Problem vs. Solution Space

17-423/723 Designing Large-Scale Software Systems

Lecture 2
Jan 15, 2025

Looking Ahead

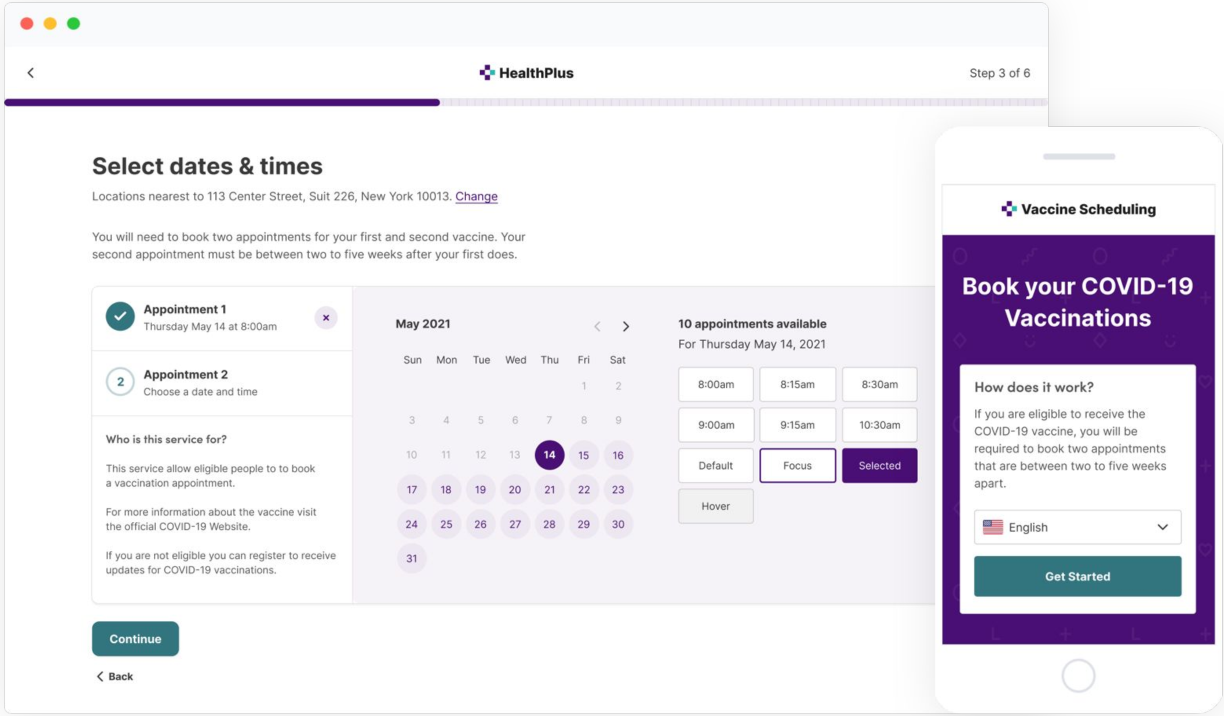
Next 2~3 weeks: Foundational techniques and tools for design

Domain & design modeling, quality attributes & trade-offs, generating design ideas, design review, design processes

Second half of the course: Designing for quality attributes

Design for change, interoperability, reuse, scalability, robustness, security, AI,...

Project Overview: Medical Appointment App



Select dates & times

Locations nearest to 113 Center Street, Suit 226, New York 10013. Change

You will need to book two appointments for your first and second vaccine. Your second appointment must be between two to five weeks after your first does.

Appointment 1
Thursday May 14 at 8:00am

Appointment 2
Choose a date and time

Who is this service for?

This service allow eligible people to to book a vaccination appointment.

For more information about the vaccine visit the official COVID-19 Website.

If you are not eligible you can register to receive updates for COVID-19 vaccinations.

May 2021

Sun	Mon	Tue	Wed	Thu	Fri	Sat
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

10 appointments available
For Thursday May 14, 2021

8:00am	8:15am	8:30am
9:00am	9:15am	10:30am
Default	Focus	Selected
Hover		

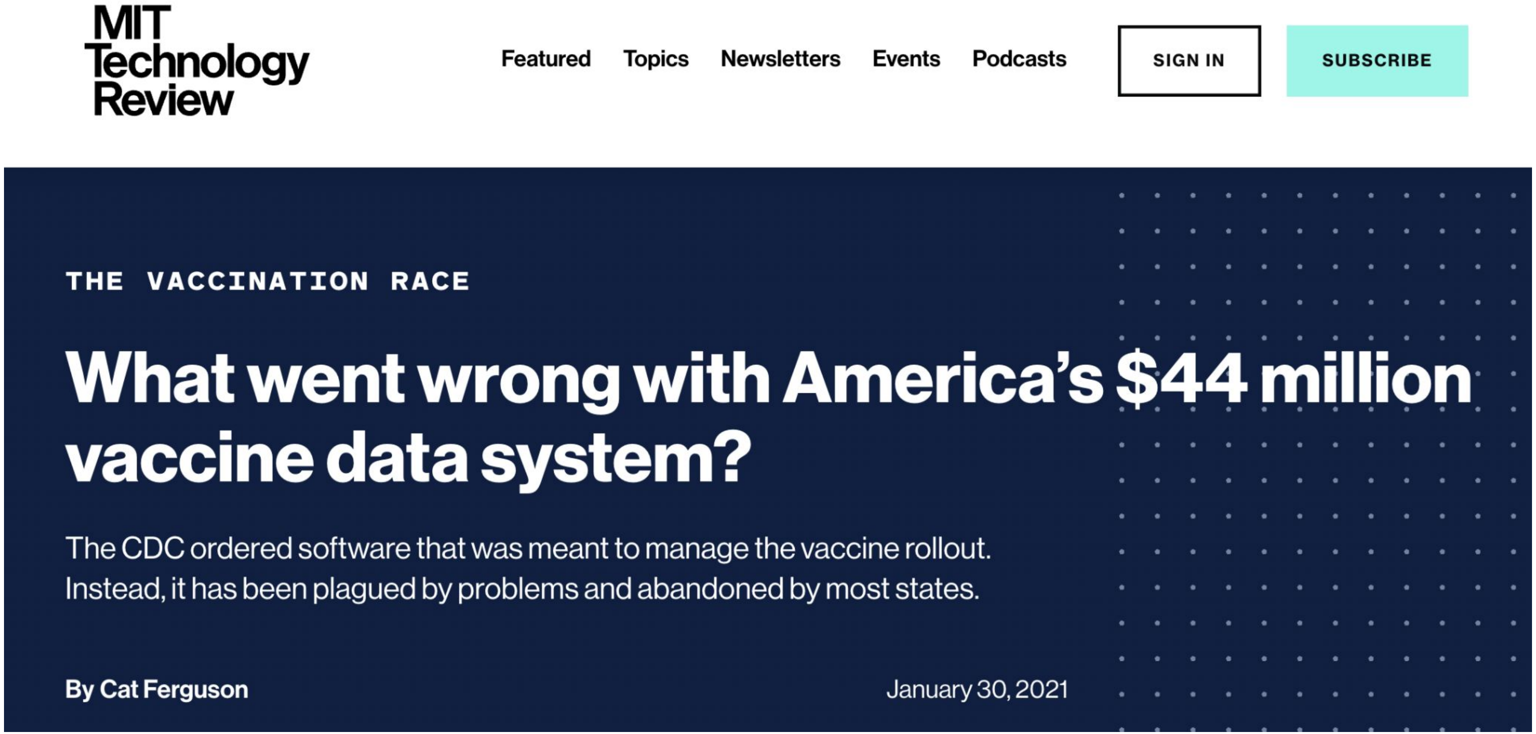
Book your COVID-19 Vaccinations

How does it work?

If you are eligible to receive the COVID-19 vaccine, you will be required to book two appointments that are between two to five weeks apart.

English

Challenges



THE VACCINATION RACE

What went wrong with America's $44 million vaccine data system?

The CDC ordered software that was meant to manage the vaccine rollout. Instead, it has been plagued by problems and abandoned by most states.

By Cat Ferguson

January 30, 2021

https://www.technologyreview.com/2021/01/30/1017086/cdc-44-million-vaccine-data-vams-problems/

Challenges

Changeability: Changing vaccine requirements, policies, user requirements

Reusability: Service reuse across multiple locations with varying policies

Interoperability: Sharing information across multiple systems

Scalability: Increasing number of appointment requests

Usability: Users with varying experience in technology

Security/privacy: Storage and sharing of sensitive data

Project Milestones

M1: Initial system design

M2: Prototype implementation & deployment

M3: Iterative design for feature extension **<-- cross-team collaboration**

M4: Service integration **<-- cross-team collaboration**

M5: Iterative design for additional qualities

M6: Final project presentation

Today’s Learning Goals

- Recognize the distinction between the problem and solution space
- Describe requirements, domain assumptions, and specifications for a system
- Specify a context model to communicate key elements of a domain
- Describe two perspectives on design: Design as problem solving vs. design as problem setting

Problem vs. Solution Space

Problem vs. Solution Space

Problem space (aka **domain** or **world**)

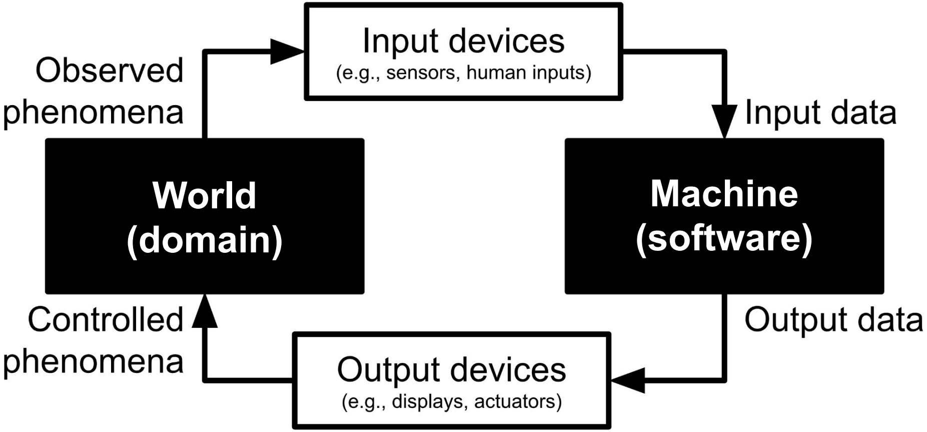
Physical entities in the real world, their behaviors & relationships

Part of the world that software may influence, but cannot directly control

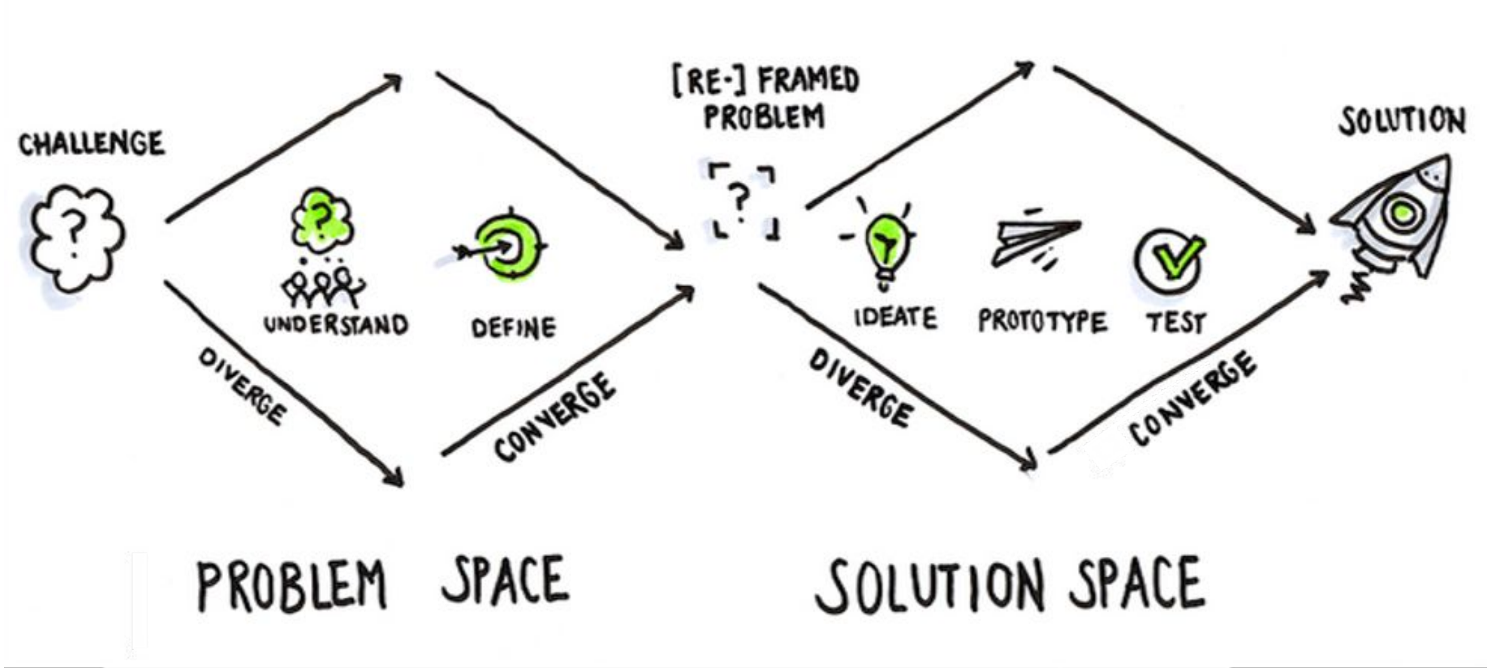
Solution space (aka **machine**)

A product (i.e., software) to be developed to solve the customers' problem

A combination of software components that you have creative control over



Understanding problem space is a critical part of design!



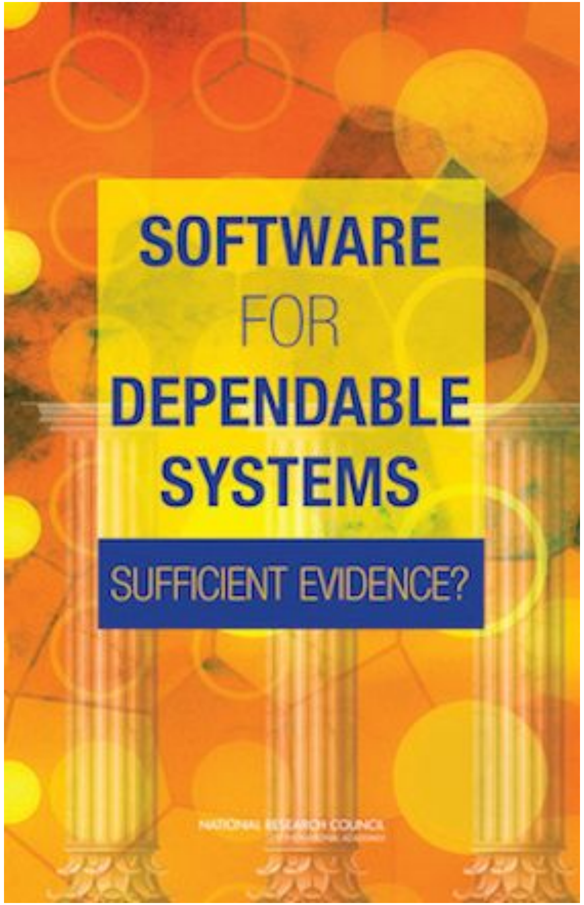
Major Cause of Software Failures

An investigation of software-related failures by the US National Research Council

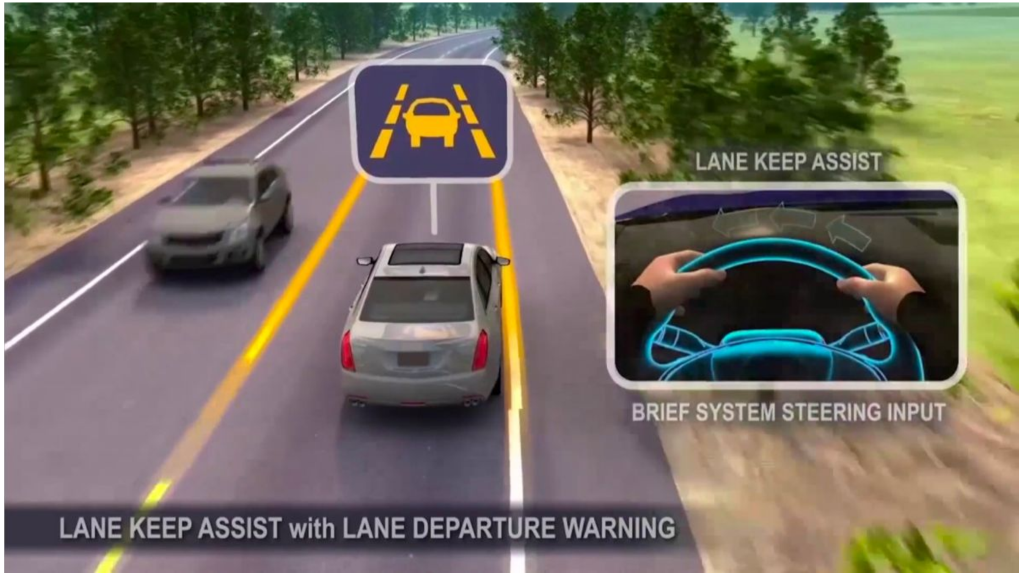
Studied failures in a wide range of domains such as aeronautics, electricity grids, automotive, healthcare, financial services

Bugs in code account only for 3% of fatal software accidents

Most failures due to poor understanding of the problem space or usability issues

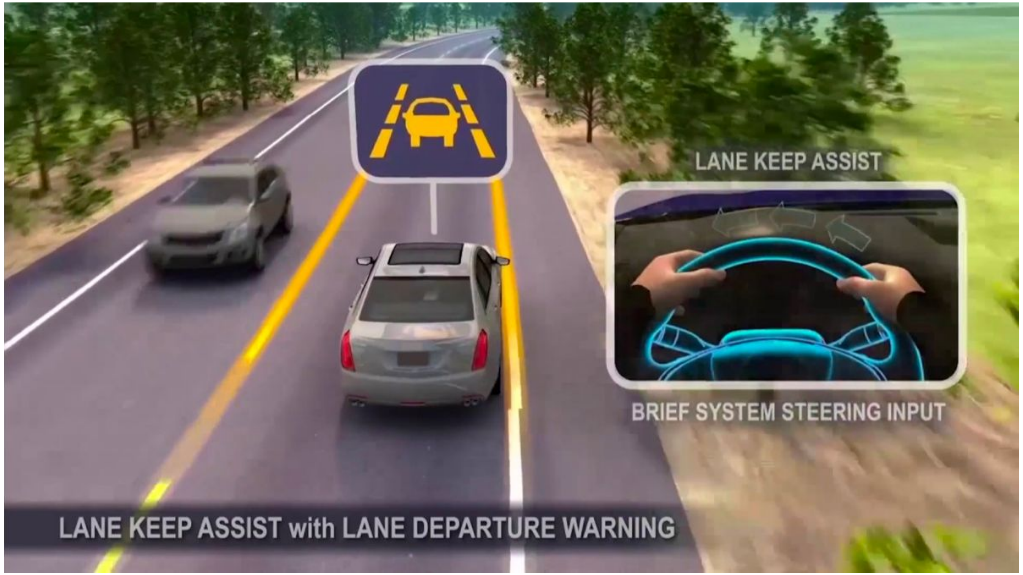


Example: Lane Departure Warning (LDW) System


LANE KEEP ASSIST
BRIEF SYSTEM STEERING INPUT
LANE KEEP ASSIST with LANE DEPARTURE WARNING

System (LDW) Requirement: Alert the driver by displaying a warning when the car is about to go over the lane

Example: Lane Departure Warning (LDW) System


LANE KEEP ASSIST
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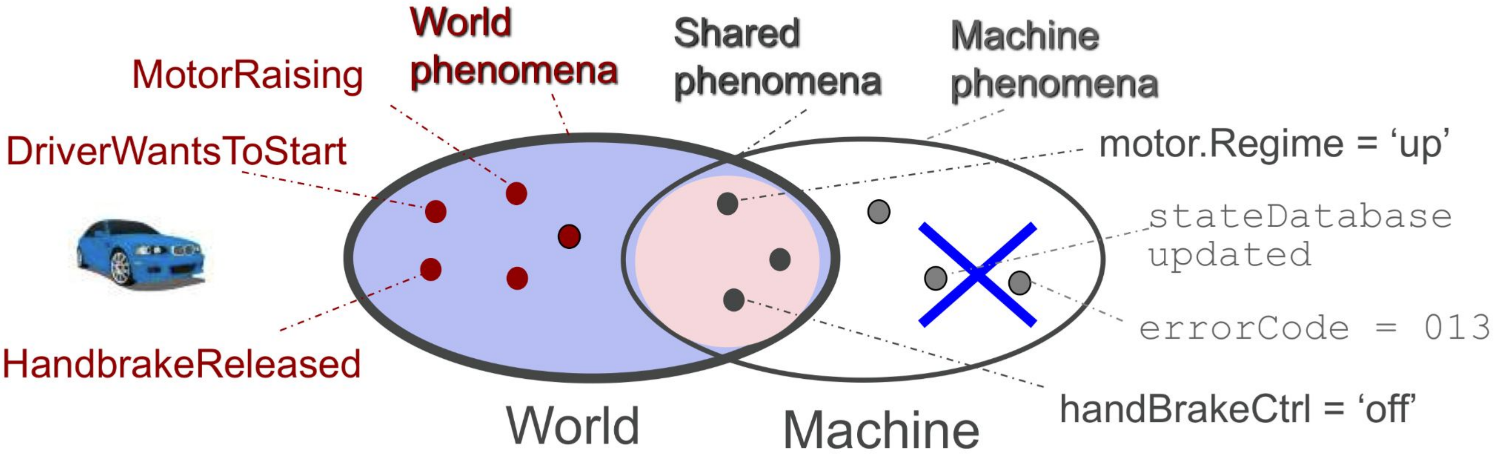
Q. What are different types of entities in the world (problem space)?

Shared Phenomena



Shared phenomena: Interface between the world & software

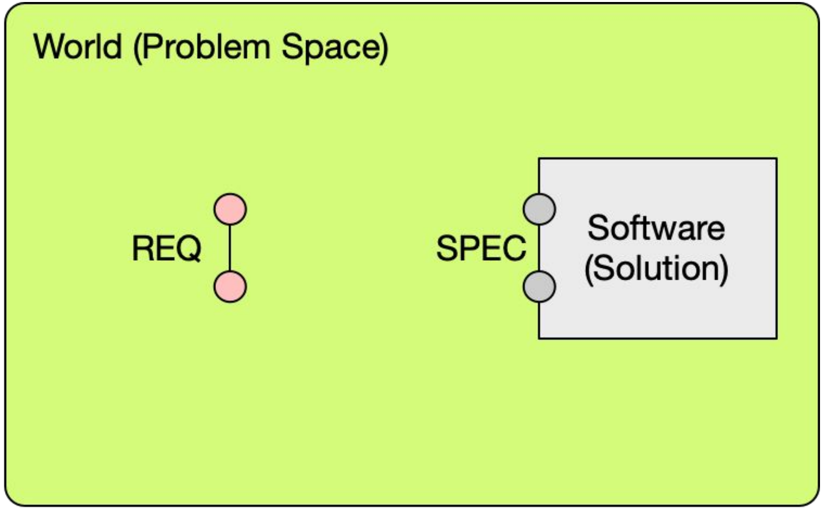
Input: Information generated through Lidar, camera, pressure sensors, GPS

Output: Signals generated & sent to the departure warning system

Software can influence the world **only through the shared interface**

Beyond this interface, we can only assume how the entities in the world will behave

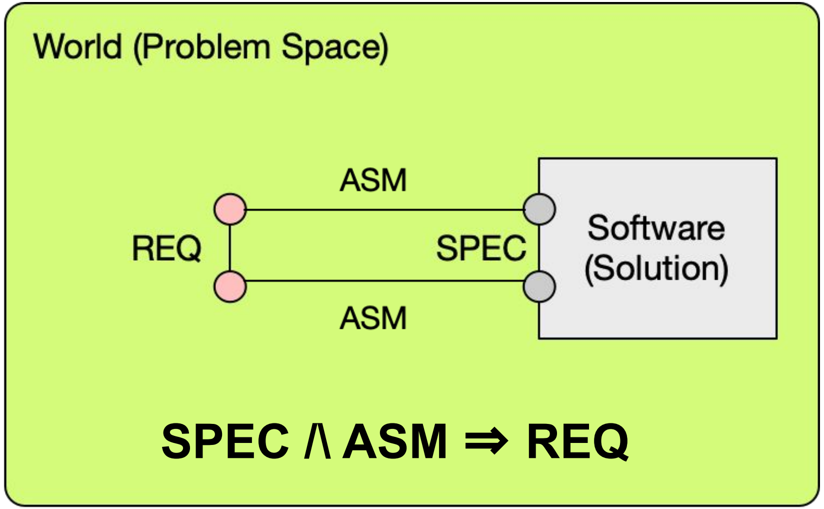
Requirement, Assumptions, and Specification



Requirement (REQ): What the system must achieve, in terms of desired effects on the world

Specification (SPEC): What software must implement, expressed over the shared interface

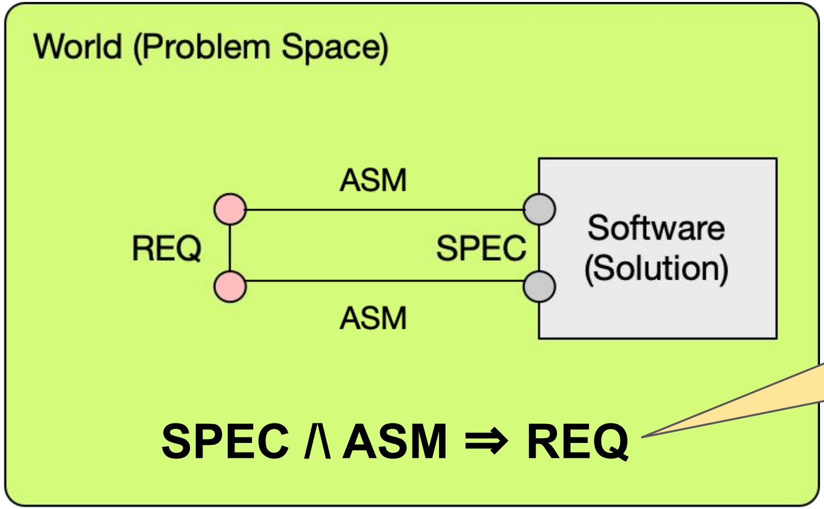
Requirement, Assumptions, and Specification



SPEC /\ ASM ⇒ REQ

Requirement (REQ): What the system must achieve, in terms of desired effects on the world
Specification (SPEC): What software must implement, expressed over the shared interface
Domain assumptions (ASM): What’s assumed about the behavior/properties of the world; bridges the gap between REQ and SPEC

Satisfaction Argument



SPEC /\ ASM ⇒ REQ

“If my software is implemented correctly (SPEC) and the world behaves as assumed (ASM), then the system achieves its requirement (REQ)”

Requirement (REQ): What the system must achieve, in terms of desired effects on the world
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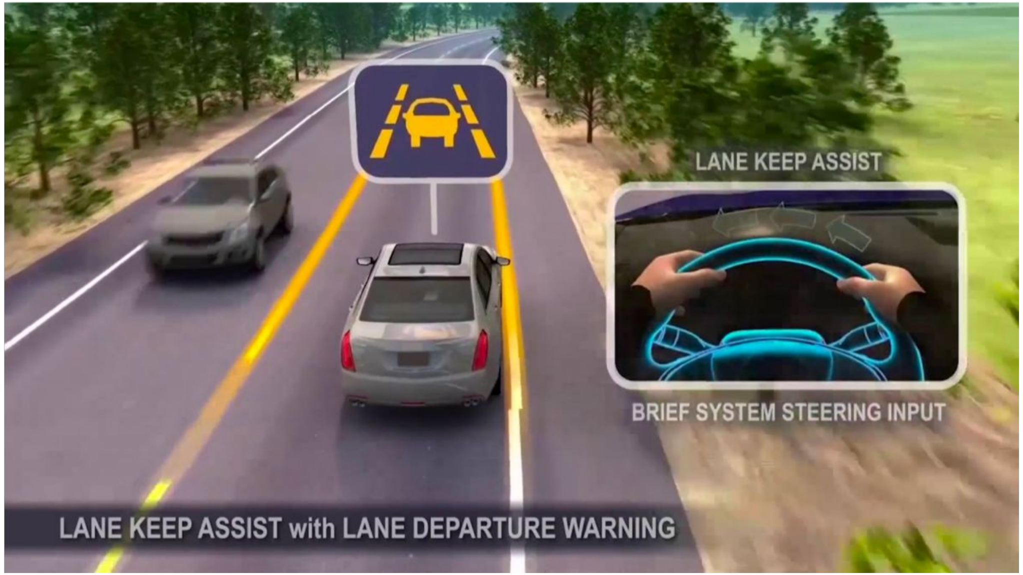
Example: Lane Departure Warning (LDW) System


LANE KEEP ASSIST
BRIEF SYSTEM STEERING INPUT
LANE KEEP ASSIST with LANE DEPARTURE WARNING

Domain entities: Lane markings, lane sensors, vehicle, driver

Q. What are assumptions (ASM) that are necessary to ensure the system requirement (REQ)?

Q. What is the responsibility of the LDW software (SPEC)?

Why do we care about domain assumptions?

Missing or incorrect assumptions are a common cause of system failures

Assumptions constraint the space of possible solutions (i.e., software)

- Determine what’s actually viable as a product
- Determine what the responsibility of software should be

Identifying domain entities & assumptions is one of the first steps in any design process!

Assumptions: Other Examples

Q. Examples from your own experience?

Assumptions: Other Examples

“The nurse always enters the correct amount of medicine”

“Both of the engines on a plane will not fail at the same time”

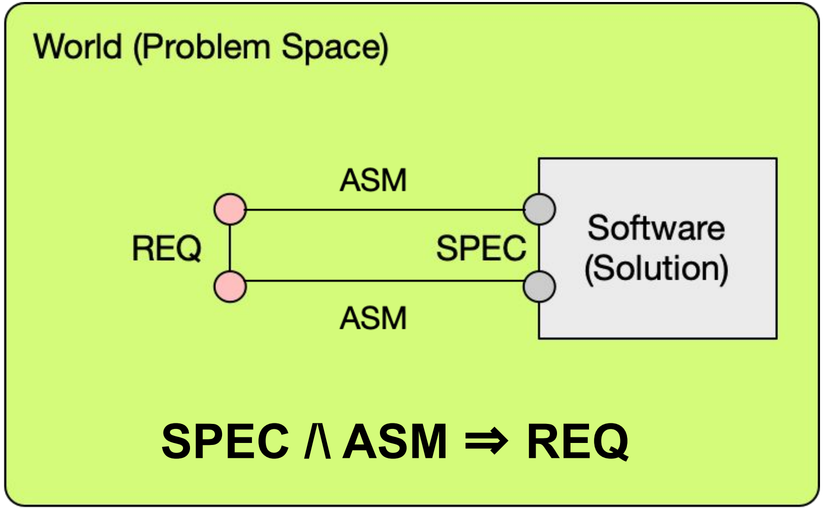
“Users will have access to a mobile device with GPS enabled”

“The battery will last for the next 300 hours”

“The user will never store the password in a plaintext on Github”

“The driver will be fully attentive and always have their hands on the steering wheel”

What could go wrong?



SPEC /\ ASM ⇒ REQ

- Missing or invalid assumptions (ASM)
- Missing or inconsistent requirement (REQ)
- Incorrect/violated specification - for example, due to a bug in code (SPEC)
- Inconsistent spec and assumptions (SPEC /\ ASM implies false)

Assumptions are often violated!

VASILIKI DOLAS VIA STORYFUL
TESLA DRIVER CAUGHT SLEEPING AT THE WHEEL
TEMECULA
abc 7
#abc7eyewitness

Assumption violations are a common cause of failures

Tesla is sued by drivers over alleged false Autopilot, Full Self-Driving claims

[Tesla]… has also said both technologies "require active driver supervision," with a "fully attentive" driver whose hands are on the wheel, "and do not make the vehicle autonomous."

Another Example: Lufthansa 2904 Runway Crash

RT enabled ⟺ On ground

Reverse thrust (RT):

Decelerates plane during landing

When plane is on the ground, the RT system should be activated

Conversely, if the plane is in the air, it is unsafe to enable RT!

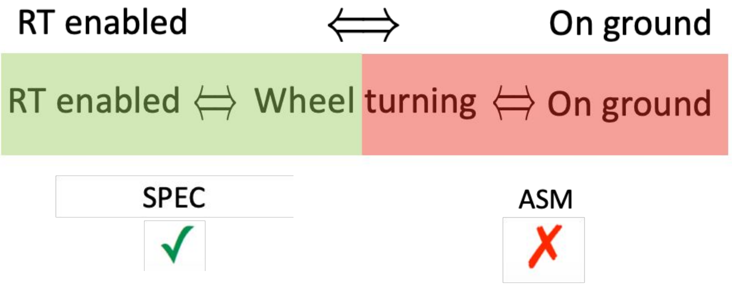
Safety requirement (REQ):

RT is enabled if and only if plane is on the ground

Q. Suppose you want to implement this feature using software. How should the software know if the plane is on the ground?

One answer: Check whether the wheel is turning

Another Example: Lufthansa 2904 Runway Crash



RT enabled ⟺ On ground

RT enabled ⟺ Wheel turning ⟺ On ground

SPEC ✓

ASM ✗

Reverse thrust (RT): Decelerates plane during landing

Safety requirement (REQ):

RT is enabled if and only if plane is on the ground

What was implemented by software (SPEC):

RT is enabled if and only if wheel turning

What was assumed (ASM):

Wheel is turning if and only if it's on ground

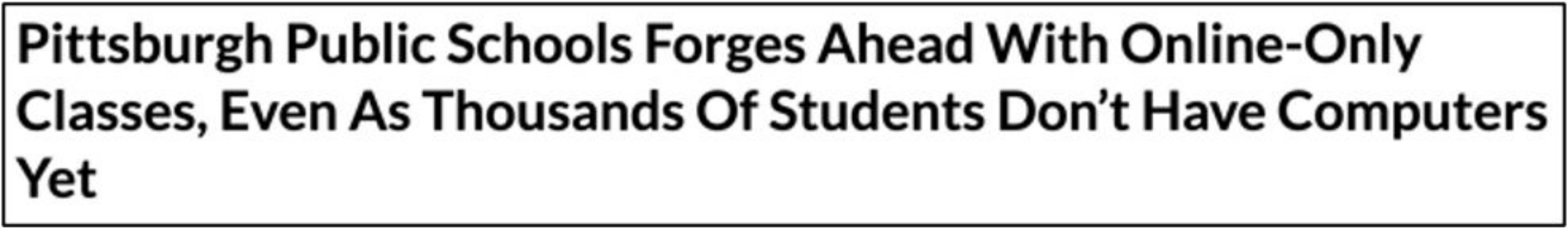
But sometimes runway gets wet due to rain!

- Wheel failed to turn fast enough when plane was on ground
- **Assumption (ASM) was violated!**
- Pilot attempted to enable RT, but it was overridden by the software
- Plane went off the runway and crashed

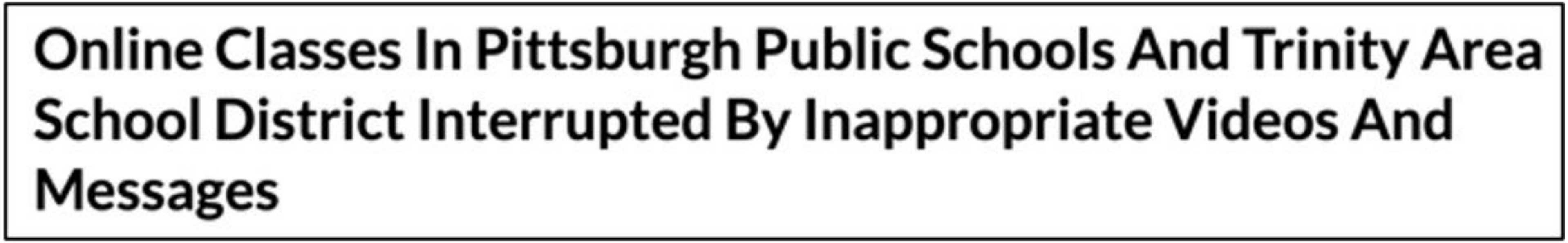
Discussion: Remote Classroom

As an IT developer for the Pittsburgh Public School, you’ve been tasked with designing a system for enabling transition to remote education during pandemic.

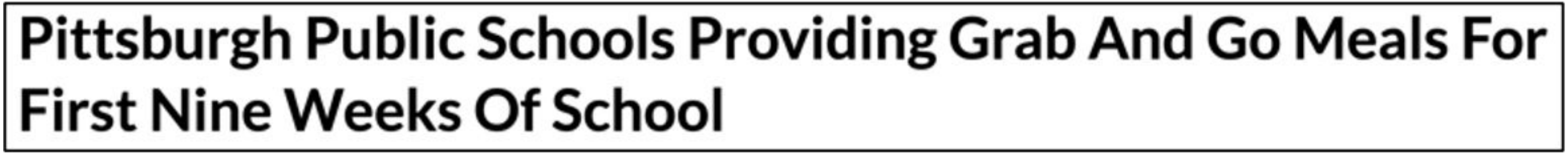
Q. What are different entities and stakeholders in the problem space?
Q. What are domain assumptions (ASM) needed to ensure that every student continues to receive education (REQ)?



Pittsburgh Public Schools Forges Ahead With Online-Only Classes, Even As Thousands Of Students Don’t Have Computers Yet



Online Classes In Pittsburgh Public Schools And Trinity Area School District Interrupted By Inappropriate Videos And Messages



Pittsburgh Public Schools Providing Grab And Go Meals For First Nine Weeks Of School

Communicating Domain Knowledge

Domain Models

Textual/graphical descriptions of the domain (i.e,. problem space), depicting its key entities and assumptions

Why build a domain model?

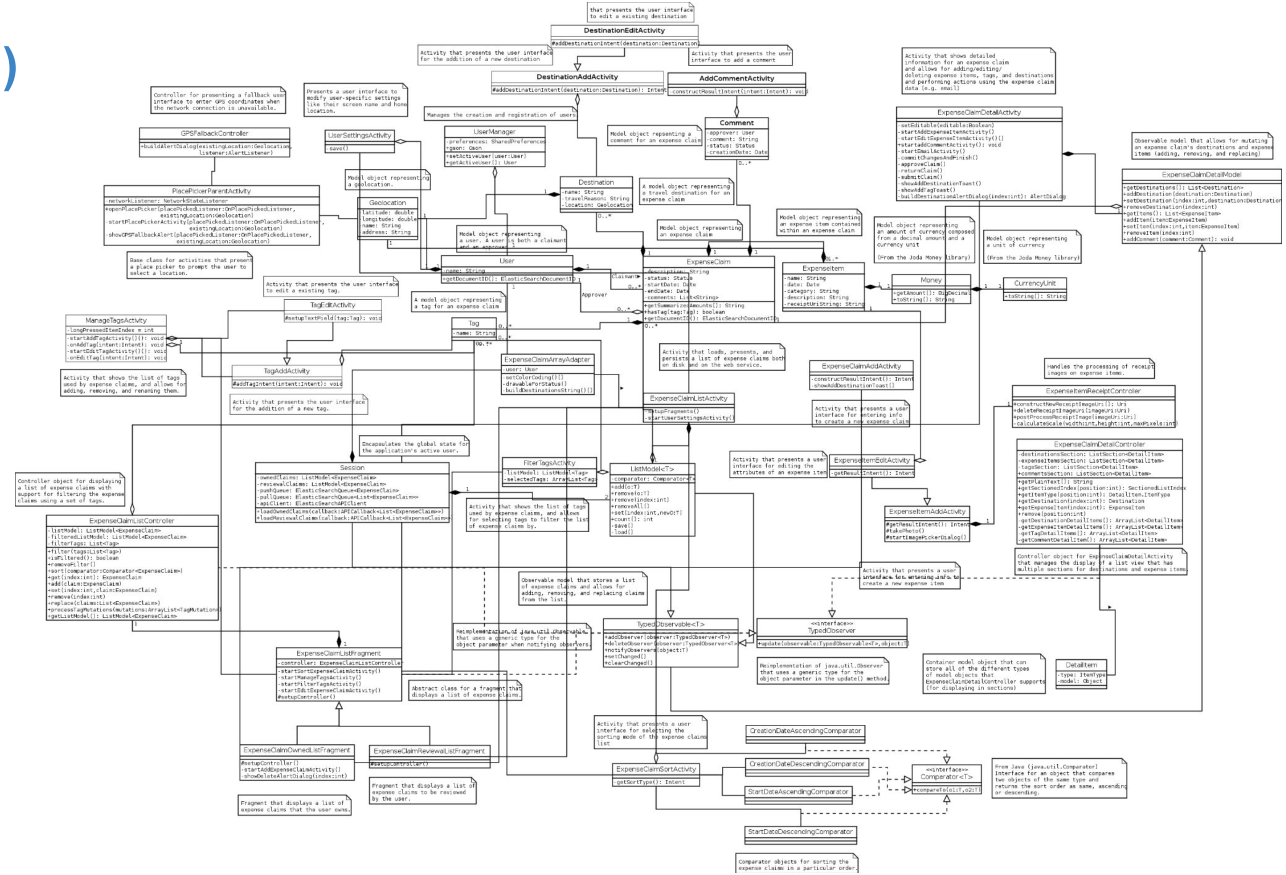
Establish common terminology & assumptions with stakeholders and other teams

Analyze to identify missing entities or missing/incorrect assumptions

Serve as a reference for subsequent design decisions

In this class, we will use a type of domain model called a **context model**

(Digression)



There are many notations/diagrams/approaches for specifying models (e.g., UML)
In this class, we will stick to simple, lightweight notations for modeling
Our goal is to communicate ideas, not to document everything!

Context Model: Elements

Entity

Stakeholders, users, physical objects, conceptual objects

One **single, special “machine” entity** is reserved for the software component

Interaction

A relationship between a pair of entities: Physical interactions, events, information, etc.,

Requirement (REQ)

A relationship among entities that is desired, but not satisfied yet; a system will be designed & built to make this true

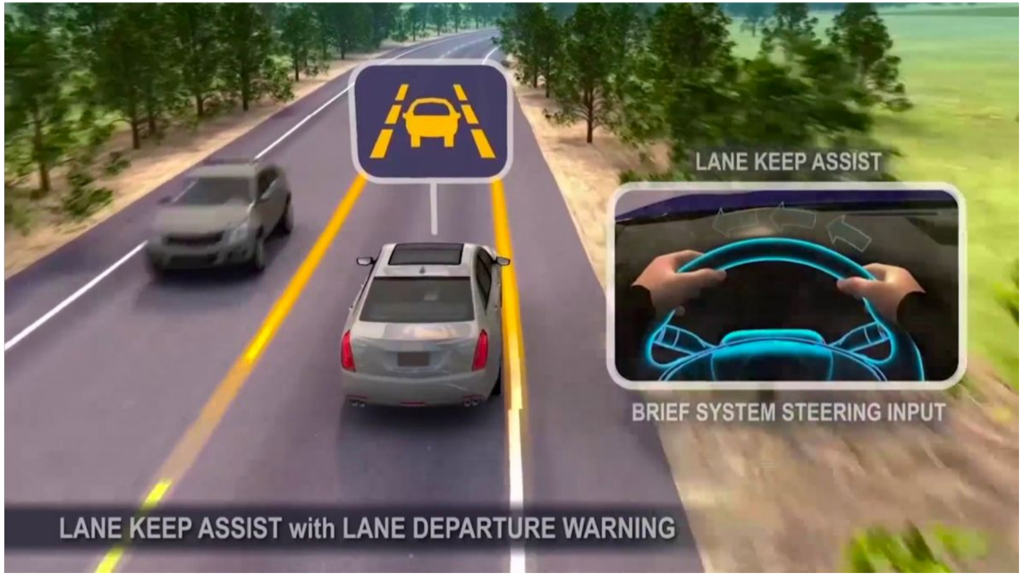
Assumptions (ASM)

A statement about a property or behavior of an entity, necessary for satisfying a requirement

Specification (SPEC)

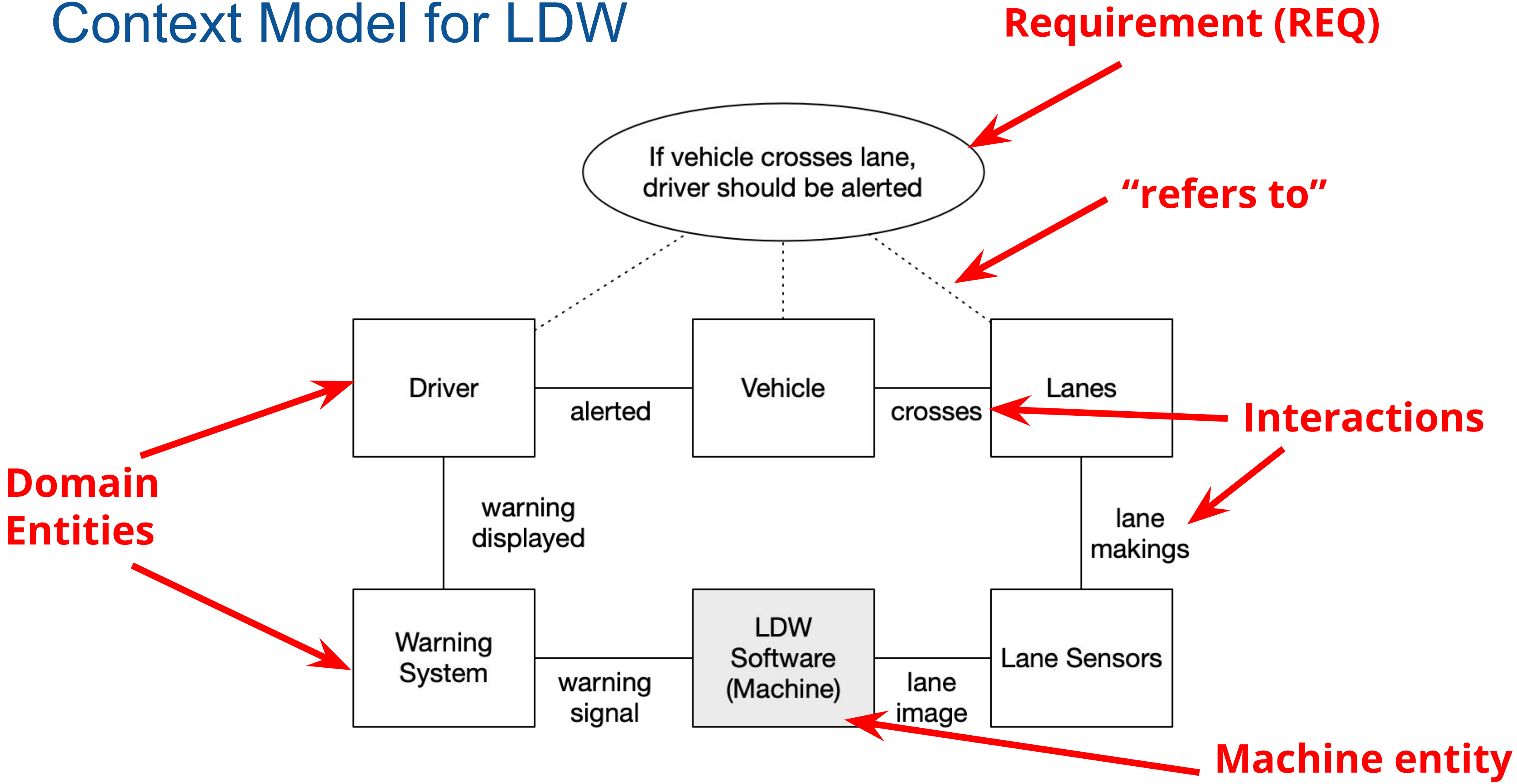
A statement about the responsibility of the machine (i.e., software)

Example: Lane Departure Warning (LDW) System

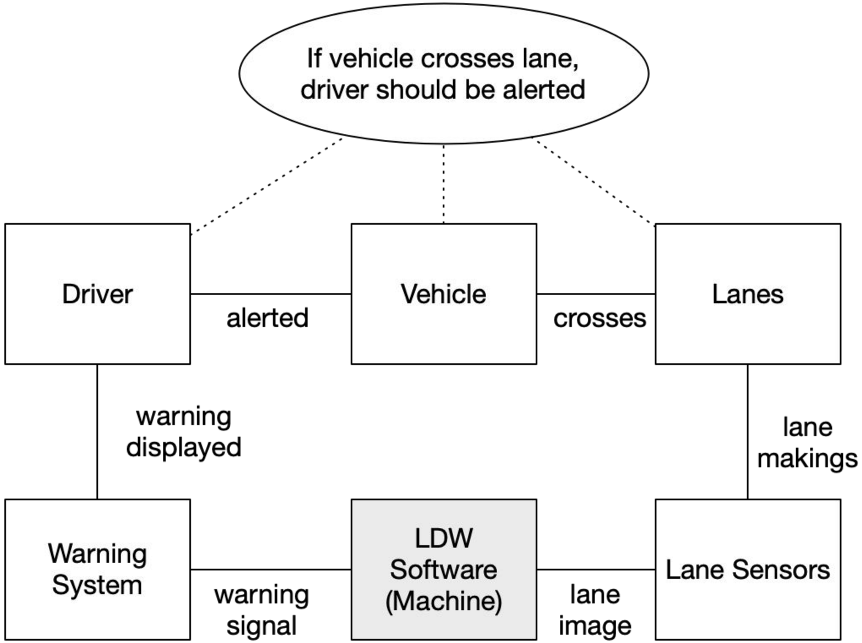

LANE KEEP ASSIST
BRIEF SYSTEM STEERING INPUT
LANE KEEP ASSIST with LANE DEPARTURE WARNING

Requirement (REQ): If the vehicle is about to cross the lane, alert the driver by displaying a warning

Context Model for LDW



Context Model for LDW



Assumptions (ASM)

Lanes: Lane markings are continuous and clearly visible

Lane sensors: Sensors capture the lane markings at a sufficiently high resolution

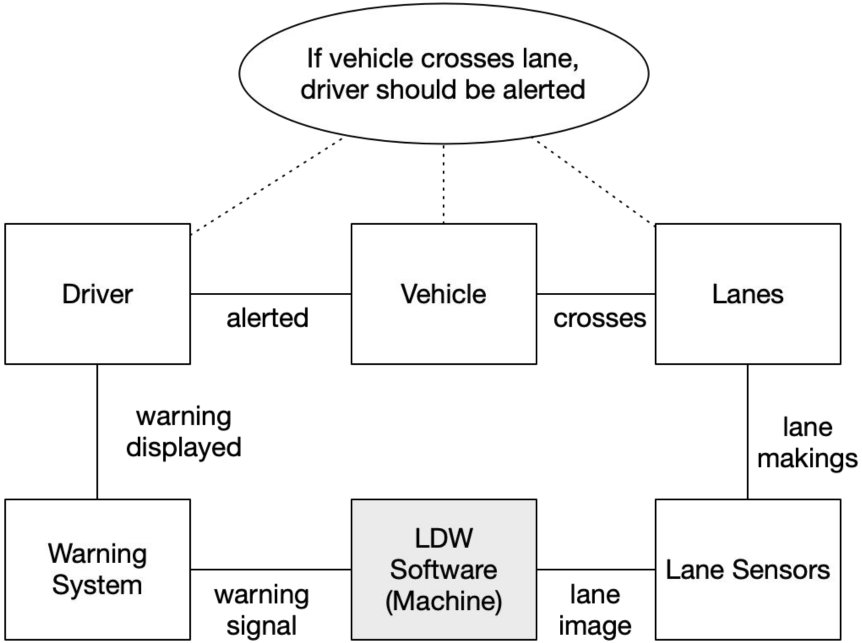
Driver: Driver is attentive of the dashboard display

Warning system: Given a warning signal, it immediately displays the warning on the dashboard

Specification (SPEC)

LDW software shall detect lane departure in input images & generate a warning signal if detected

Context Model for LDW



Q. Why isn’t the machine (LDW software) entity directly connected to the lanes or drivers?

Q. Why isn’t the warning system part of the machine (software) entity?

Q. Why didn’t I include an entity for the steering wheel?

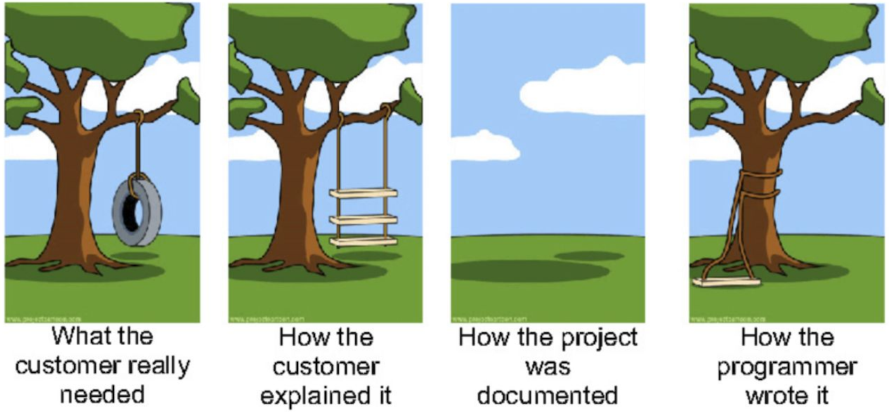
Machine Entity

One **single, special “machine” entity** is reserved for the software component

Q. Why don’t we further describe this in detail by breaking it into multiple entities?

A. Avoid premature design decisions! At this point, we are still trying to understand the problem space.

Where do domain assumptions come from?

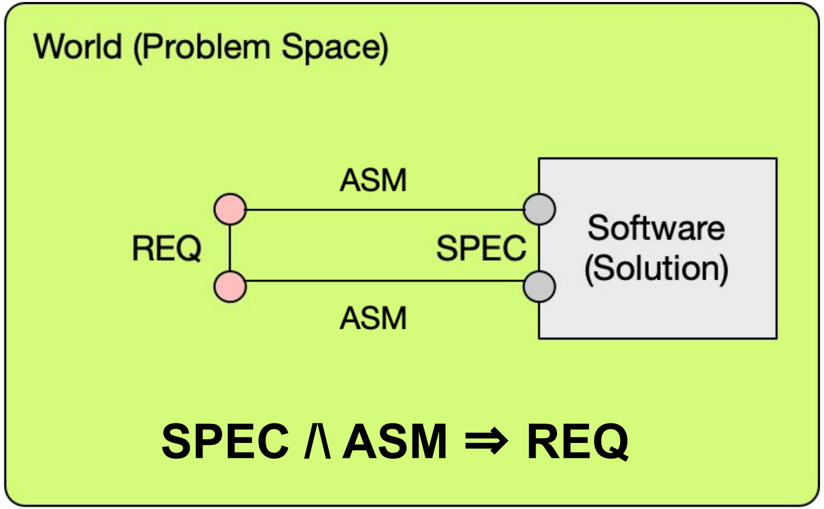

What the customer really needed
How the customer explained it
How the project was documented
How the programmer wrote it

Short answer: From talking to stakeholders, users, and domain experts!

There is an entire subarea of software engineering called **requirements engineering**, which studies how to elicit, specify, and analyze requirements from the problem domain

In this class, we will not go deep into this topic (but we will come back to it from time to time!)

Analyzing the context model

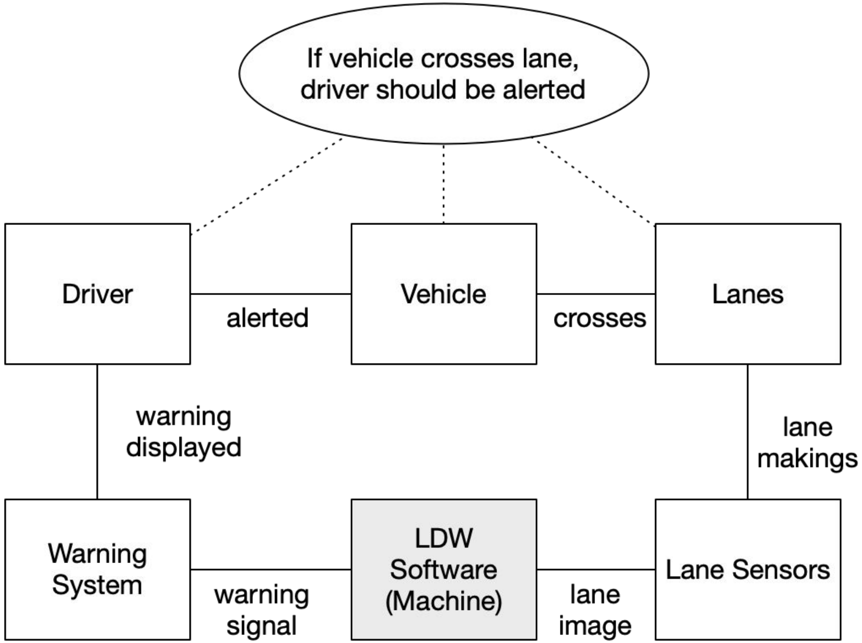


SPEC /\ ASM ⇒ REQ

Apply adversarial thinking!
- What are possible ways to break the argument “SPEC /\ ASM => REQ”?
- What are possible ways to violate an assumption?

- **Missing or invalid assumptions (ASM)**
- Missing or inconsistent requirement (REQ)
- Incorrect/violated specification (SPEC)
- Inconsistent spec and assumptions (SPEC /\ ASM implies false)

Context Model for LDW



Assumptions (ASM)

Lanes: Lane markings are continuous and clearly visible

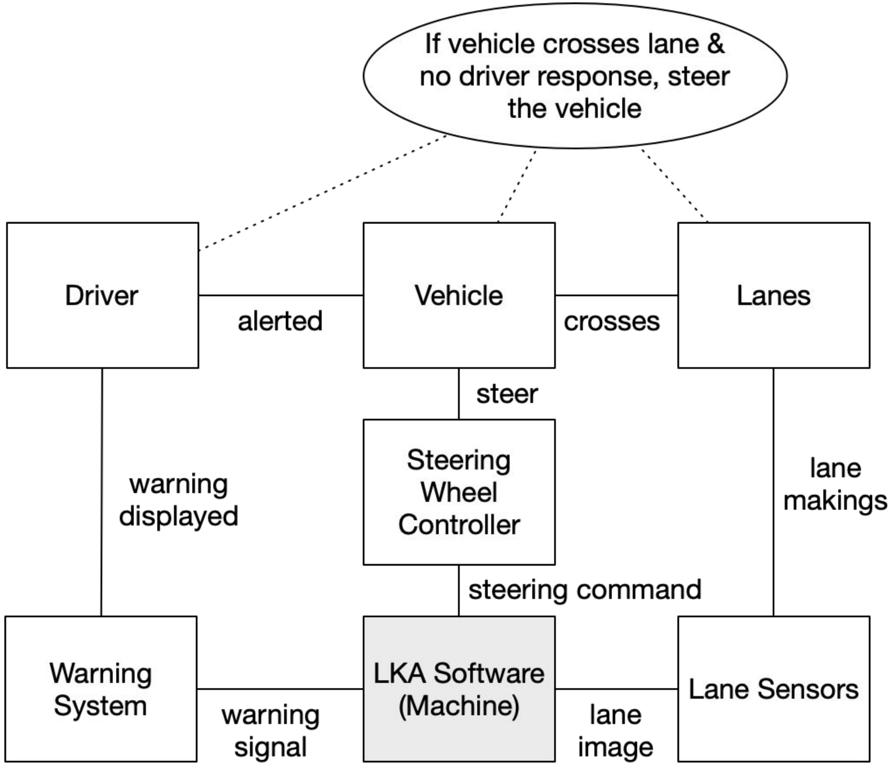
Lane sensors: Sensors capture the lane markings at a sufficiently high resolution

Driver: Driver is attentive of the dashboard display

Warning system: Given a warning signal, it immediately displays the warning on the dashboard

Q. Which of these assumptions may not hold in practice? What's a more reasonable assumption? How does this change the responsibility of software?

Context Model for Lane Keeping Assist (LKA)



Assumptions (ASM)

Driver: Driver might not be fully attentive of the dashboard display

Steering Wheel Controller: It steers the vehicle based on the command received

Specification (SPEC)

LKA software shall detect lane departure in input images & generate a warning signal; if the driver does not respond in time, it shall generate a command to steer the vehicle back into the lane

A recipe for building a context model

1. State a requirement to be achieved by the system (REQ)
2. Identify entities that are referenced by the requirement
3. Identify other entities that interact with those entities in the real world
4. Connect domain entities to the software entity (machine)
5. Identify assumptions (ASM) that are needed to satisfy REQ
6. Identify specification (SPEC) on the software component that are needed to ensure REQ along with ASM
7. Check whether any of the assumptions may be violated in practice
8. If not, go back and modify assumptions (Step 5), specification (Step 6), or even possibly the requirement (Step 1)

More in recitation!

Closing Thoughts

Missing or incorrect assumptions are a common cause of system failures

Assumptions constraint the space of possible solutions and determine the responsibility of software

In most cases, it is impossible to come up with a complete list of domain assumptions (**Q. Why?**)

But the process of identifying and documenting assumptions can help reduce potential risks & communicate domain knowledge to stakeholders & other team members

Two Perspectives on Design

Perspective: Design as Problem Solving

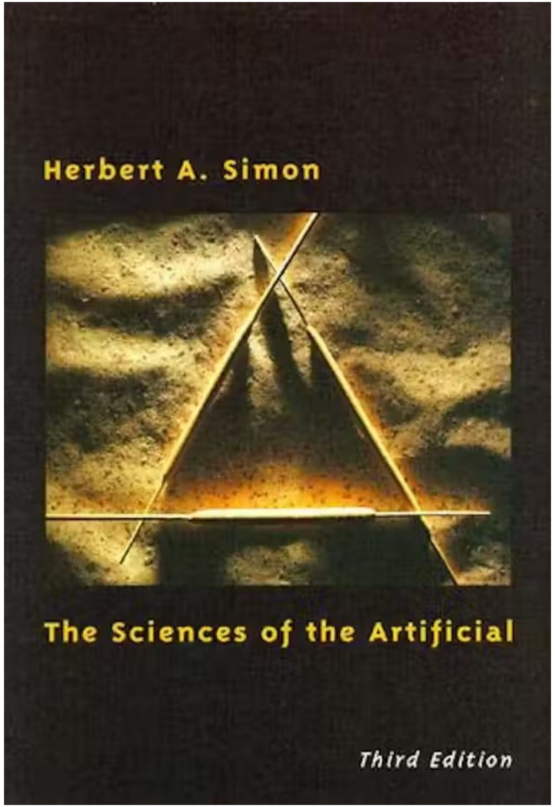
Design is a **systematic**, **rational** process

A description of a problem space & constraints (i.e., assumptions) is given

Designer makes a sequence of design decisions

Each candidate solution is evaluated until a satisfactory design is found

Simon hinted that one day, this process could be automated by computers



Perspective: Design as Problem Setting

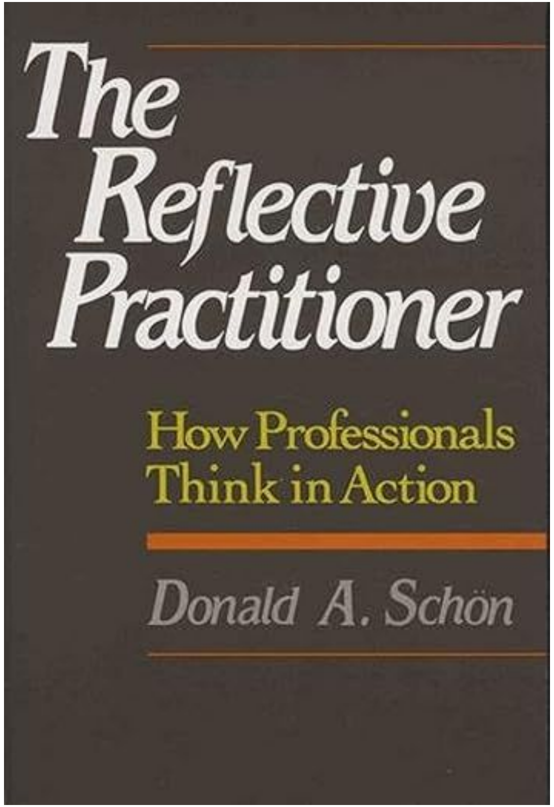
Design is a conversation between the problem space & the designer

Simon’s model is flawed; designers don’t actually work like this in practice

As the designer explores possible solutions, they learn more about the problem itself

Outcome of design is both the product & also an increased understanding of the problem space

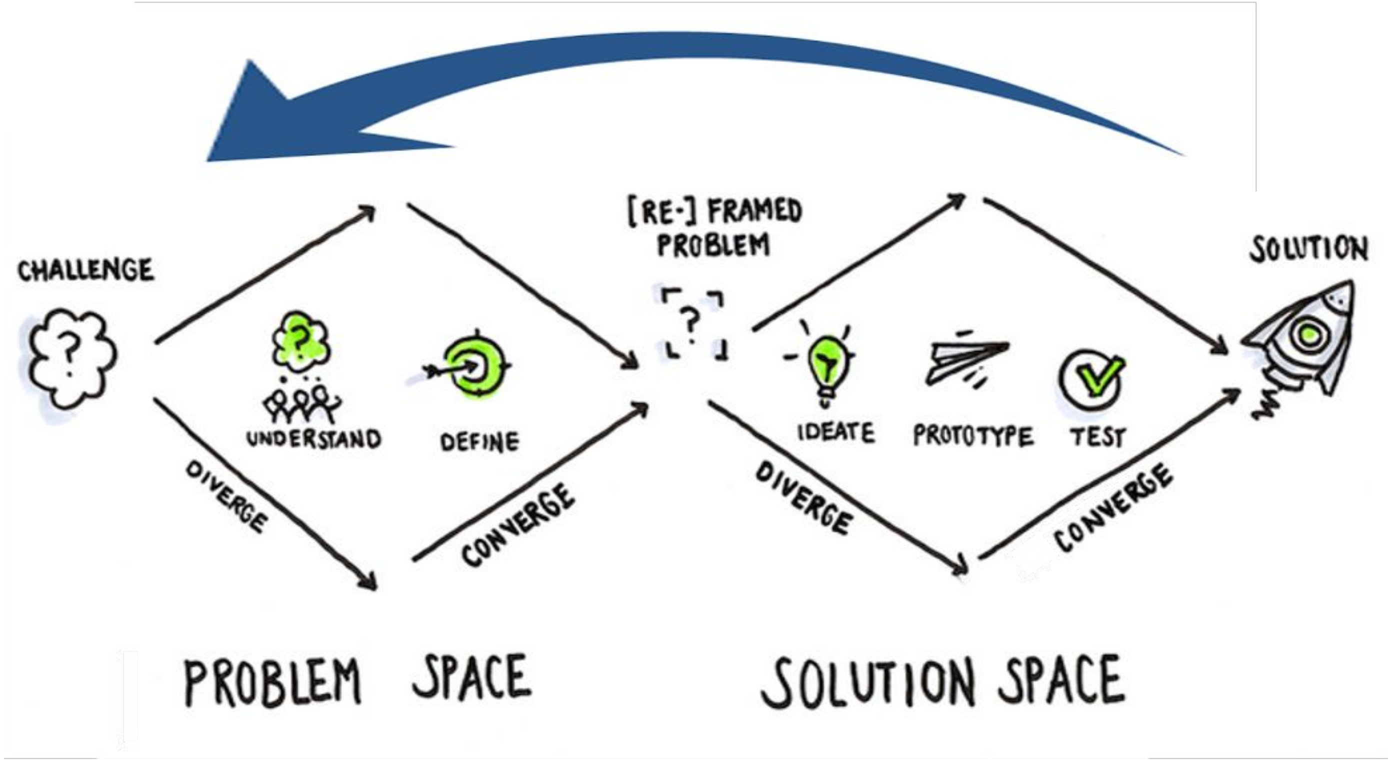
This is unlikely to be fully automatable by computers


The Reflective Practitioner
How Professionals Think in Action
Donald A. Schön

Discussion: Simon vs.Schön

Q. Which one do you think is the “right” model of design?

Design is an iterative, continuous process!



Summary

- Exit ticket!

Further Readings on Problem & Requirements Understanding

- *Problem Frames: Analysing and Structuring Software Development Problems*. Michael A. Jackson. Addison-Wesley, 2000.
- *Requirements Engineering: From System Goals to UML Models to Software Specifications.* Axel van Lamsweerde. Wiley, 2009.
- *Software Requirements and Specifications: A Lexicon of Practice, Principles and Prejudices.* Michael A. Jackson. Addison-Wesley Professional, 1995.
- *Domain-driven Design: Tackling Complexity in the Heart of Software.* Eric Evans. Addison-Wesley Professional, 2003.

Summary

- Software alone cannot fulfill system requirements
  - They are just one part of the system, and have limited control over the world
- Domain assumptions are just as critical in achieving requirements
  - If you ignore/misunderstand these, your system may fail or do poorly (no matter how perfect your software is)
- Identify and document these assumptions as early as possible
- Some of the assumptions may be violated over time as the world evolves
- You are never done with identifying