- e.g., “Client-server” or “request-response” model

Publish-Subscribe Communication



- Each process publishes or subscribes to a topic
- When a publisher sends a message, every subscriber receives it through a message broker

Publish-Subscribe Communication



- Each message reaches multiple subscribes, not just one
- Decouples publishers from subscribers; can add new publishers/subscribes without affecting each other

Discussion: Pub-Sub vs. Point-to-Point

- Compare Pub-Sub and Point-to-Point with respect to the following quality attributes:
  - **Performance**: How quickly are messages delivered from a sender to a receiver?
  - **Scalability**: How many additional concurrent messages can the system handle?
  - **Robustness**: How well does the system handle component failures or unexpected external events?

Trade-off Analysis with Decision Matrix

- **Decision matrix**: Compares different design options (columns) with respect to multiple quality attributes (rows)
- For each decision, summarize the strengths and/or weaknesses w.r.t. a particular QA

QAs	Option A	Option B
Quality 1		
Quality 2		
Quality 3		

Trade-off Analysis with Decision Matrix

- **Decision matrix**: Compares different design options (columns) with respect to multiple quality attributes (rows)
- For each decision, summarize the strengths and/or weaknesses w.r.t. a particular QA

QAs	Option: Point-to-Point	Option: Publish-Subscribe
Performance	Direct messaging; stronger guarantee on delivery time	Message delivery time affected by number of subscribers
Scalability	Limited support for large-scale messaging	Support sending messages to an arbitrary number of subscribers
Robustness	A failure in the receiver disrupts the senders	A failure in the broker disrupts all publishers & subscribers

Making Trade-off Decisions

1. Identify a list of QA scenarios that are important for the system
2. For each QA scenario, determine which of the options better supports it
3. If there is no one superior option, prioritize QAs w.r.t. risks
4. Select the option that best supports the most high-risk QA scenario

QAs	Option: Point-to-Point	Option: Publish-Subscribe
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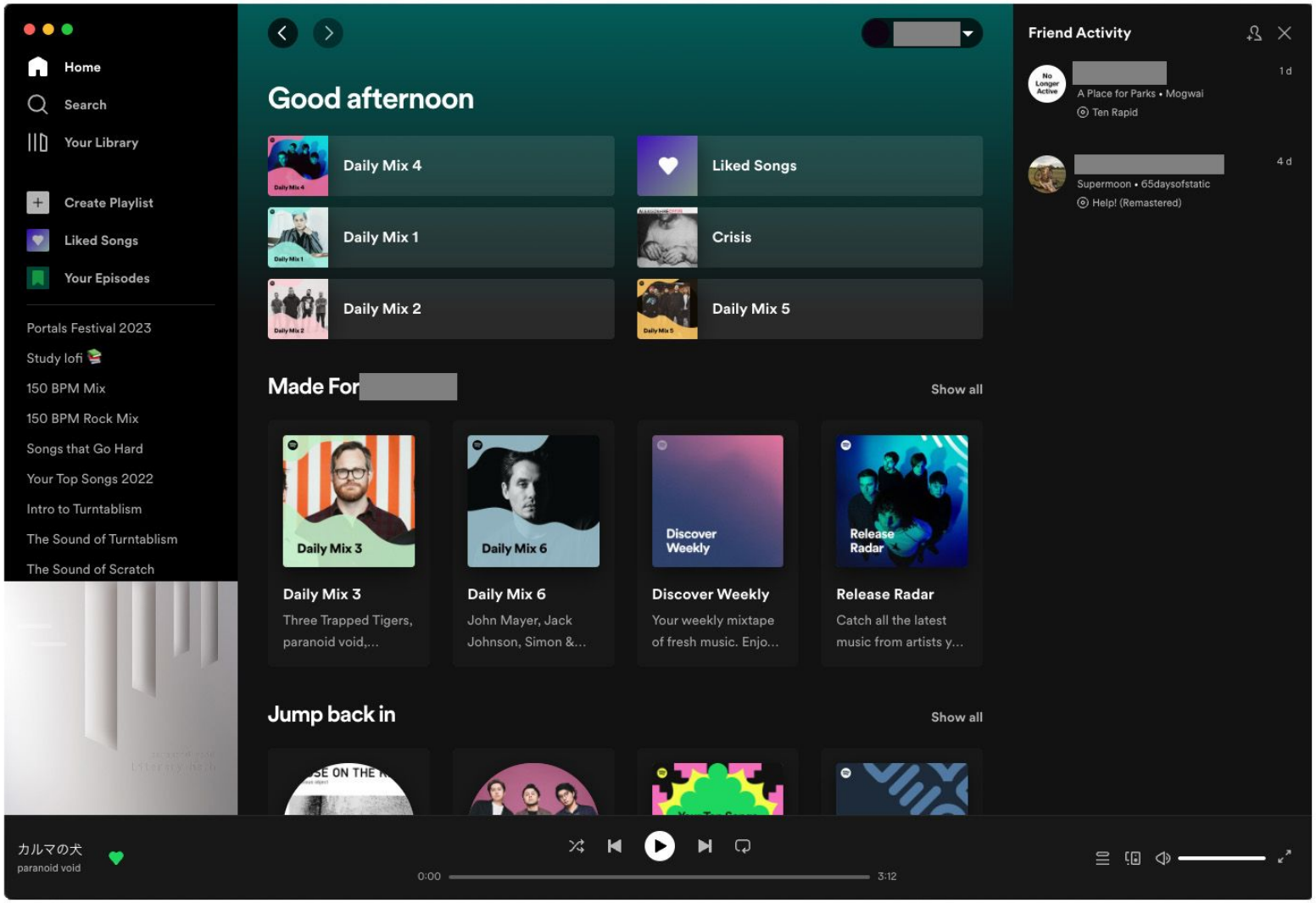
Back to Spotify



Making Trade-off Decisions

- **Scenario #1**: *When the user requests to play a song, the app must load and play the song within the next 1000 ms.*
- **Scenario #2**: *When a user's playlist is updated, every user who follows that playlist must be notified within next 2 minutes.*

QAs	Option: Point-to-Point	Option: Publish-Subscribe
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- **Scenario #2**: *When a user's playlist is updated, every user who follows that playlist must be notified within next 2 minutes.*
- **Q.** How would you decide between the two options?

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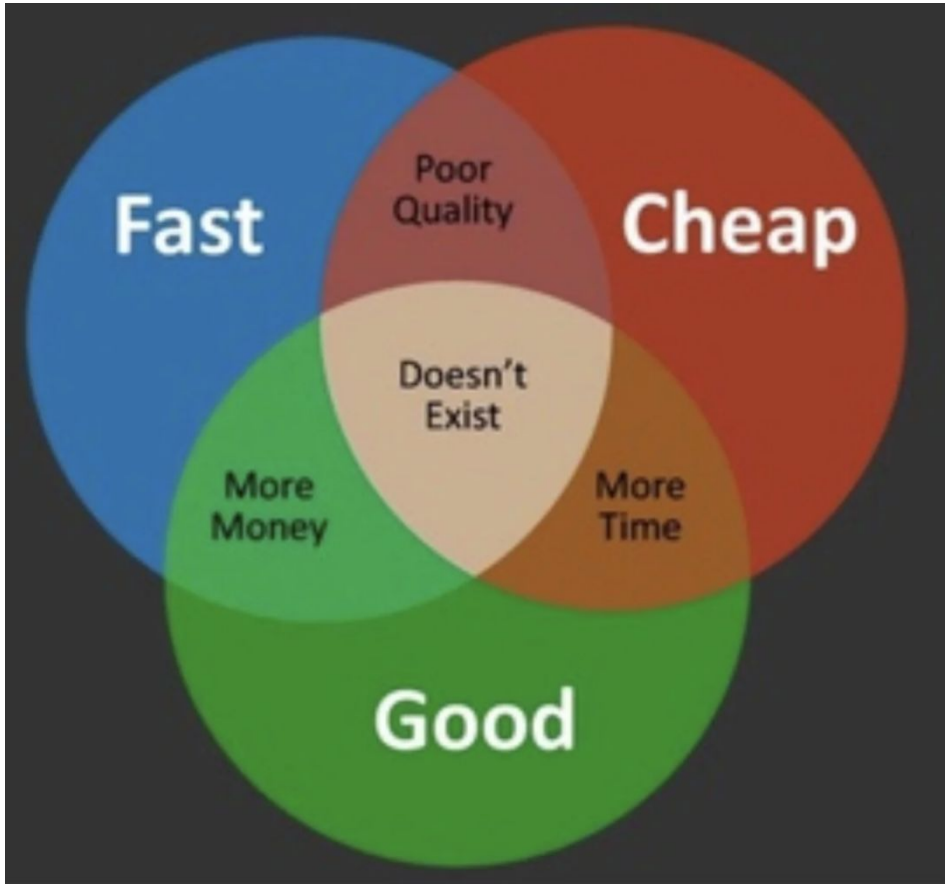
Costs in Trade-off Analysis

- Every design decision regarding a QA has some development costs associated with it
  - Achieving security involves adding encryption, storing secrets in databases, hiring a security expert/tester, etc.,
  - Achieving scalability involves purchasing more servers, implementing distributed protocols to keep the servers consistent…
- In this class, we will (mostly) ignore the issues related to costs
- In practice, costs should be considered as an additional row in the decision matrix along with other QAs



Quality Attributes: Takeaways

- Functionality is not the only concern of software design
- Quality attributes measure the “goodness” of a design along a certain dimension
- Quality attributes should be measurable
- Quality attribute requirements should be specified using a scenario that describes a particular system context
- Quality attributes are very hard to “add in later” and must be considered early in the design process
- Achieving all QAs may often be impossible, and thus trade-offs among them must be made

Summary

- Exit ticket!