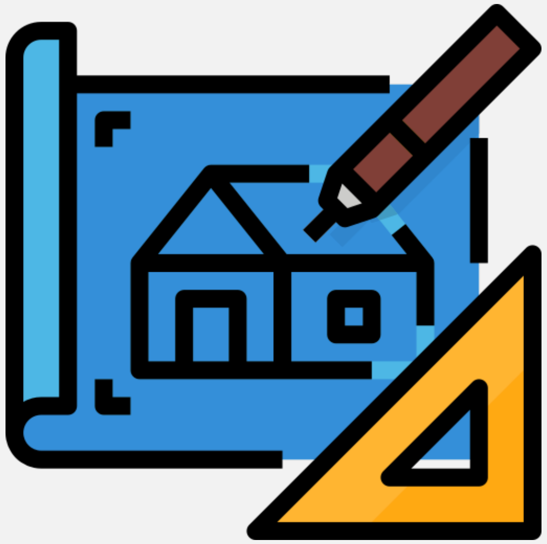
CEN 5016: Software Engineering

Spring 2026

University of Central Florida

Dr. Kevin Moran

Week 4 - Class II: Introduction to Software Architecture



Administrivia

- *SDE Project Part 1*
  - Will be Posted to Course Webpage today
  - Due on Friday, February 13th.
- *Assignment 3*
  - Posted to Course Webpage
  - Due on Monday, February 9th.
  - Make sure to accept the GitHub Organization Invitation!

Software Testing

What can We Test for?

Test Oracles

- “Oracles” are mechanisms that tell you when program execution seems abnormal or unexpected
- E.g. assert, segfault, exception
- Other examples: performance threshold, memory footprint, address sanitizer

Test Oracles

- Obvious in some applications (e.g. “sort()”) but more challenging in others (e.g. “encrypt()” or UI-based tests)
- Lack of good oracles can limit the scalability of testing. Easy to generate lots of input data, but not easy to validate if output (or other program behavior) is correct.
- Fortunately, we have some tricks.

Differential Testing

- If you have two implementations of the same specification, then their output should match on all inputs.
  - E.g. `mergeSort(x).equals(bubbleSort(x))` -> should always be true
  - Special case of a property test, with a free oracle.

- If a differential test fails, at least one of the two implementations is wrong.
  - But which one?
  - If you have N>2 implementations, run them all and compare. Majority wins (the odd one out is buggy).

- Differential testing works well when testing programs that implement standard specifications such as compilers, browsers, SQL engines, XML/JSON parsers, media players, etc.
  - Not feasible in general e.g. for UCF's custom grad application system.

Regression Testing

- Differential testing through time (or versions, say V1 and V2).

- Assuming V1 and V2 don't add a new feature or fix a known bug, then f(x) in V1 should give the same result as f(x) in V2.

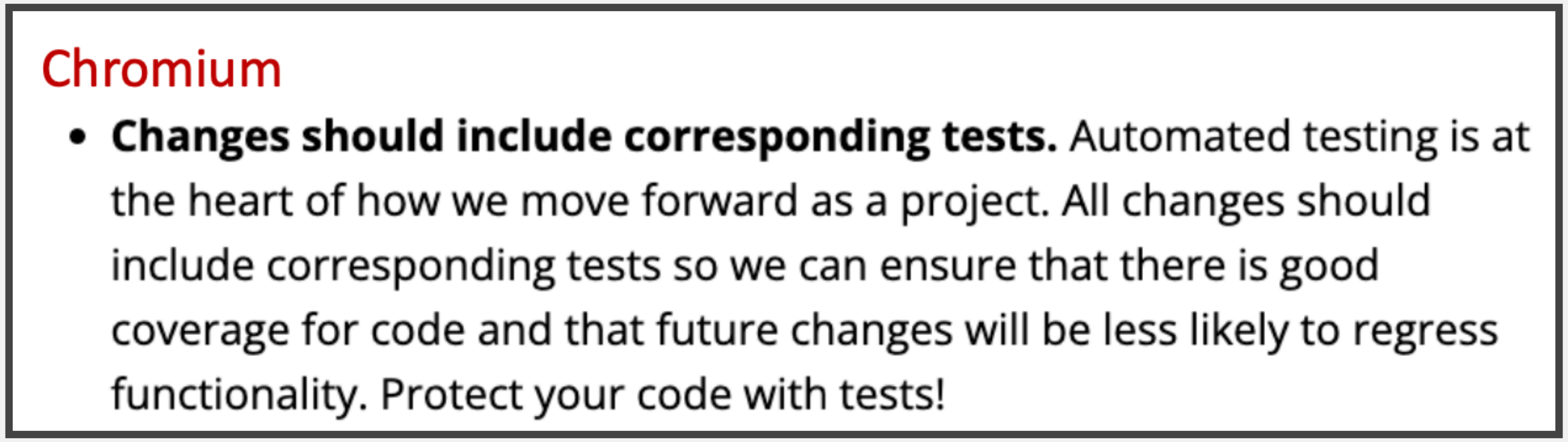
- *Key Idea:* Assume the current version is correct. Run program on current version and log output. Compare all future versions to that output.

When Should We Test?

Test Driven Development

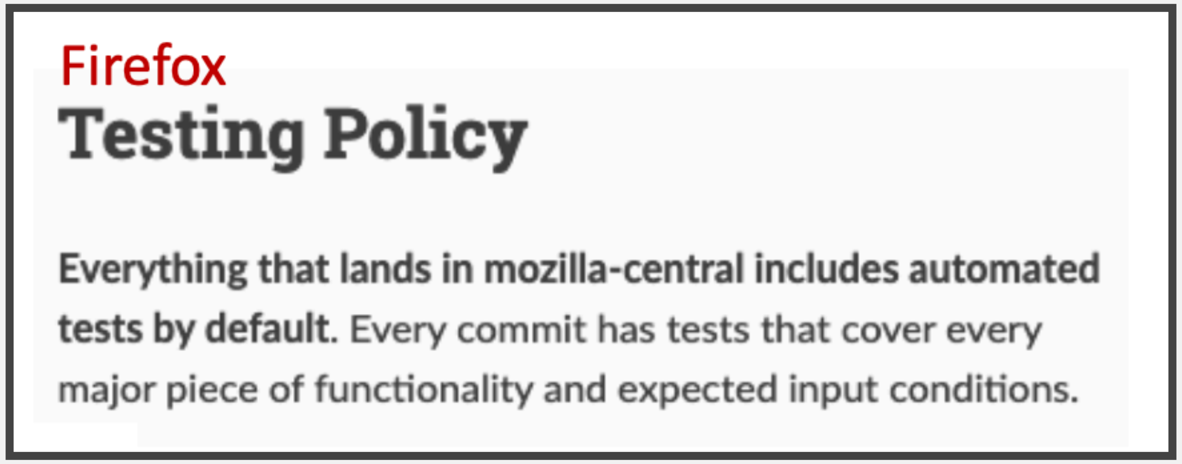
- Tests first!
- Popular agile technique
- Write tests as specifications before code
- Never write code without a failing test
- Claims:
  - Design approach toward testable design
  - Think about interfaces first
  - Avoid unneeded code
  - Higher product quality
  - Higher test suite quality
  - Higher overall productivity

Common Bar for Contributions



Chromium

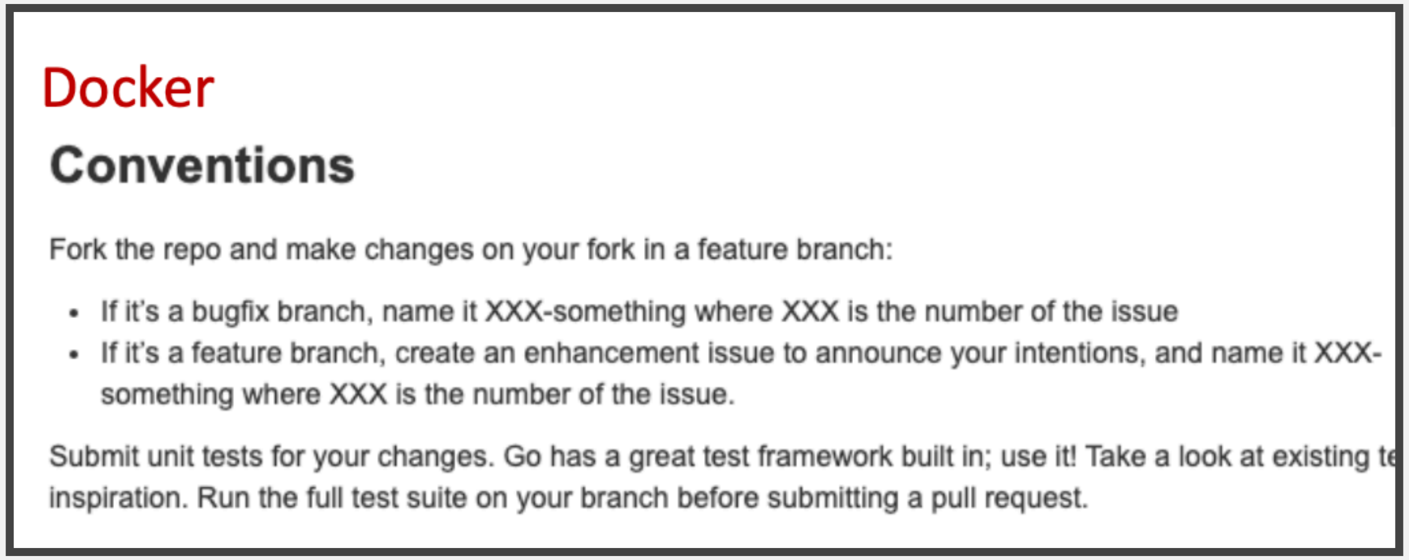
- **Changes should include corresponding tests.** Automated testing is at the heart of how we move forward as a project. All changes should include corresponding tests so we can ensure that there is good coverage for code and that future changes will be less likely to regress functionality. Protect your code with tests!



Firefox

Testing Policy

Everything that lands in mozilla-central includes automated tests by default. Every commit has tests that cover every major piece of functionality and expected input conditions.



Docker

Conventions

Fork the repo and make changes on your fork in a feature branch:

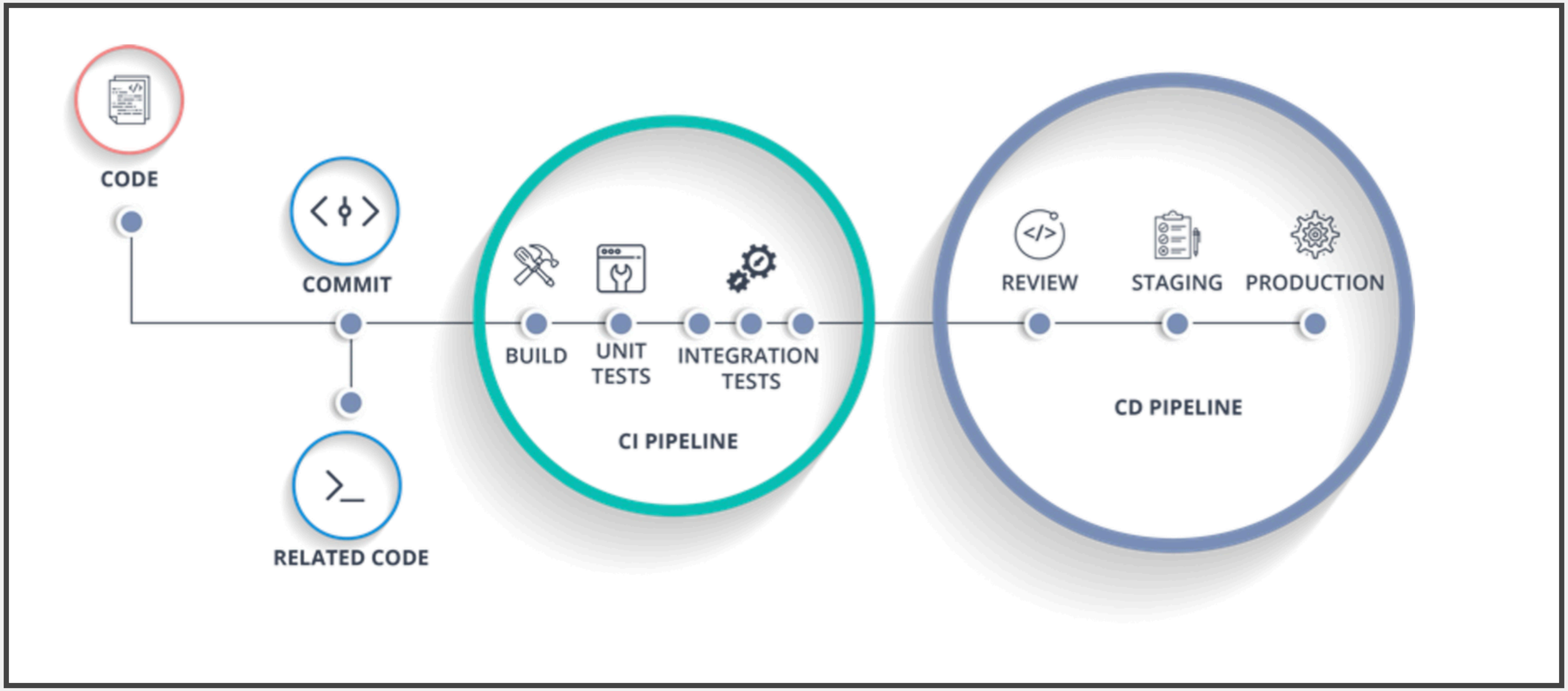
- If it's a bugfix branch, name it XXX-something where XXX is the number of the issue
- If it's a feature branch, create an enhancement issue to announce your intentions, and name it XXX-something where XXX is the number of the issue.

Submit unit tests for your changes. Go has a great test framework built in; use it! Take a look at existing te inspiration. Run the full test suite on your branch before submitting a pull request.

Regression Testing

- Usual model:
  - Introduce regression tests for bug fixes, etc.
  - Compare results as code evolves
    - Code1 + TestSet -> TestResults1
    - Code2 + TestSet -> TestResults2
  - As code evolves, compare TestResults1 with TestResults2, etc.
- Benefits:
- Ensure bug fixes remain in place and bugs do not reappear.
- Reduces reliance on specifications, as <TestSet,TestResults1> acts as one.

Continuous Integration & Deployment

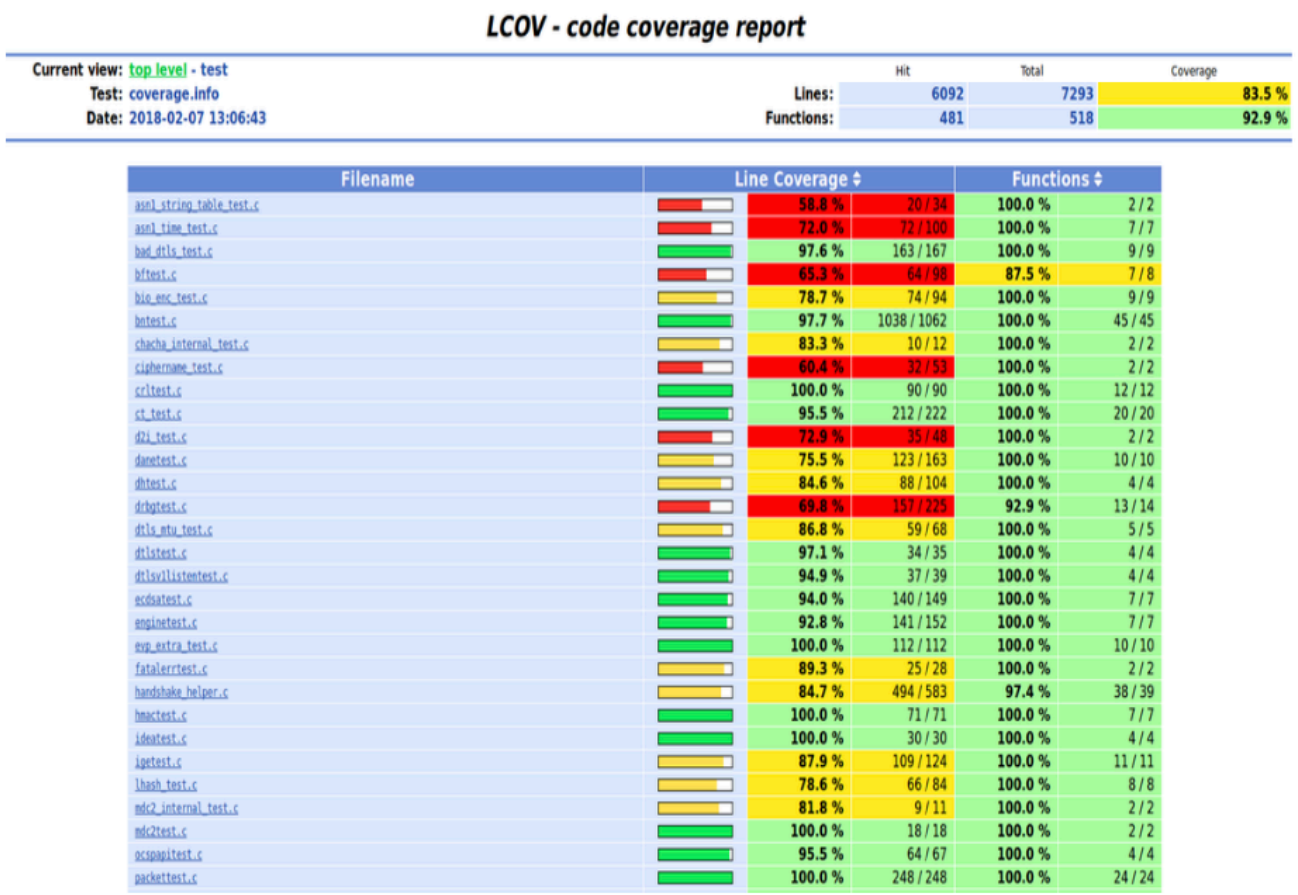


How Good Are Our Tests?

Code Coverage

- Line coverage
  - Statement coverage
  - Branch coverage
  - Instruction coverage
  - Basic-block coverage
  - Edge coverage
  - Path coverage
  - ...

Code Coverage

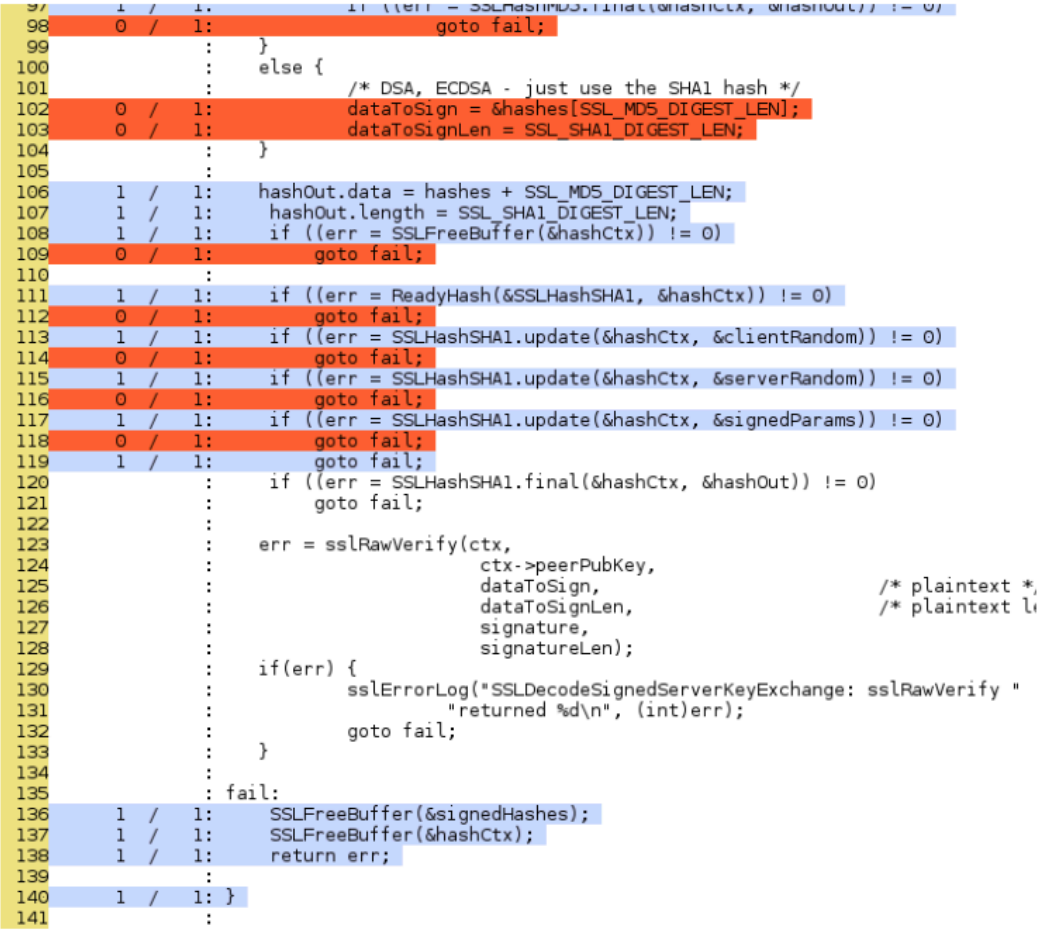


LCOV - code coverage report

Current view: top level - test
Test: coverage.info
Date: 2018-02-07 13:06:43

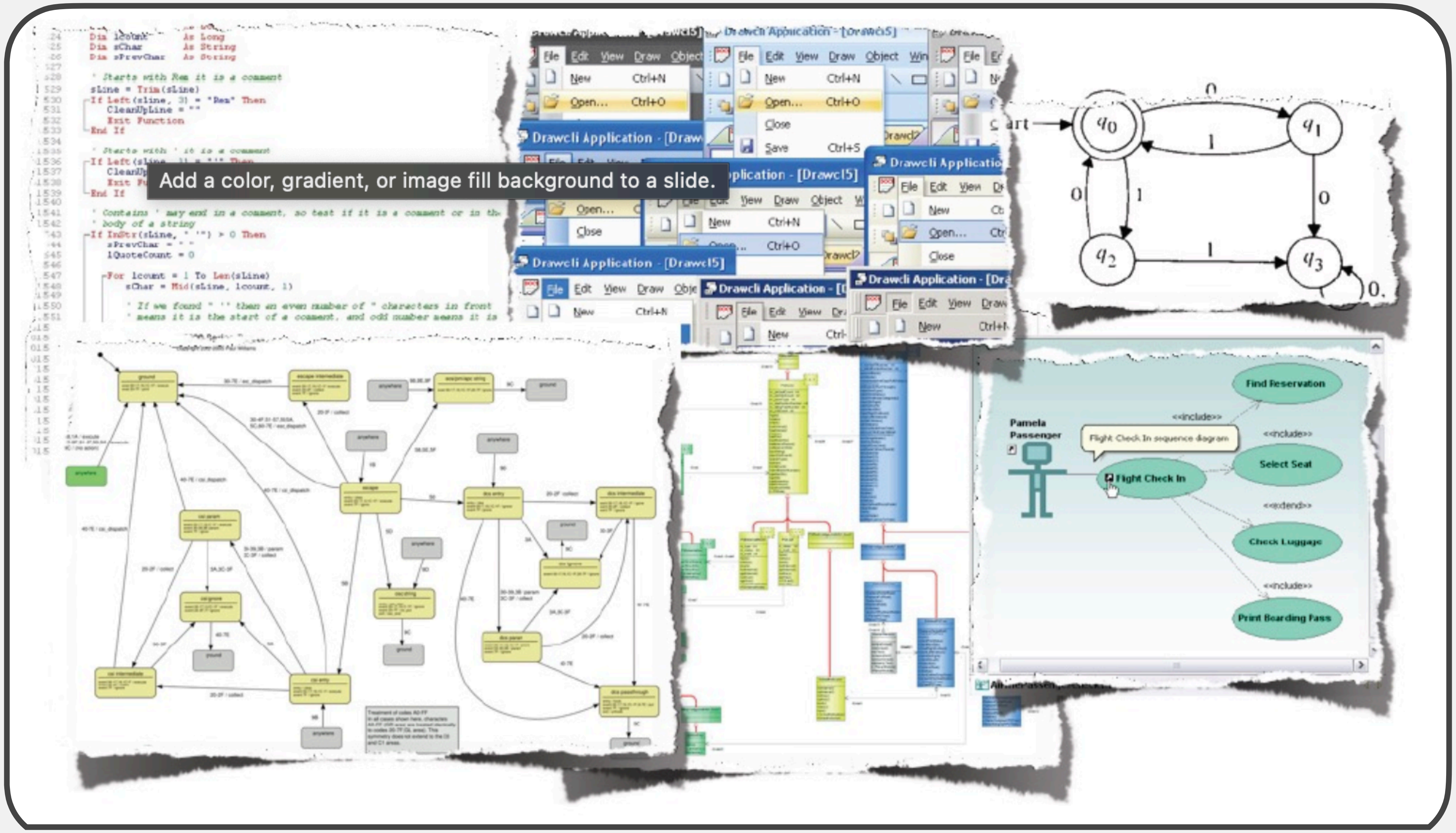
	Hit	Total	Coverage
Lines:	6092	7293	83.5 %
Functions:	481	518	92.9 %

Filename	Line Coverage ⬍			Functions ⬍	
asn1_string_table_test.c		58.8 %	20 / 34	100.0 %	2 / 2
asn1_time_test.c		72.0 %	72 / 100	100.0 %	7 / 7
bad_dtls_test.c		97.6 %	163 / 167	100.0 %	9 / 9
bftest.c		65.3 %	64 / 98	87.5 %	7 / 8
bio_enc_test.c		78.7 %	74 / 94	100.0 %	9 / 9
bntest.c		97.7 %	1038 / 1062	100.0 %	45 / 45
chacha_internal_test.c		83.3 %	10 / 12	100.0 %	2 / 2
ciphername_test.c		60.4 %	32 / 53	100.0 %	2 / 2
crltest.c		100.0 %	90 / 90	100.0 %	12 / 12
ct_test.c		95.5 %	212 / 222	100.0 %	20 / 20
d2i_test.c		72.9 %	35 / 48	100.0 %	2 / 2
danetest.c		75.5 %	123 / 163	100.0 %	10 / 10
dhtest.c		84.6 %	88 / 104	100.0 %	4 / 4
drbgtest.c		69.8 %	157 / 225	92.9 %	13 / 14
dtls_mtu_test.c		86.8 %	59 / 68	100.0 %	5 / 5
dtlstest.c		97.1 %	34 / 35	100.0 %	4 / 4
dtlsv1listentest.c		94.9 %	37 / 39	100.0 %	4 / 4
ecdsatest.c		94.0 %	140 / 149	100.0 %	7 / 7
enginetest.c		92.8 %	141 / 152	100.0 %	7 / 7
evp_extra_test.c		100.0 %	112 / 112	100.0 %	10 / 10
fatalerrtest.c		89.3 %	25 / 28	100.0 %	2 / 2
handshake_helper.c		84.7 %	494 / 583	97.4 %	38 / 39
hmactest.c		100.0 %	71 / 71	100.0 %	7 / 7
ideatest.c		100.0 %	30 / 30	100.0 %	4 / 4
igetest.c		87.9 %	109 / 124	100.0 %	11 / 11
lhash_test.c		78.6 %	66 / 84	100.0 %	8 / 8
mdc2_internal_test.c		81.8 %	9 / 11	100.0 %	2 / 2
mdc2test.c		100.0 %	18 / 18	100.0 %	2 / 2
ocspapitest.c		95.5 %	64 / 67	100.0 %	4 / 4
packettest.c		100.0 %	248 / 248	100.0 %	24 / 24



```
    1 /    1:                if ((err = SSLHashMD5.final(&hashCtx, &hashOut)) != 0)
    0 /    1:                        goto fail;
           :        }
           :        else {
           :                /* DSA, ECDSA - just use the SHA1 hash */
    0 /    1:                dataToSign = &hashes[SSL_MD5_DIGEST_LEN];
    0 /    1:                dataToSignLen = SSL_SHA1_DIGEST_LEN;
           :        }
           :
    1 /    1:        hashOut.data = hashes + SSL_MD5_DIGEST_LEN;
    1 /    1:         hashOut.length = SSL_SHA1_DIGEST_LEN;
    1 /    1:         if ((err = SSLFreeBuffer(&hashCtx)) != 0)
    0 /    1:             goto fail;
           :
    1 /    1:         if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
    0 /    1:             goto fail;
    1 /    1:         if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
    0 /    1:             goto fail;
    1 /    1:         if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
    0 /    1:             goto fail;
    1 /    1:         if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
    0 /    1:             goto fail;
    1 /    1:             goto fail;
           :         if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
           :             goto fail;
           :
           :        err = sslRawVerify(ctx,
           :                           ctx->peerPubKey,
           :                           dataToSign,                              /* plaintext *
           :                           dataToSignLen,                           /* plaintext l
           :                           signature,
           :                           signatureLen);
           :        if(err) {
           :                sslErrorLog("SSLDecodeSignedServerKeyExchange: sslRawVerify "
           :                            "returned %d\n", (int)err);
           :                goto fail;
           :        }
           :
           : fail:
    1 /    1:         SSLFreeBuffer(&signedHashes);
    1 /    1:         SSLFreeBuffer(&hashCtx);
    1 /    1:         return err;
           :
    1 /    1: }
           :
```

We Can Measure Coverage on Almost Anything



```
Dim lcount       As Long
Dim sChar        As String
Dim sPrevChar    As String

' Starts with Rem it is a comment
sLine = Trim(sLine)
If Left(sline, 3) = "Rem" Then
   CleanUpLine = ""
   Exit Function
End If

' Starts with ' it is a comment
If Left(sLine, 1) = "'" Then
   CleanUp
   Exit Fu
End If

' Contains ' may end in a comment, so test if it is a comment or in the
' body of a string
If InStr(sLine, "'") > 0 Then
   sPrevChar = " "
   lQuoteCount = 0

  For lcount = 1 To Len(sLine)
     sChar = Mid(sLine, lcount, 1)

     ' If we found " '' then an even number of " characters in front
     ' means it is the start of a comment, and odd number means it is
```

Add a color, gradient, or image fill background to a slide.

Be Aware of Coverage Chasing

- Recall: issues with metrics and incentives
  - Also: Numbers can be deceptive

- 100% coverage != exhaustively tested
  - “Coverage is not strongly correlated with suite effectiveness”

- Based on empirical study on GitHub projects [Inozemtseva and Holmes, ICSE’14]

- Still, it’s a good low bar
  - Code that is not executed has definitely not been tested

Coverage of What?

- Distinguish code being tested and code being executed
- Library code >>>> Application code
    - Can selectively measure coverage
- All application code >>> code being tested
    - Not always easy to do this within an application

Coverage != Outcome

- What’s better, tests that always pass or tests that always fail?
- Tests should ideally be falsifiable. Boundary determines
- specification
- Ideally:
  - Correct implementations should pass all tests
  - Buggy code should fail at least one test
  - Intuition behind mutation testing (we’ll revisit this next week)
- What if tests have bugs?
  - Pass on buggy code or fail on correct code
- Even worse: flaky tests
  - Pass or fail on the same test case nondeterministically
- What’s the worst type of test?

Test Design Principles

- Use public APIs only
- Clearly distinguish inputs, configuration, execution, and oracle
- Be simple; avoid complex control flow such as conditionals and loops
- Tests shouldn't need to be frequently changed or refactored
    - Definitely not as frequently as the code being tested changes

Anti-Patterns

- Snoopy oracles
  - Relying on implementation state instead of observable behavior
  - E.g. Checking variables or fields instead of return values
- Brittle tests
  - Overfitting to special-case behavior instead of general principle
  - E.g. hard-coding message strings instead of behavior
- Slow tests
  - Self-explanatory(beware of heavy environments, I/O, and sleep())
- Flaky tests
  - Tests that pass or fail nondeterministically
  - Often because of reliance on random inputs, timing (e.g. sleep(1000)), availability of external services (e.g. fetching data over the network in a unit test), or dependency on order of test execution (e.g. previous test sets up global variables in certain way)

Takeaways

- Most tests that you will write will be muuuuuuch more complex than testing a sort function.

- Need to set up environment, create objects whose methods to test, create objects for test data, get all these into an interesting state, test multiple APIs with varying arguments, etc.

- Many tests will require mocks (i.e., faking a resource-intensive component).

- General principles of many of these strategies still apply:
  - Writing tests can be time consuming
  - Determining test adequacy can be hard (if not impossible)
  - Test oracles are not easy
  - Advanced test strategies have trade-offs (high costs with high returns)

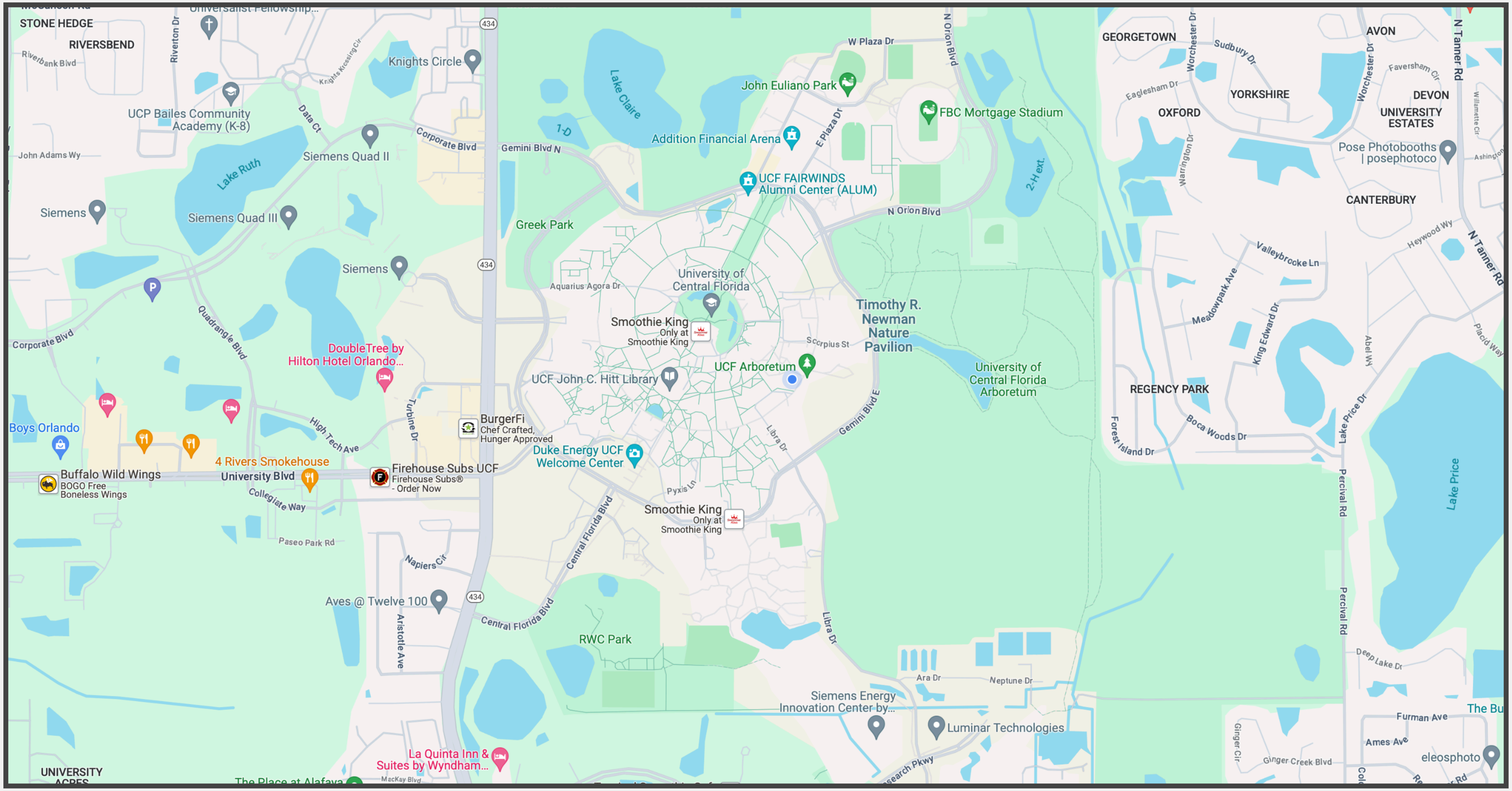
Intro to Software Architecture

Learning Goals

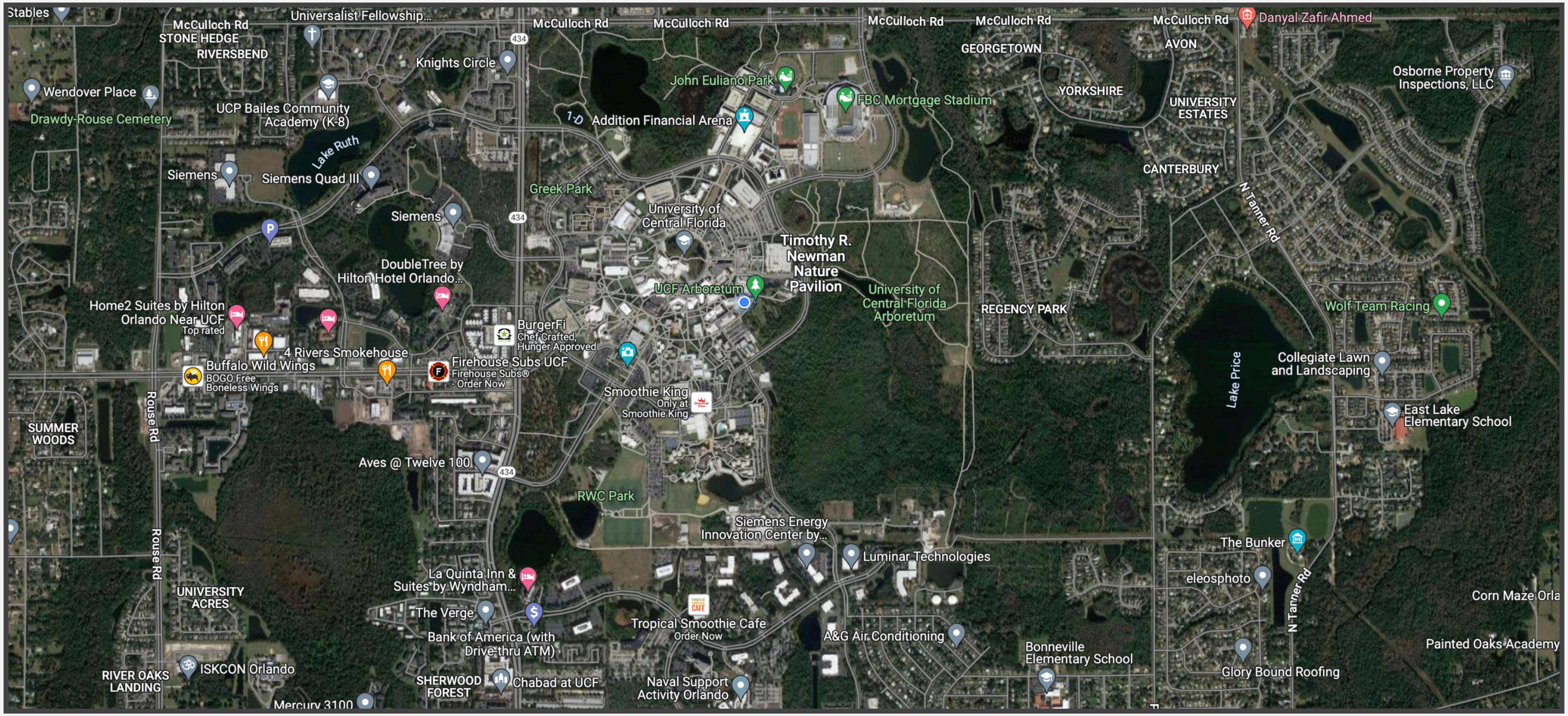
- Understand the abstraction level of architectural reasoning
- Appreciate how software systems can be viewed at different abstraction levels
- Distinguish software architecture from (object-oriented) software design
- Use notation and views to describe the architecture suitable to the purpose
- Document architectures clearly, without ambiguity

Views and Abstraction

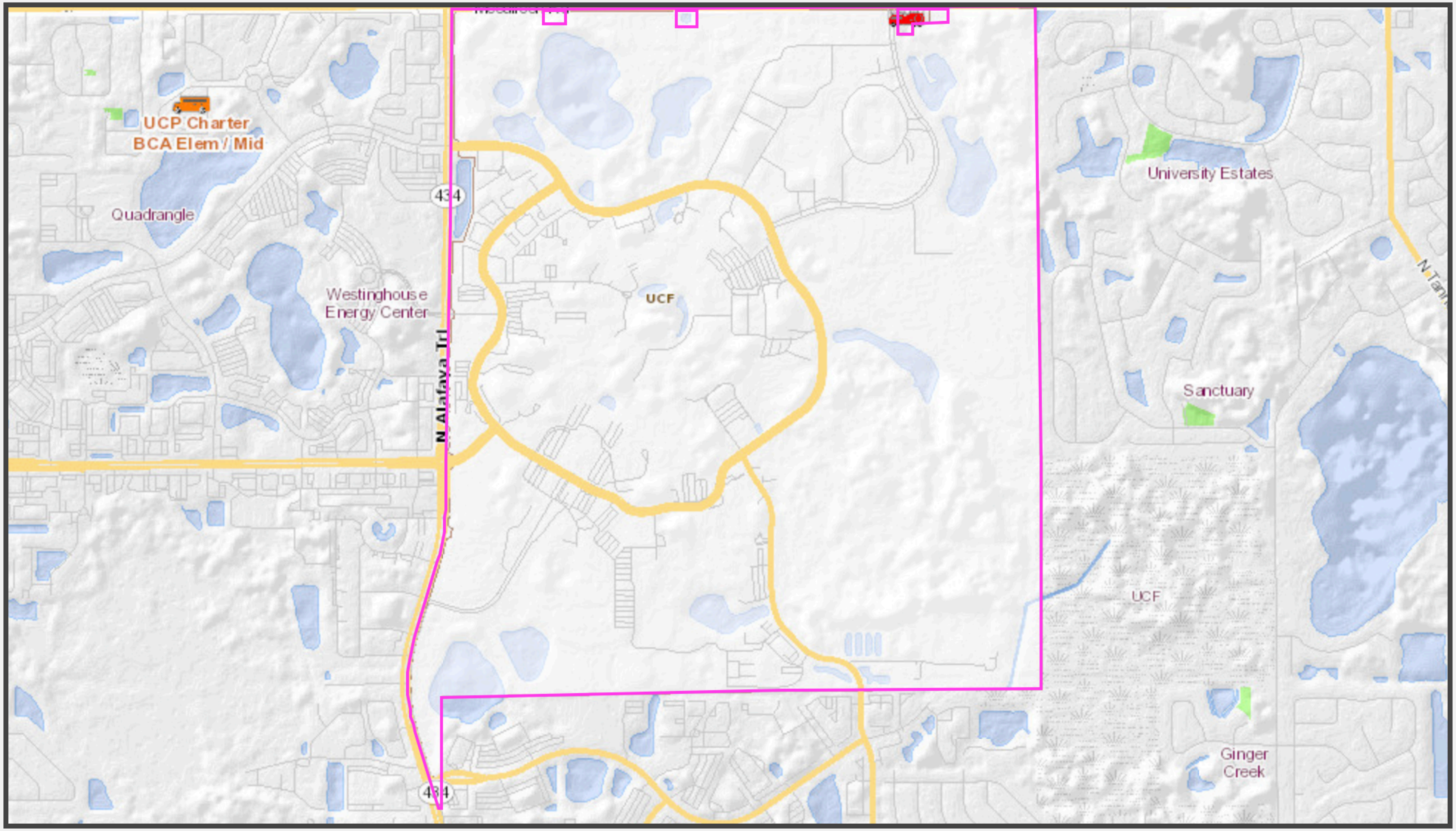
Views & Abstraction



Views & Abstraction



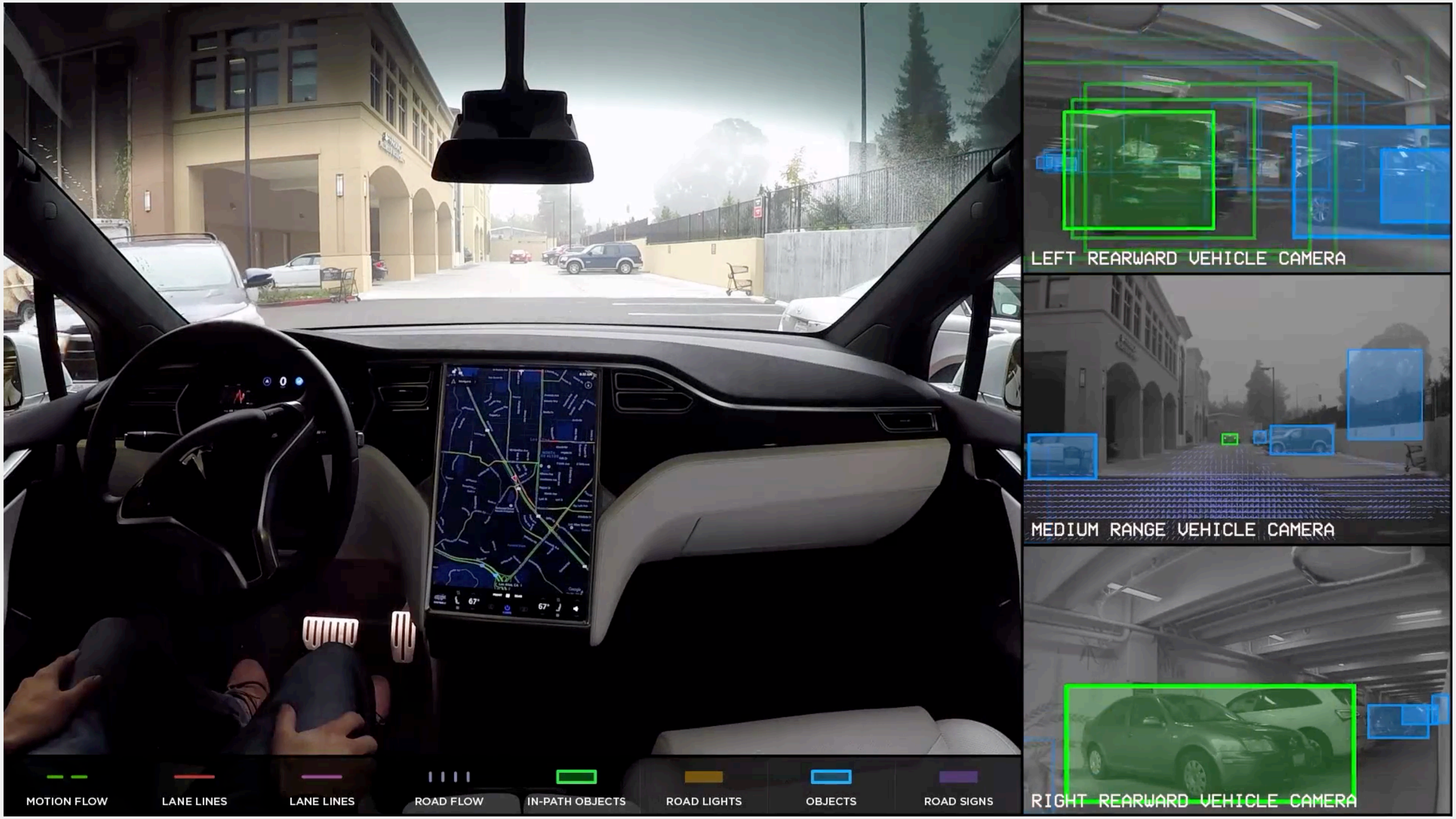
Views & Abstraction



Abstracted Views Focus on Conveying Information

- They have a well-defined purpose
- Show only necessary information
- Abstract away unnecessary details
- Use legends/annotations to remove ambiguity
- Multiple views of the same object tell a larger story

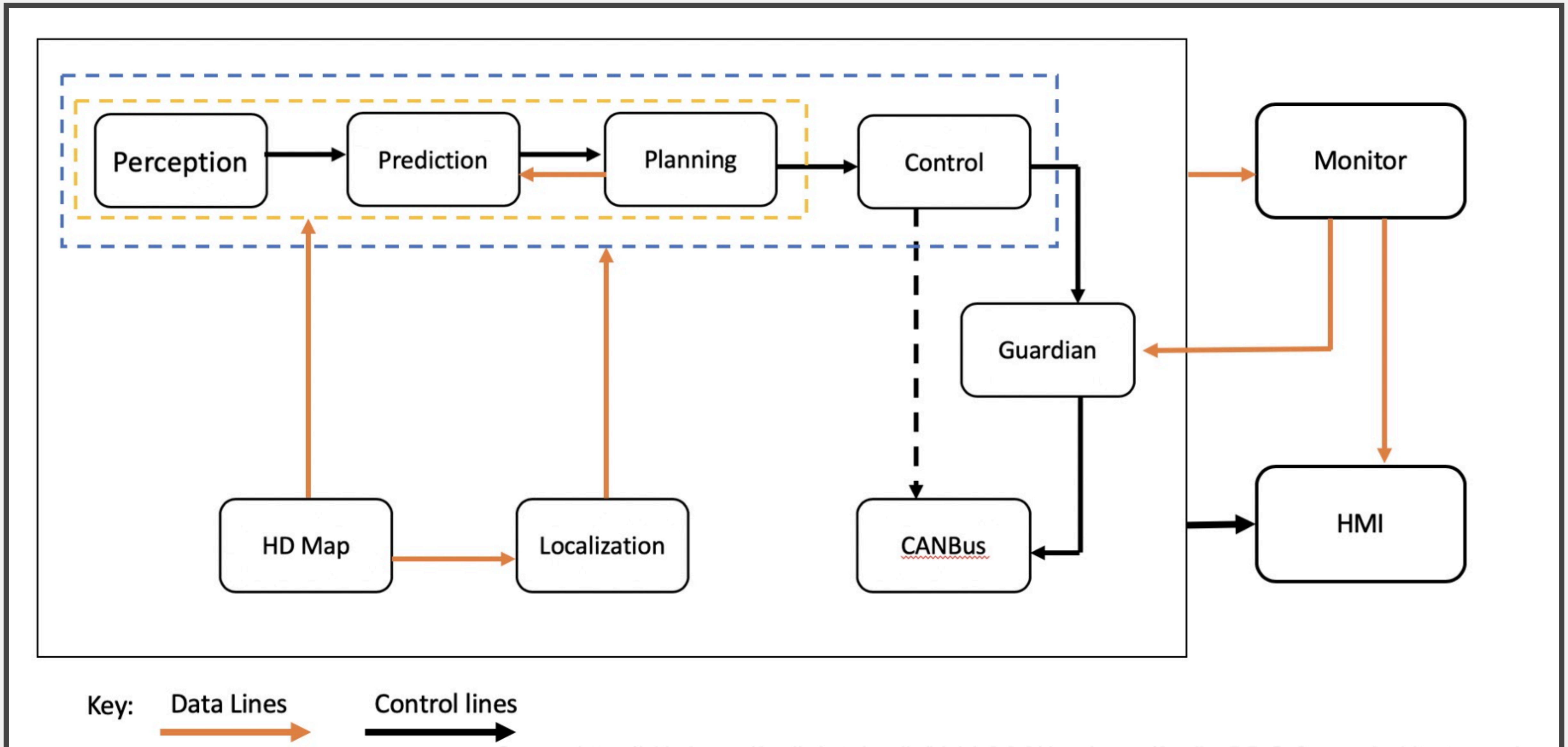
Software Architecture Case Study: Autonomous Vehicles


LEFT REARWARD VEHICLE CAMERA
MEDIUM RANGE VEHICLE CAMERA
RIGHT REARWARD VEHICLE CAMERA
MOTION FLOW
LANE LINES
LANE LINES
ROAD FLOW
IN-PATH OBJECTS
ROAD LIGHTS
OBJECTS
ROAD SIGNS

Case Study: Apollo

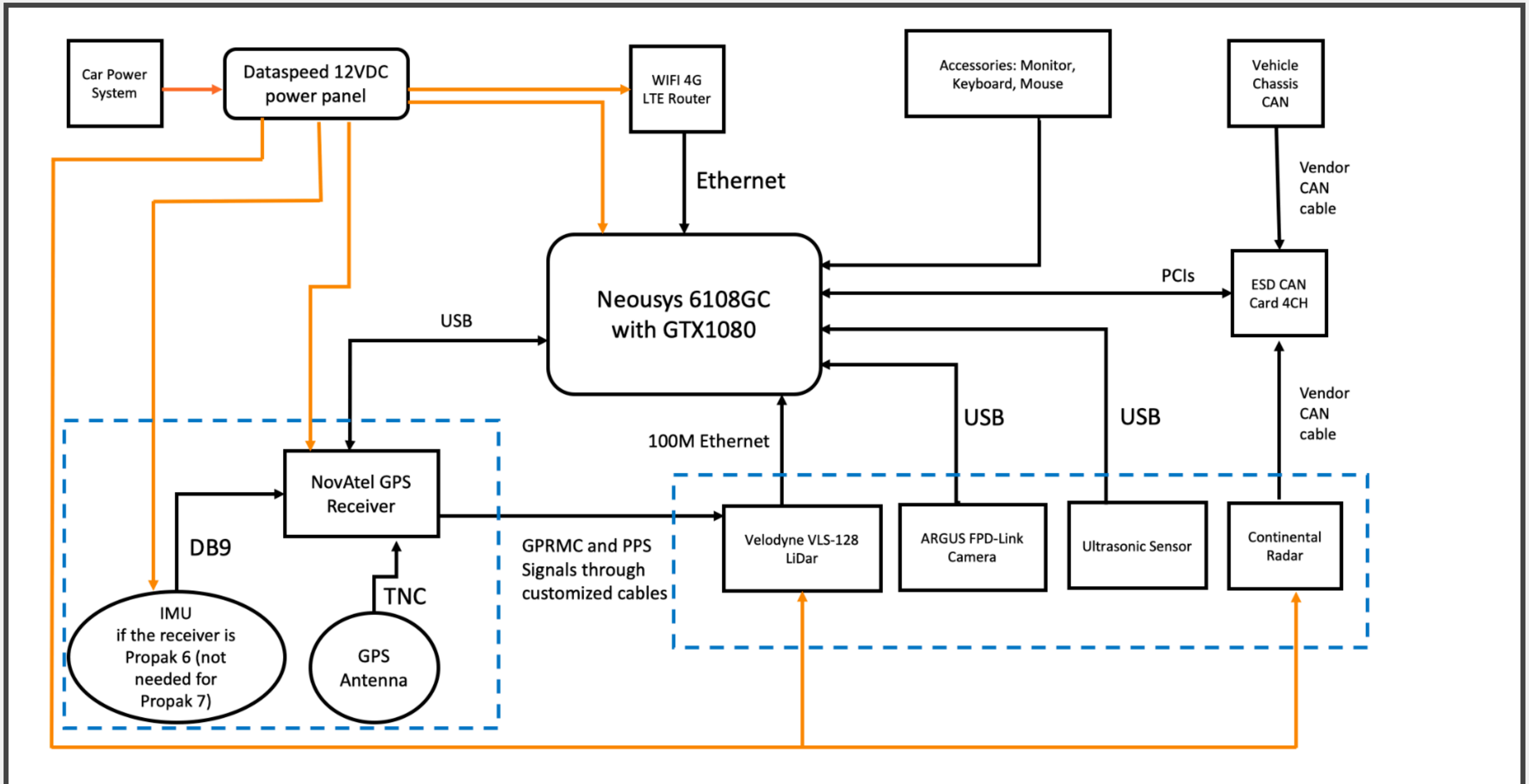
- Check out the “side pass” feature from the video:
  - http://tinyurl.com/cen24-vid
- **Source:** https://github.com/ApolloAuto/apollo
- **Doxygen:** https://hidetoshi-furukawa.github.io/apollo/doxygen/index.html

Apollo Software Architecture



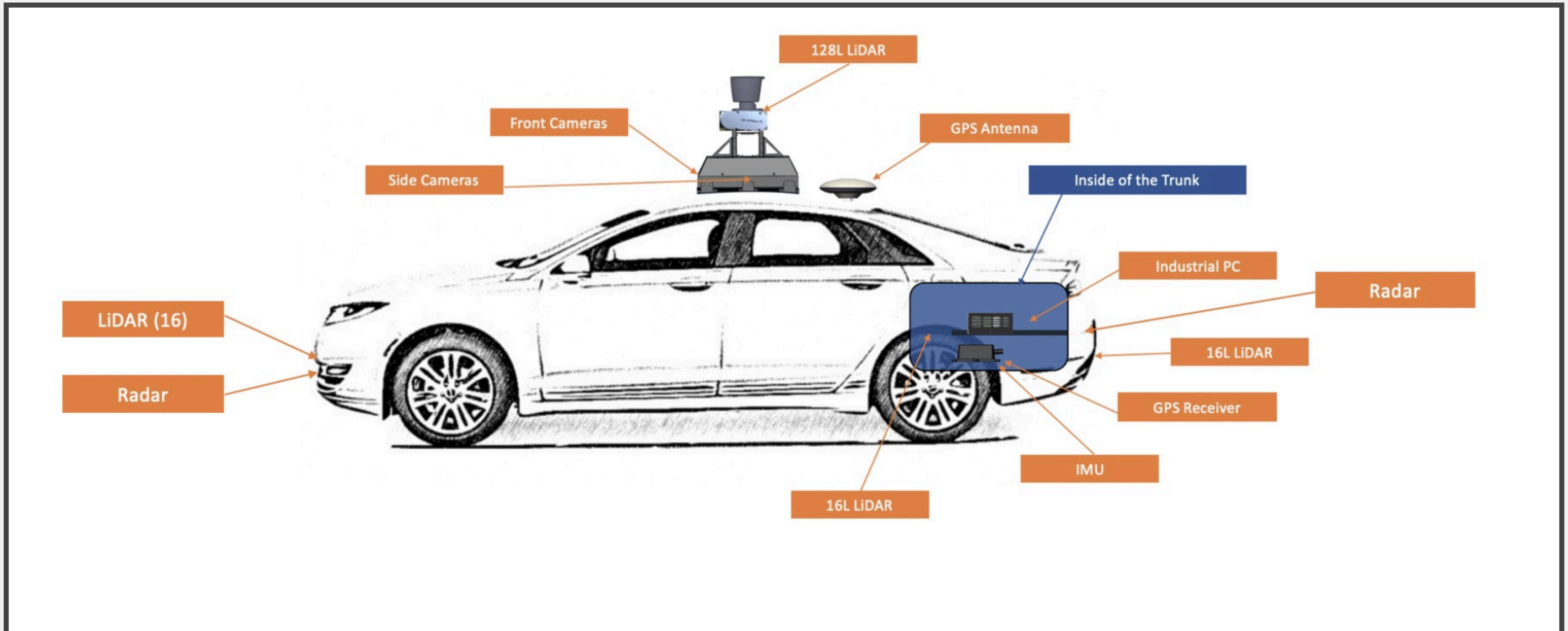
Source: https://github.com/ApolloAuto/apollo/blob/v6.0.0/docs/specs/Apollo_5.5_Software_Architecture.md

Apollo Hardware Architecture



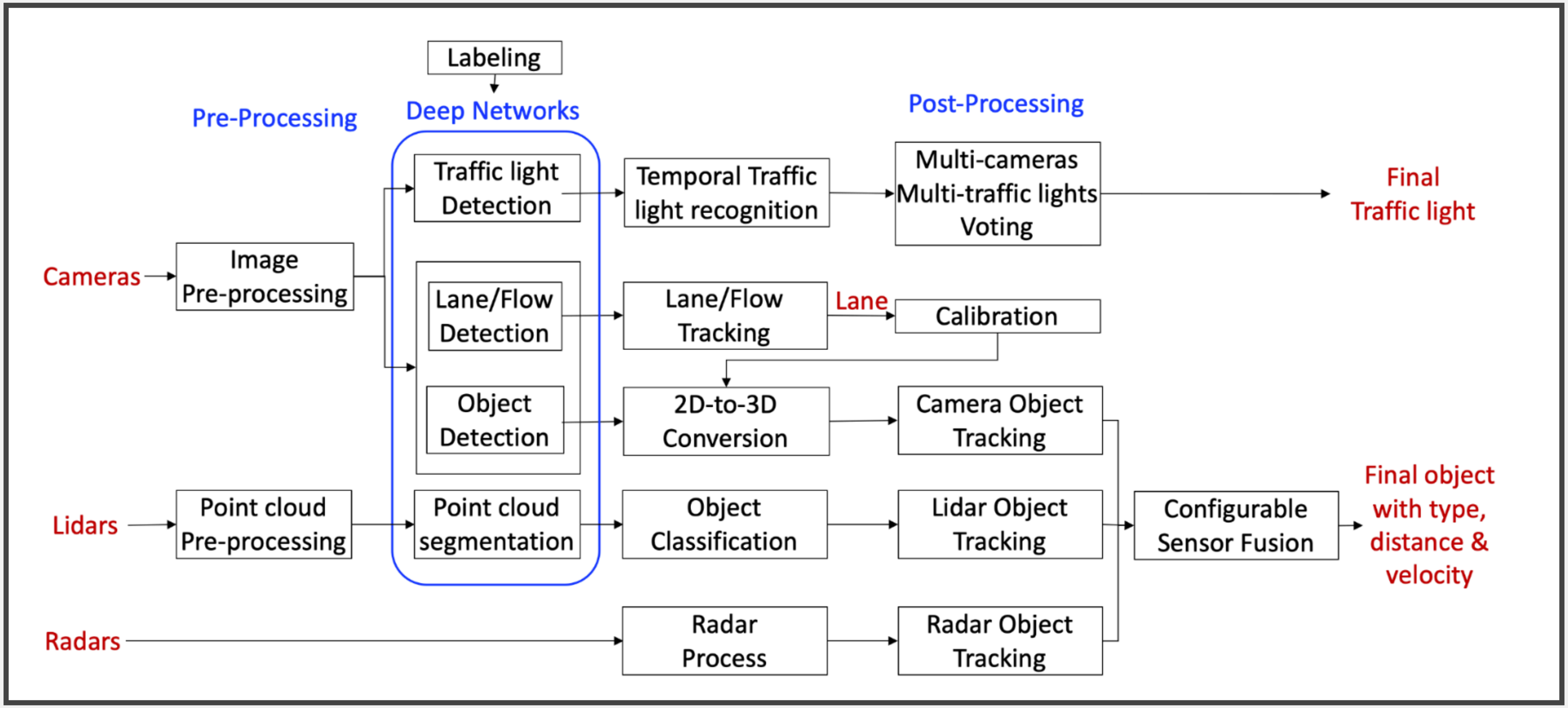
Source: https://github.com/ApolloAuto/apollo/blob/v6.0.0/README.md

Apollo Hardware/Vehicle Overview

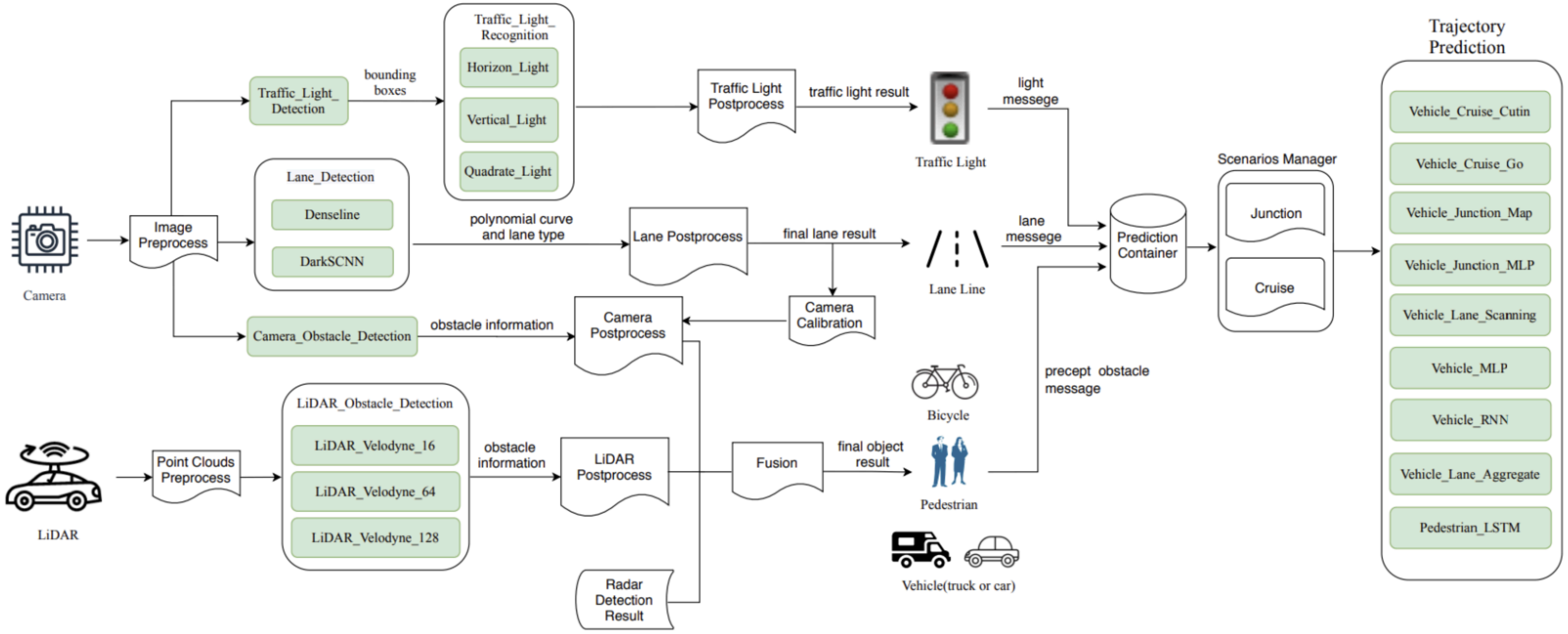


Source: https://github.com/ApolloAuto/apollo/blob/v6.0.0/README.md

Apollo Perception Module

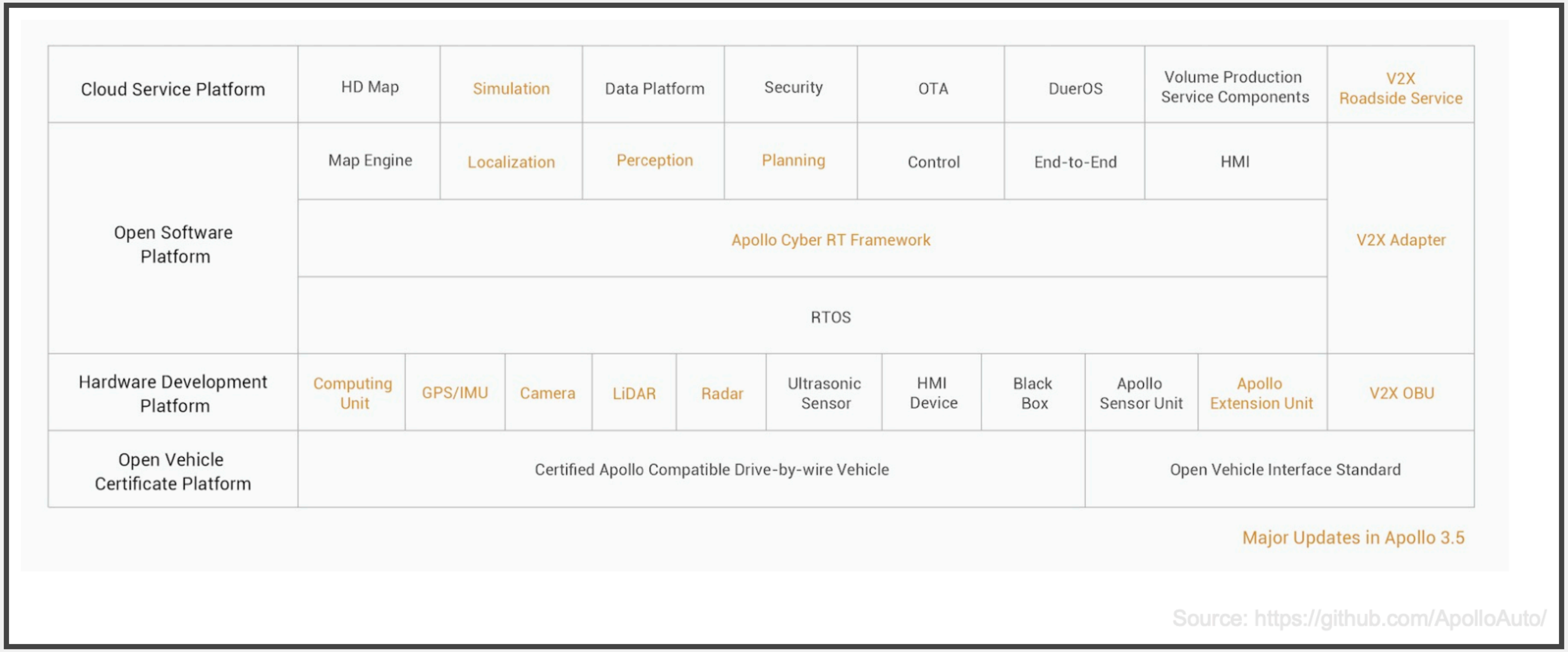


Apollo ML Models



Source: Zi Peng, Jinqiu Yang, Tse-Hsun (Peter) Chen, and Lei Ma. 2020. A First Look at the Integration of Machine Learning Models in Complex Autonomous Driving Systems: A Case Study on Apollo. In Proceedings of the 28th ACM Joint European Software Engineering Conference and Symposium on the Foundations of Software Engineering (ESEC/FSE '20), https://doi.org/10.1145/ 3368089.3417063

Apollo Software Stack

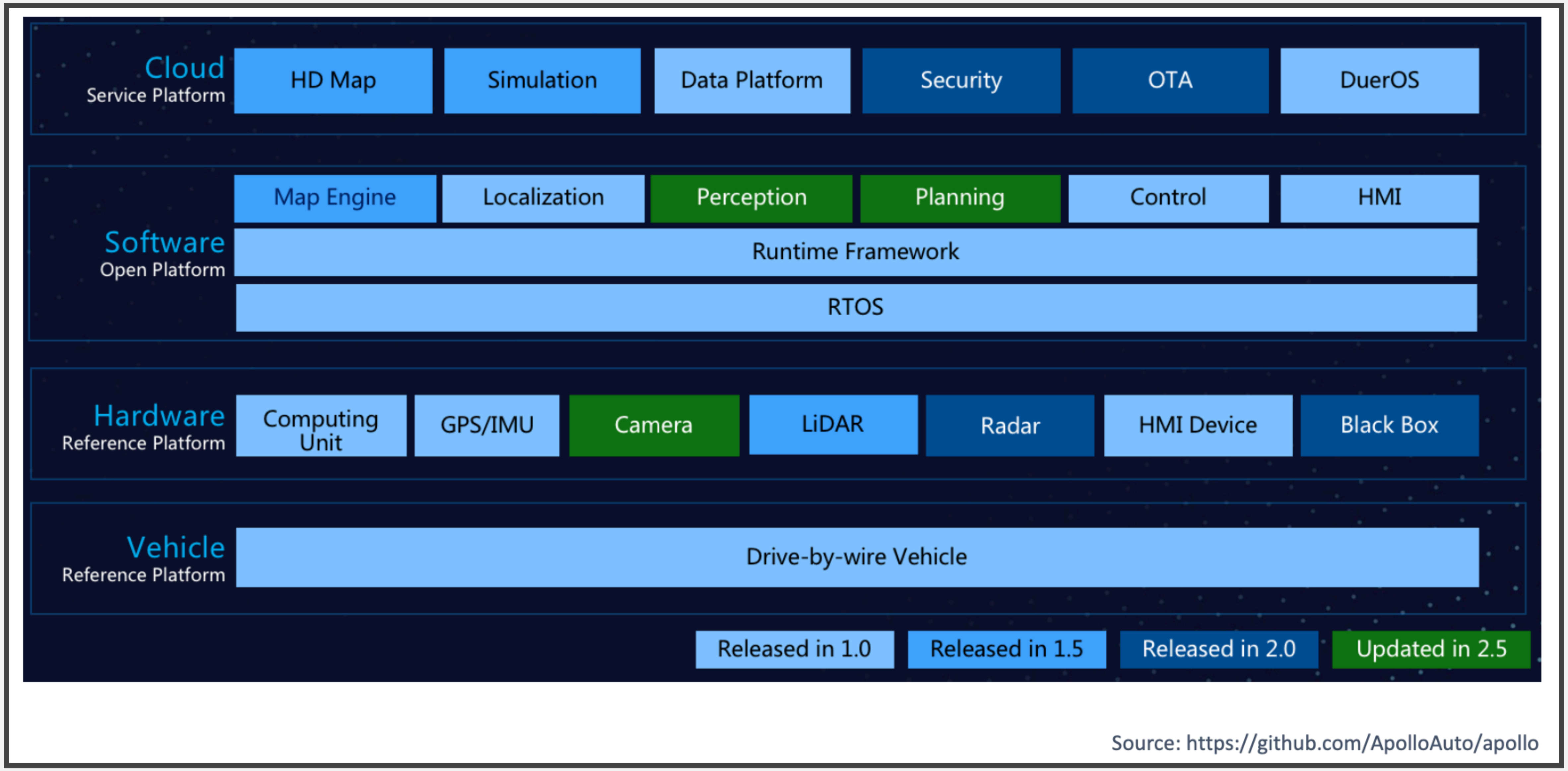


Cloud Service Platform	HD Map	Simulation	Data Platform	Security	OTA	DuerOS	Volume Production Service Components				V2X Roadside Service
Open Software Platform	Map Engine	Localization	Perception	Planning	Control	End-to-End	HMI				V2X Adapter
	Apollo Cyber RT Framework										
	RTOS										
Hardware Development Platform	Computing Unit	GPS/IMU	Camera	LiDAR	Radar	Ultrasonic Sensor	HMI Device	Black Box	Apollo Sensor Unit	Apollo Extension Unit	V2X OBU
Open Vehicle Certificate Platform	Certified Apollo Compatible Drive-by-wire Vehicle								Open Vehicle Interface Standard		

Major Updates in Apollo 3.5

Source: https://github.com/ApolloAuto/

Feature Evolution (Software Stack View)



Source: https://github.com/ApolloAuto/apollo

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.

[Bass et al. 2003]

Note: this definition is ambivalent to whether the architecture is known, or whether it's any good!

Software Design vs. Architecture

Levels of Abstraction

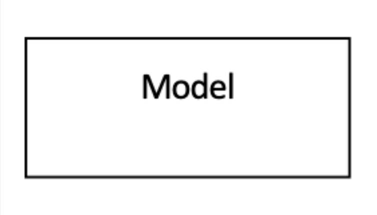
- Requirements
  - high-level “what” needs to be done
- Architecture (High-level design)
  - high-level “how”, mid-level “what”
- OO-Design (Low-level design, e.g. design patterns)
  - mid-level “how”, low-level “what”
- Code
  - low-level “how”

Design vs. Architecture

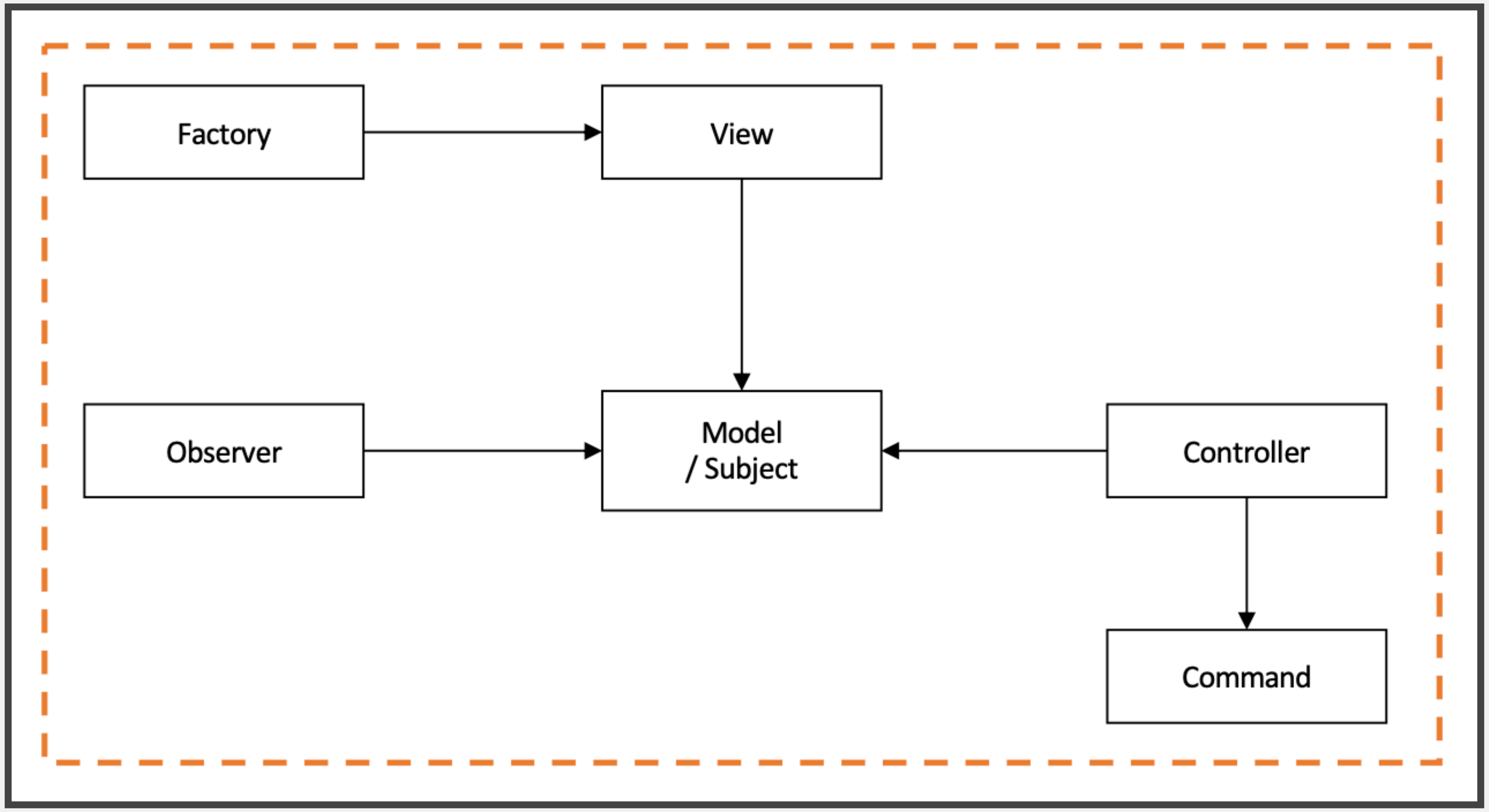
- Design Questions
  - *How do I add a menu item in VSCode?*
  - *How can I make it easy to add menu items in VSCode?*
  - *What lock protects this data?*
  - *How does Google rank pages?*
  - *What encoder should I use for secure communication?*
  - *What is the interface between objects?*

- Architectural Questions
  - *How do I extend VSCode with a plugin?*
  - *What threads exist and how do they coordinate?*
  - *How does Google scale to billions of hits per day?*
  - *Where should I put my firewalls?*
  - *What is the interface between subsystems?*

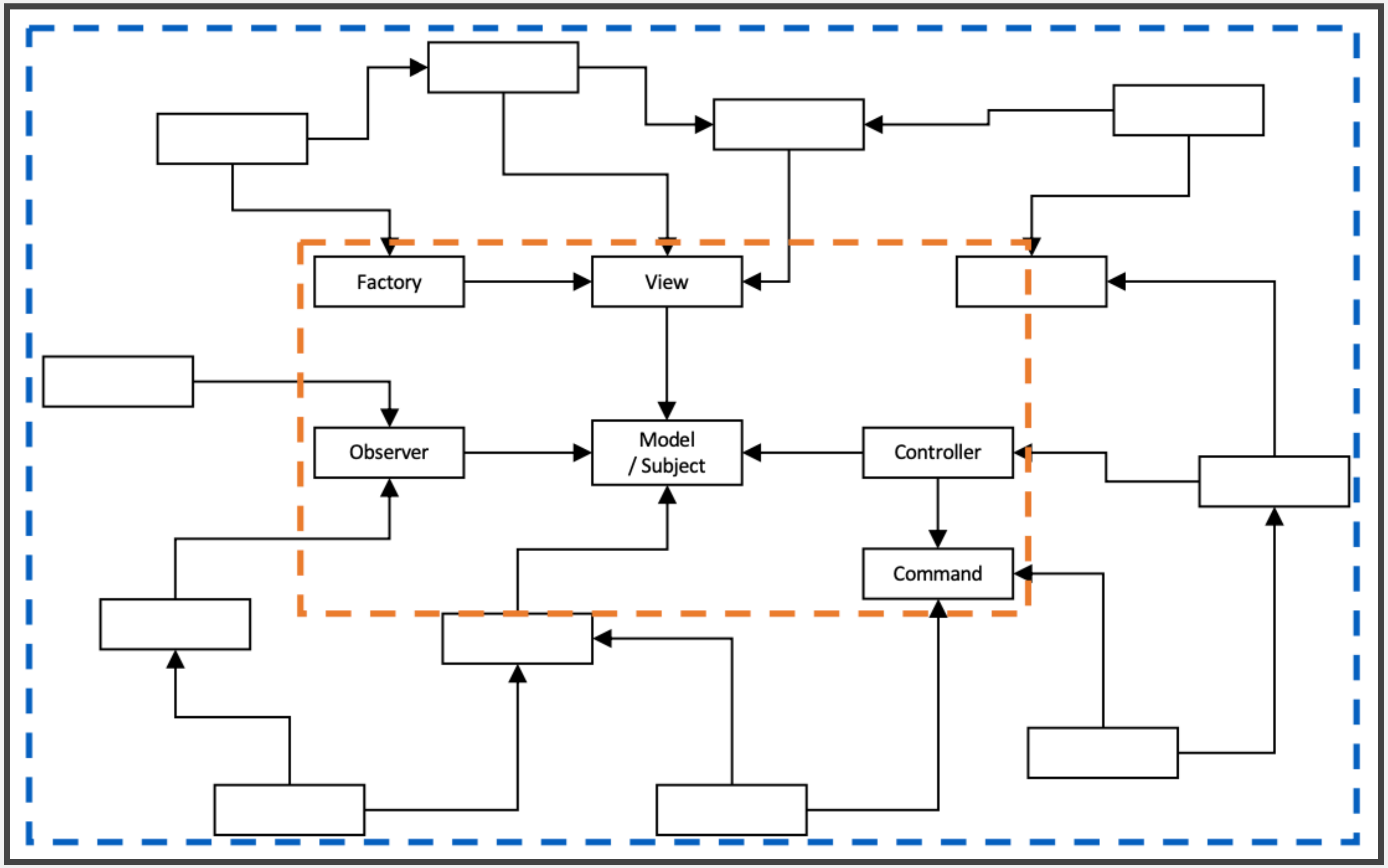
Objects



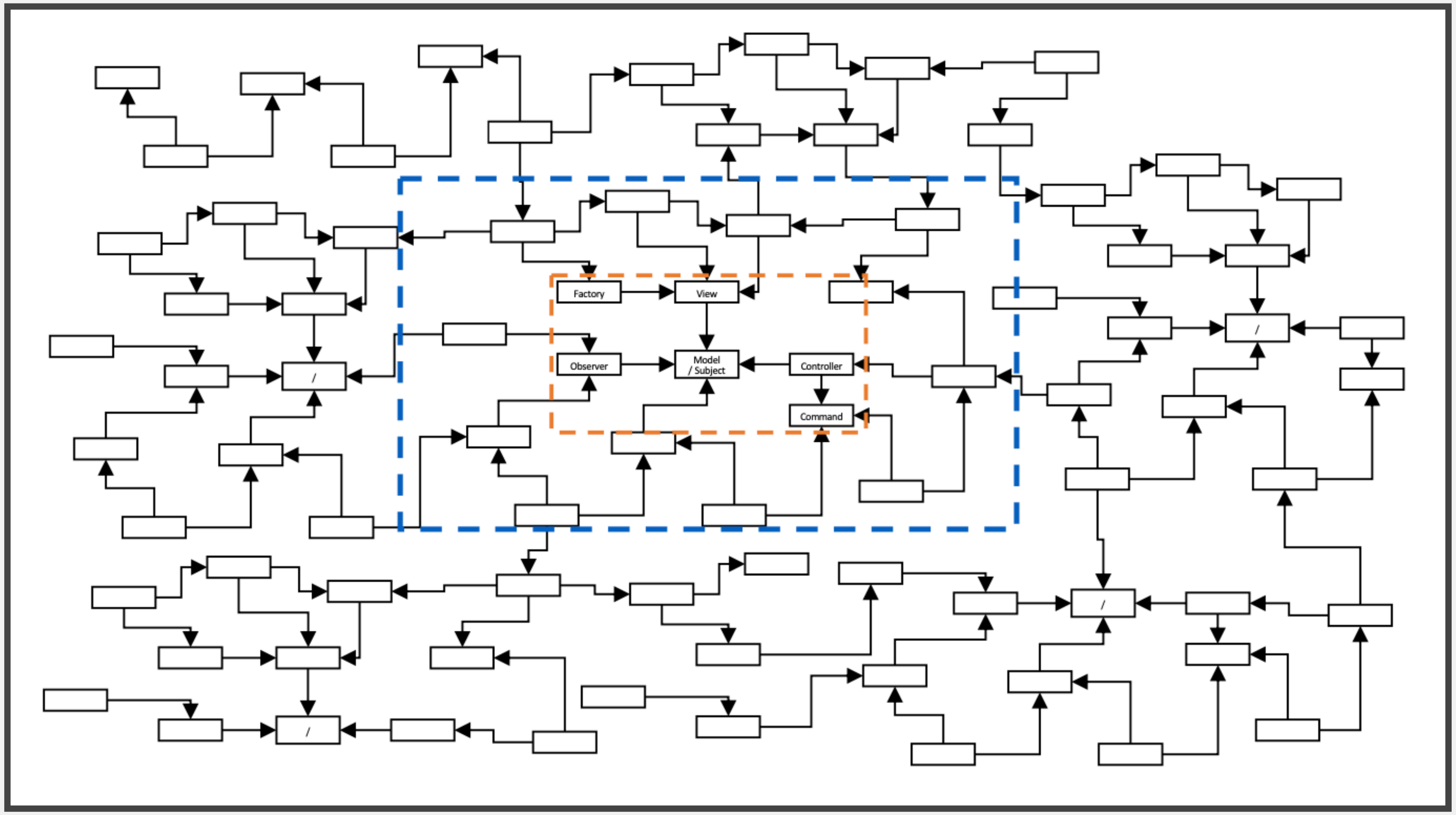
Design Patterns



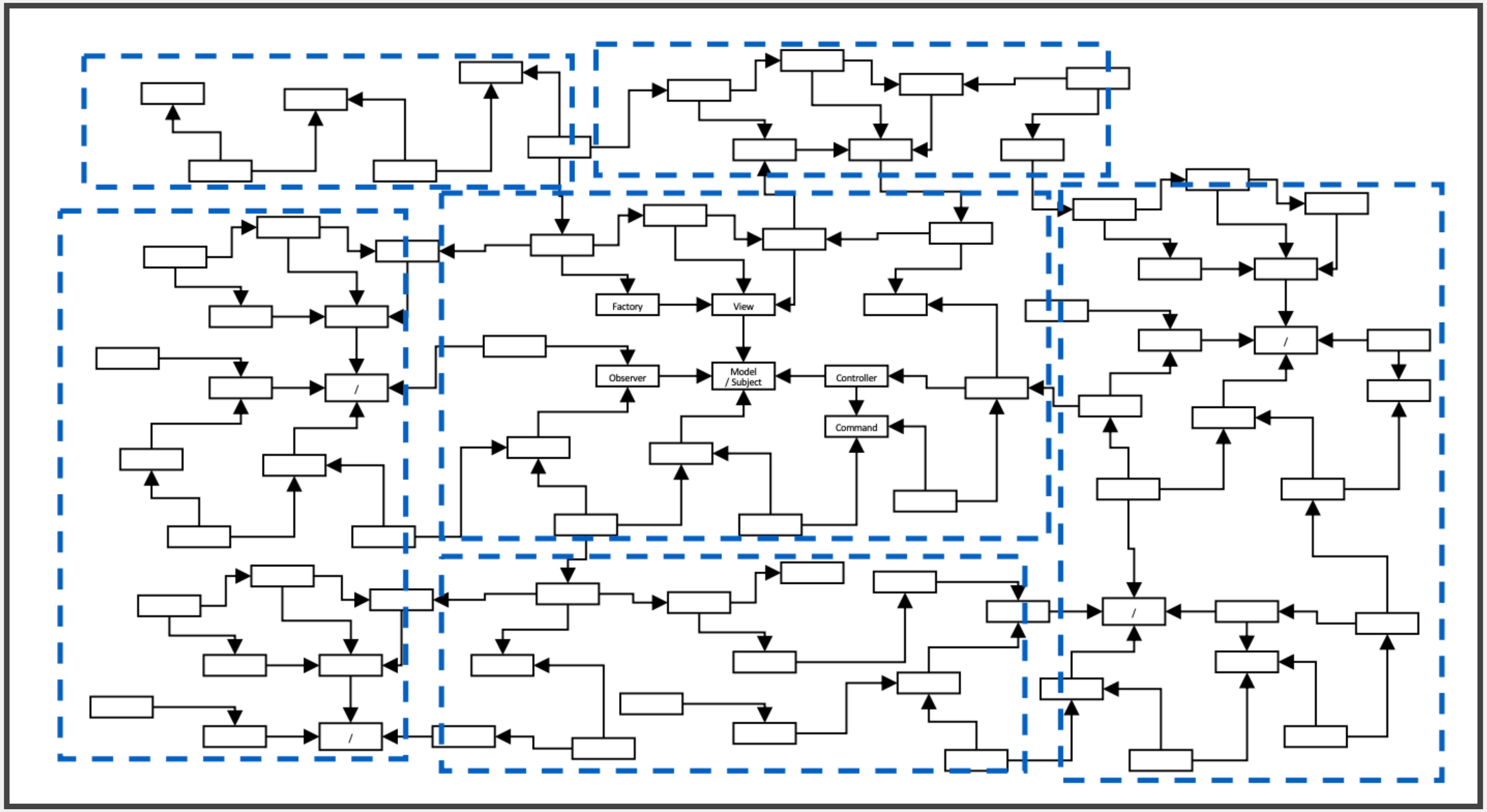
Design Patterns



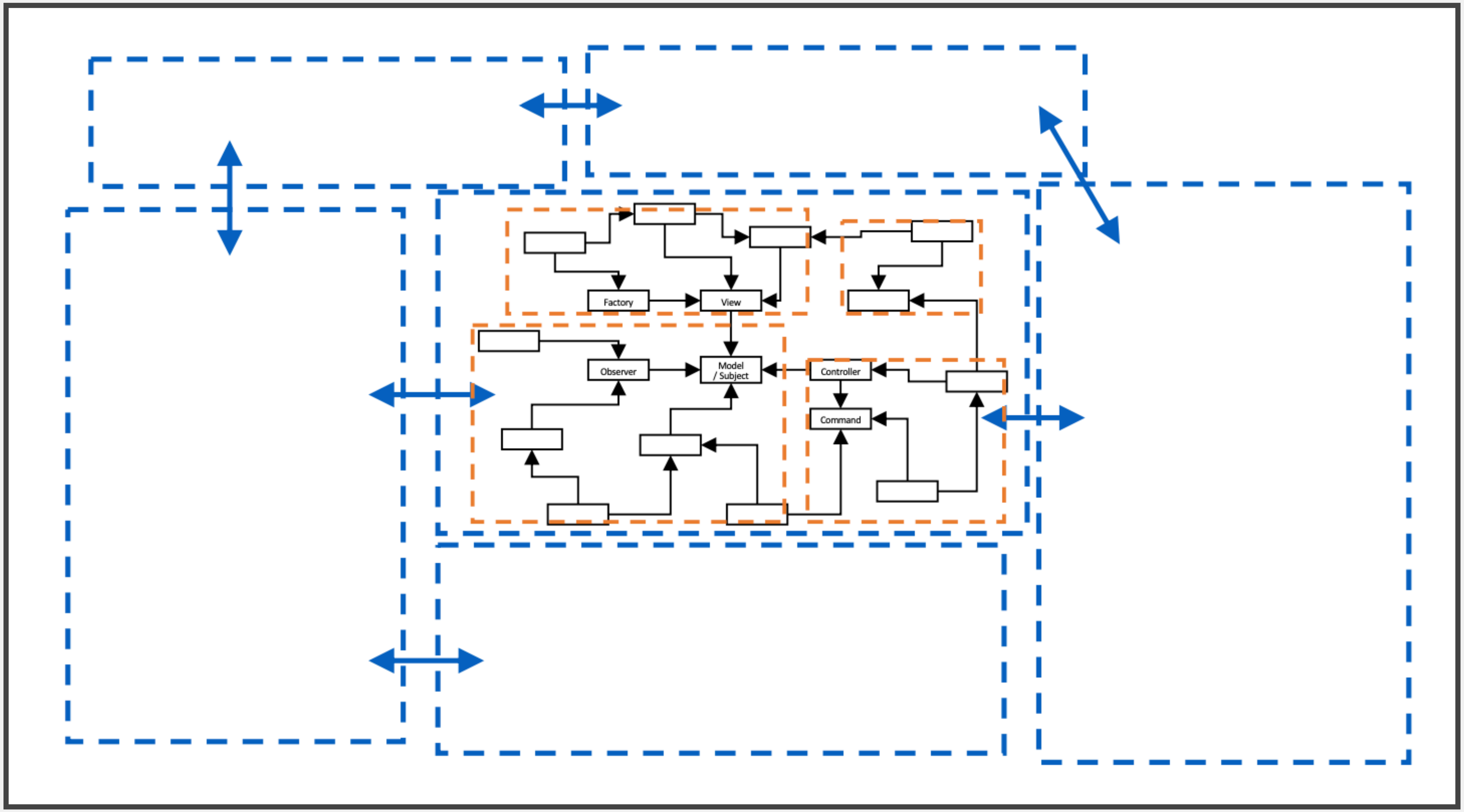
Design Patterns



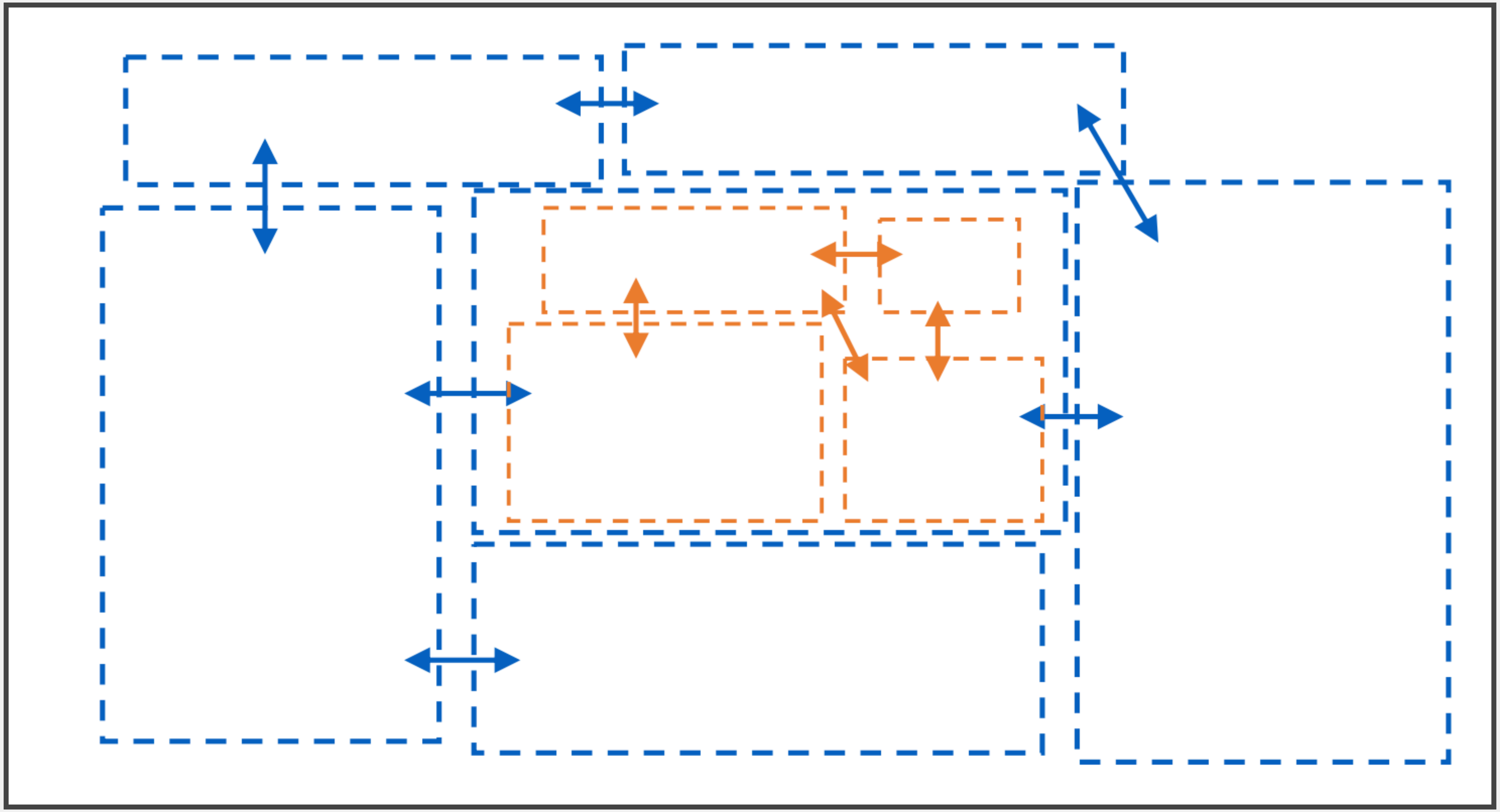
Architecture



Architecture



Architecture



Why Document Architecture?

- Blueprint for the system
  - Artifact for early analysis
  - Primary carrier of quality attributes
  - Key to post-deployment maintenance and enhancement
- Documentation speaks for the architect, today and 20 years from today
  - As long as the system is built, maintained, and evolved according to its documented architecture
- Support traceability.

Views & Purposes

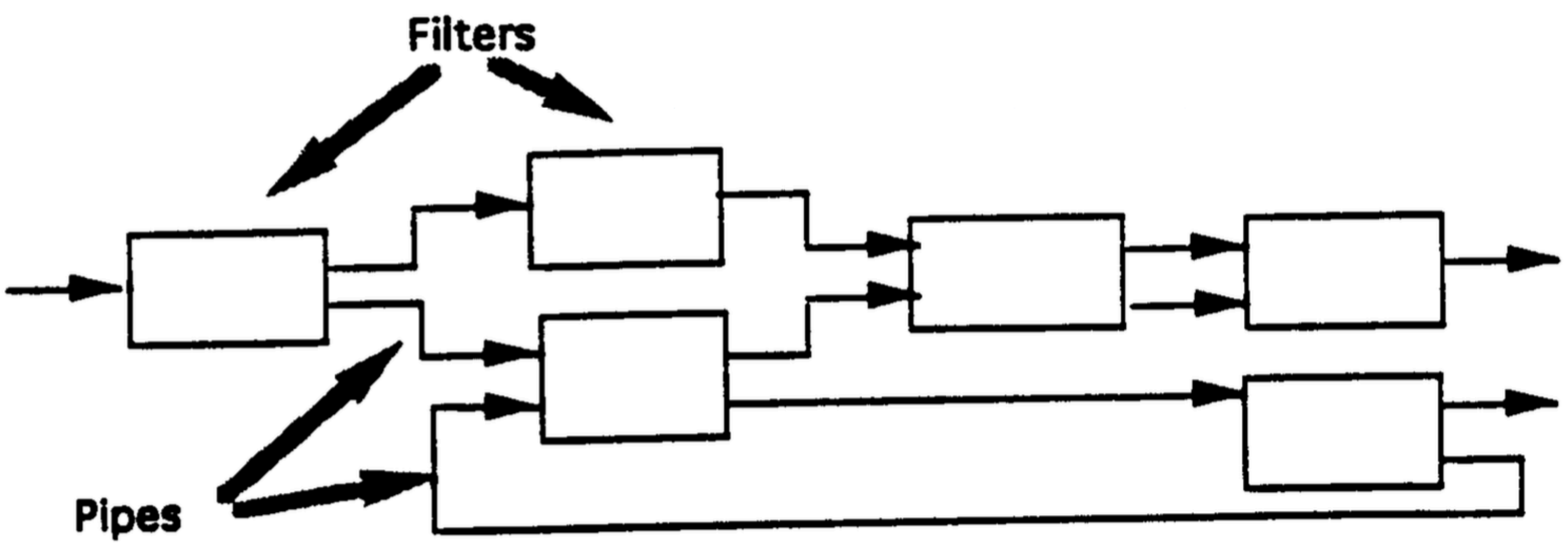
- Every view should align with a purpose
- • Views should only represent information relevant to that purpose
  - Abstract away other details
  - Annotate view to guide understanding where needed
- • Different views are suitable for different reasoning aspects (different quality goals), e.g.,
  - Performance
  - Extensibility
  - Security
  - Scalability
  - ...

Common Views in Documenting Software Architecture

- Static View
    - Modules (subsystems, structures) and their relations (dependencies, ...)
- Dynamic View
    - Components (processes, runnable entities) and connectors (messages, data flow, ...)
- Physical View (Deployment)
    - Hardware structures and their connections

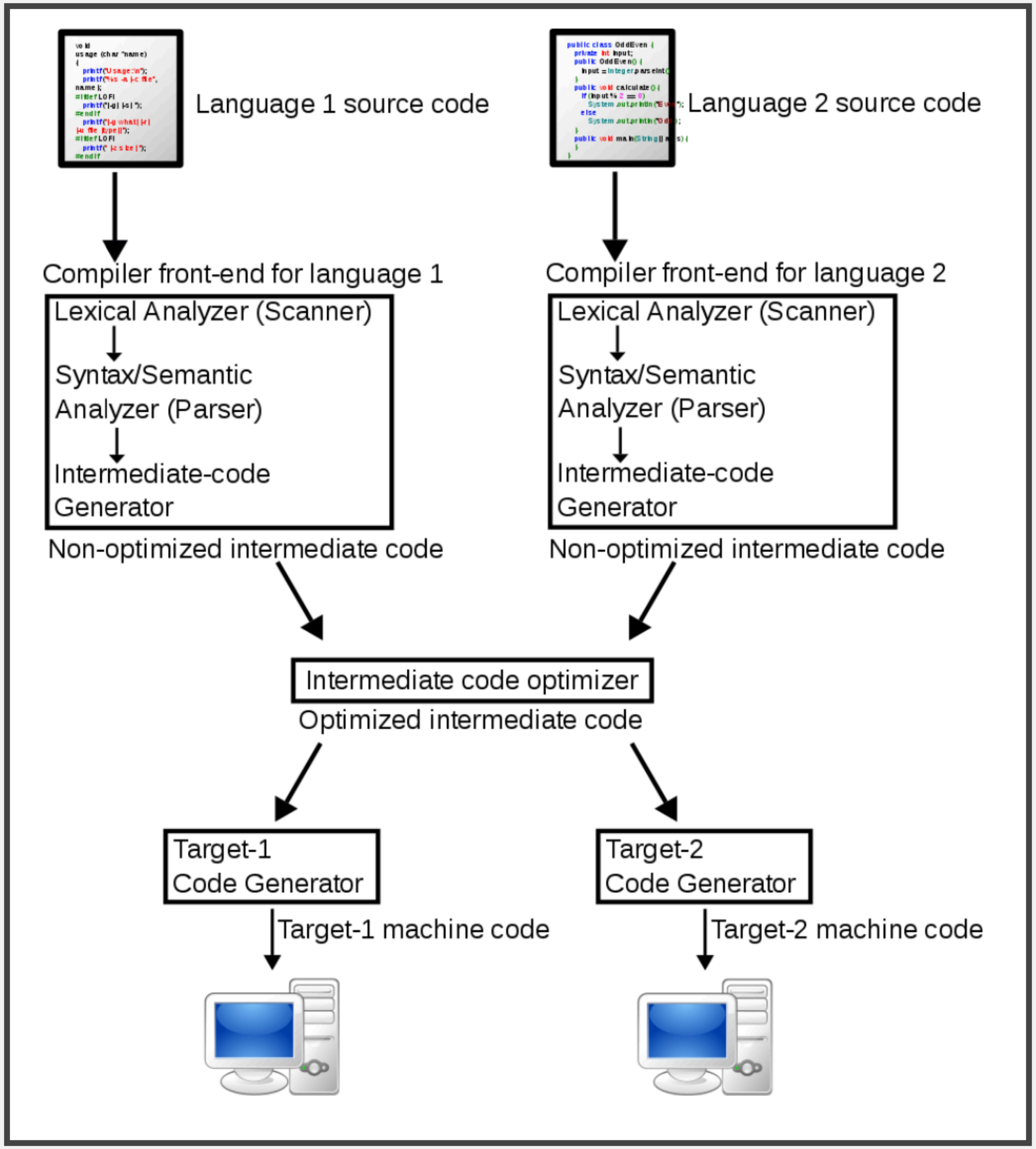
Common Software Architectures

1. Pipes & Filters



© David Garlan and Mary Shaw, CMU/SEI-94-TR-021

Pipes & Filters Example: Compilers



Language 1 source code

Language 2 source code

Compiler front-end for language 1

Lexical Analyzer (Scanner)

Syntax/Semantic Analyzer (Parser)

Intermediate-code Generator

Non-optimized intermediate code

Compiler front-end for language 2

Lexical Analyzer (Scanner)

Syntax/Semantic Analyzer (Parser)

Intermediate-code Generator

Non-optimized intermediate code

Intermediate code optimizer

Optimized intermediate code

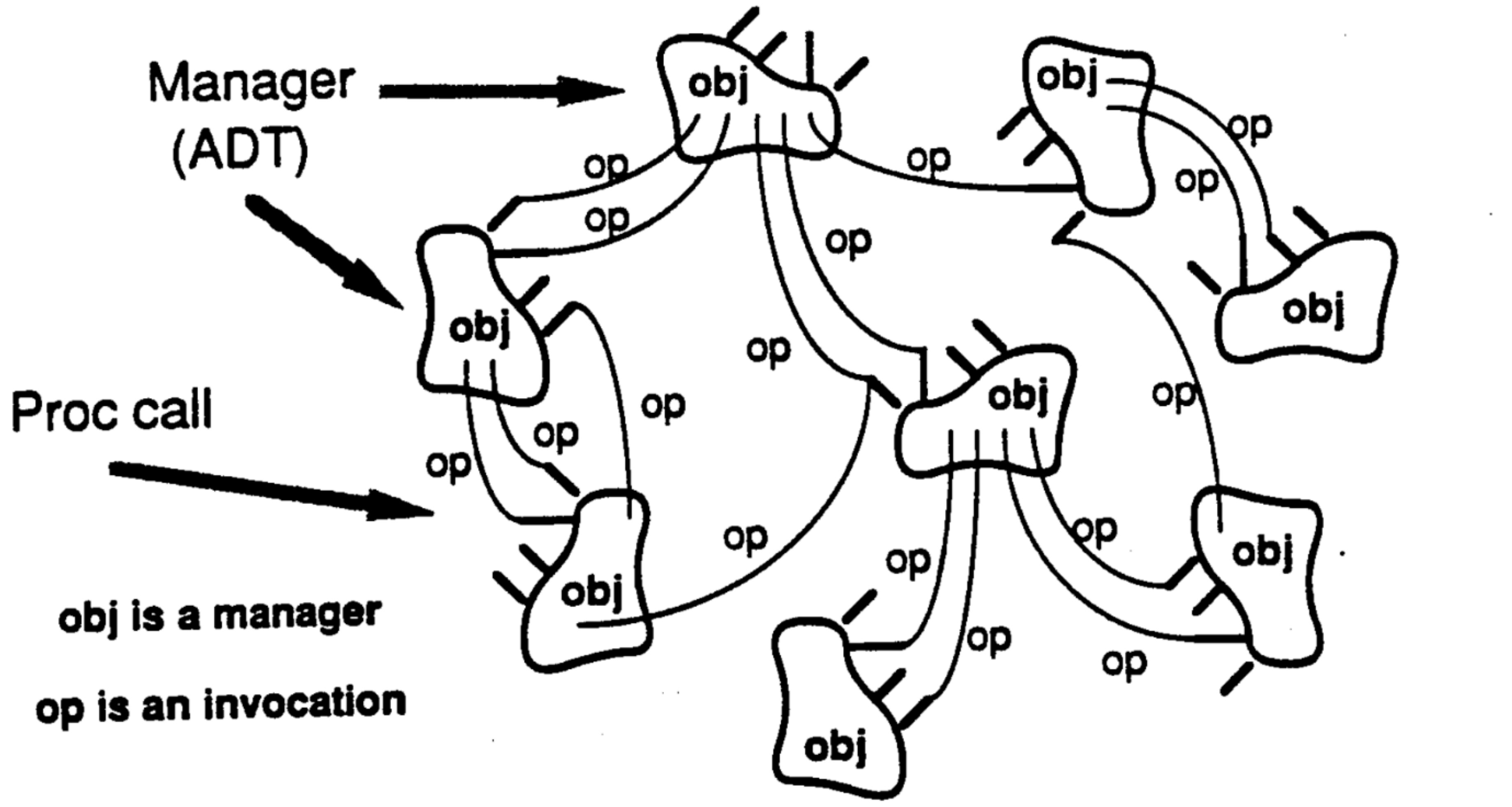
Target-1 Code Generator

Target-1 machine code

Target-2 Code Generator

Target-2 machine code

2. Object Oriented Organization



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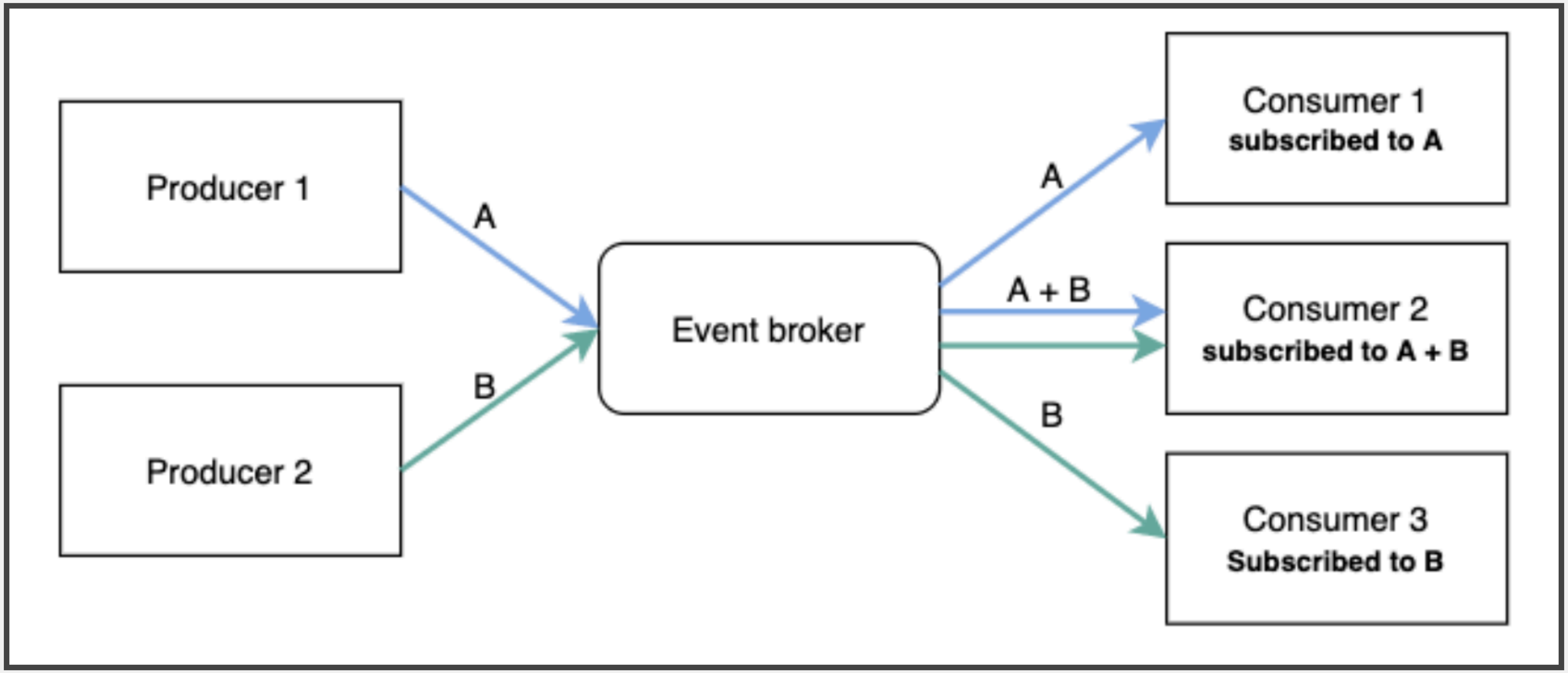
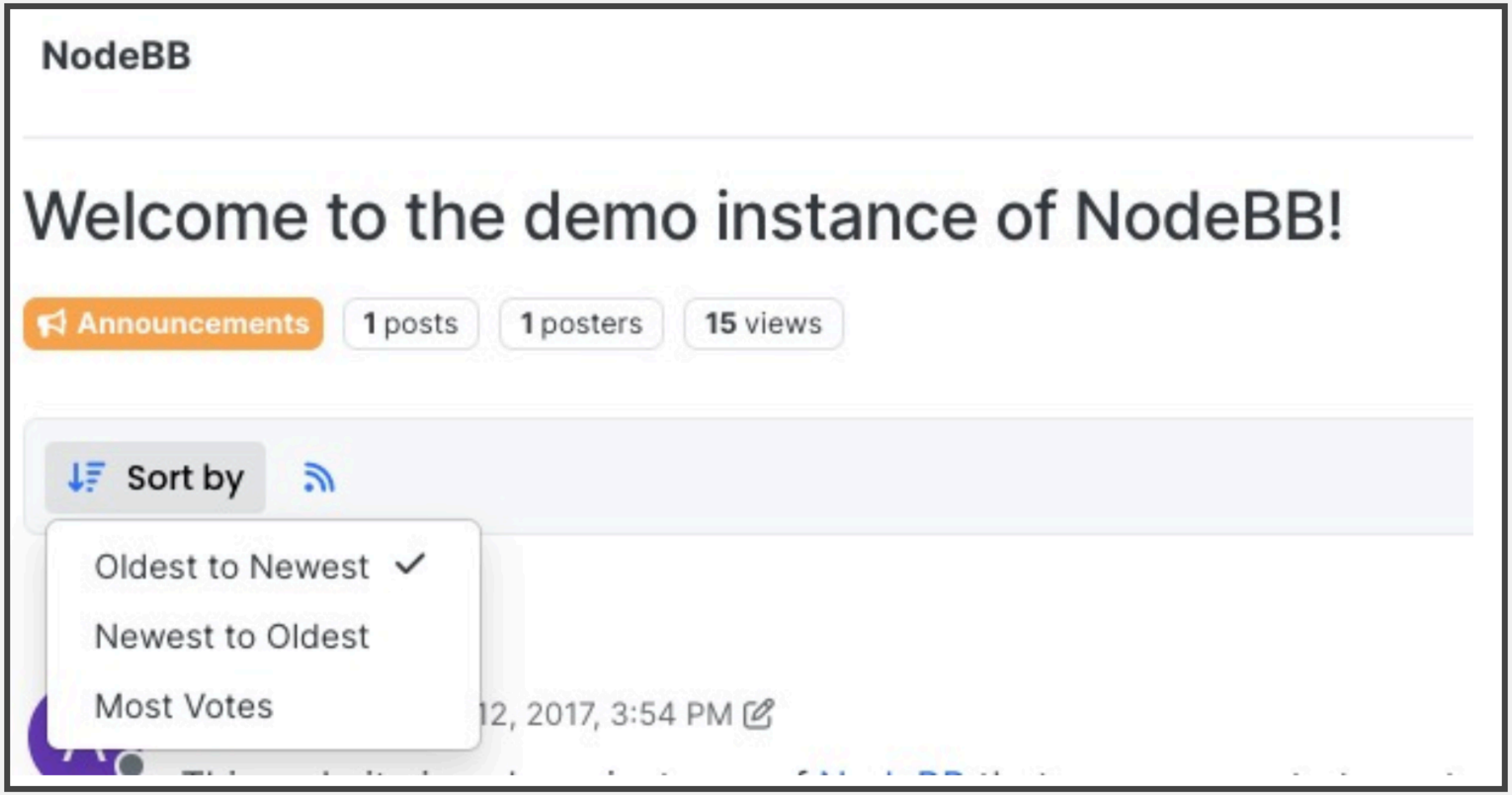
3. Event-Driven Architecture



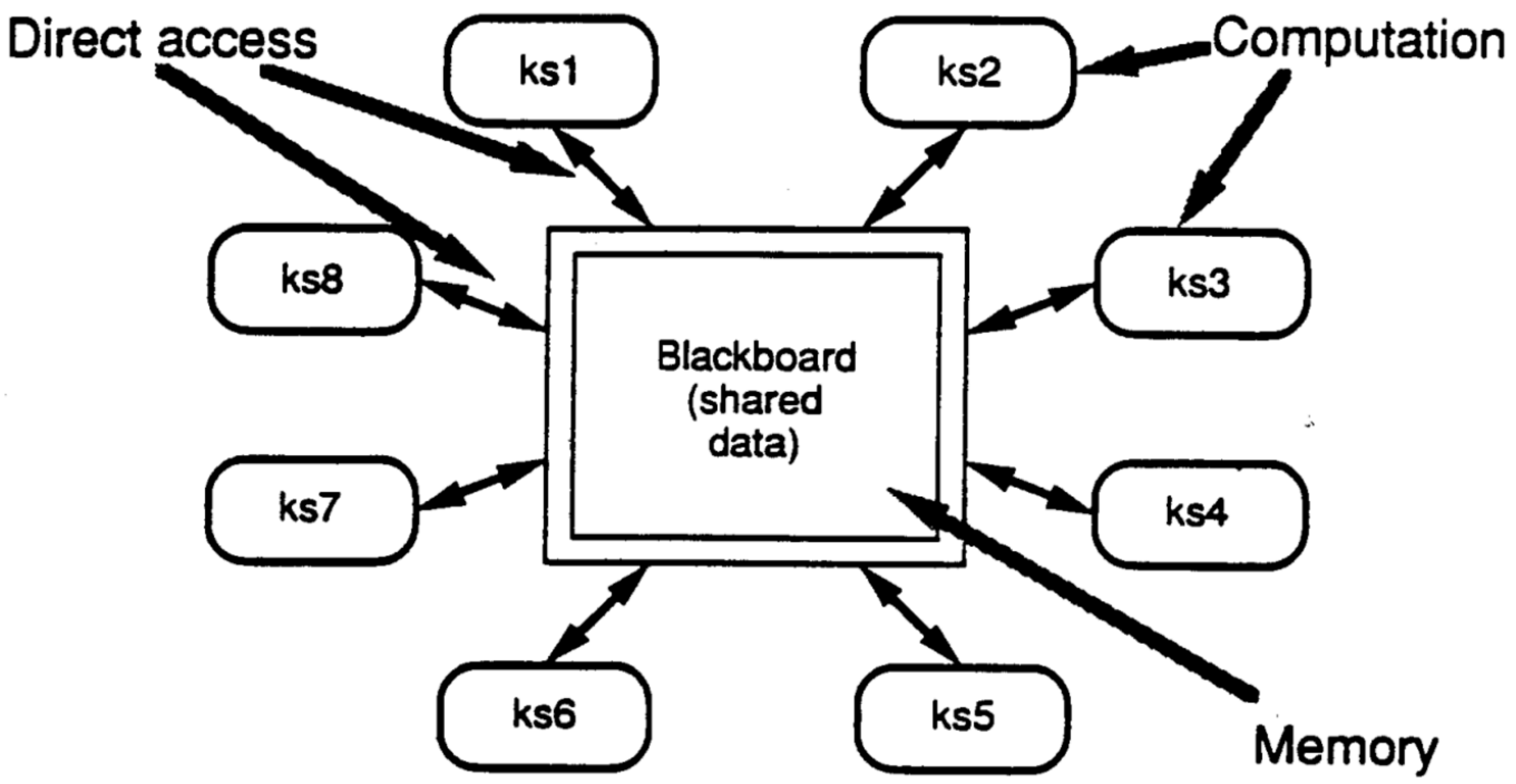
Example: HTML DOM + Javascript



NodeBB

Welcome to the demo instance of NodeBB!

4. Blackboard Architecture



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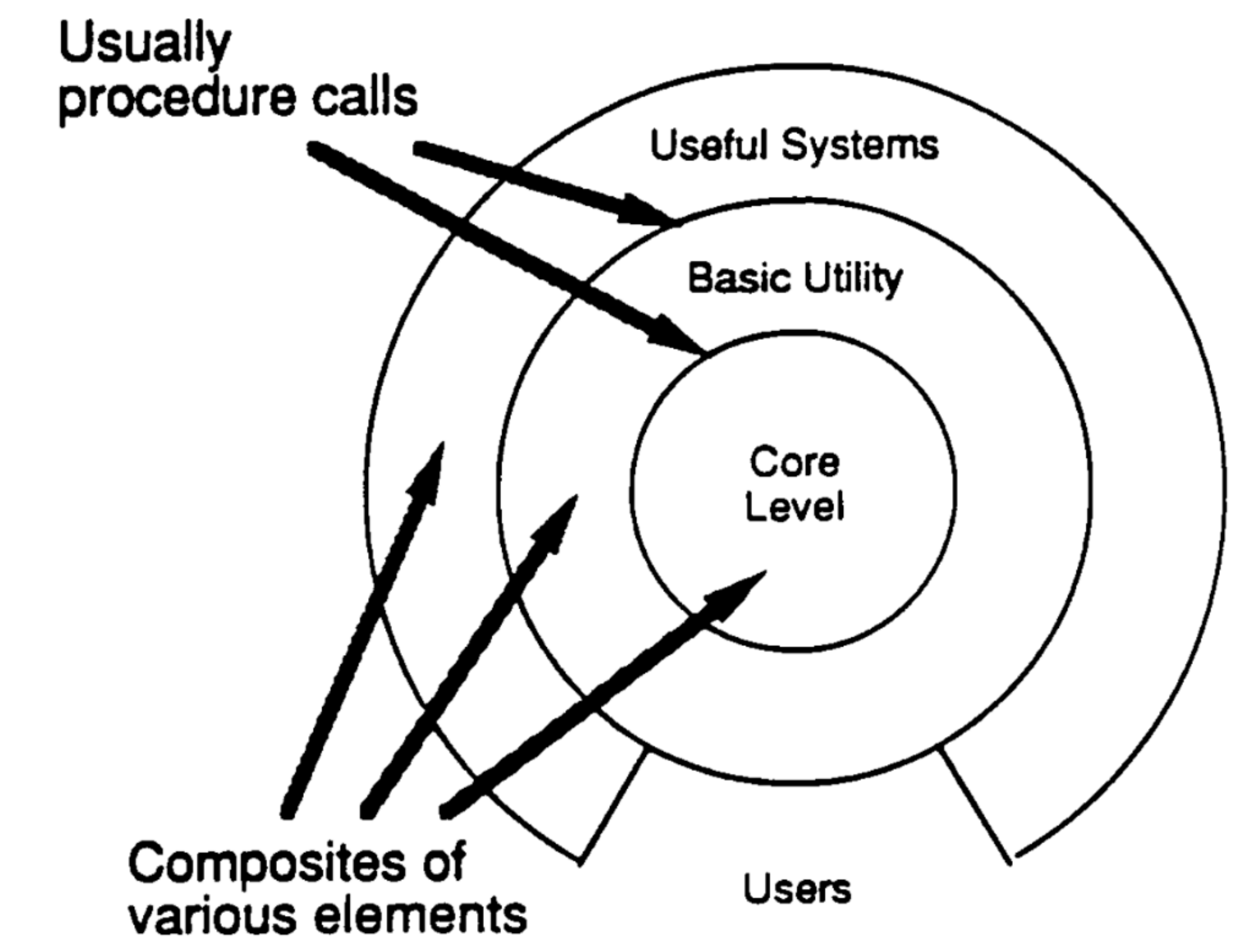
5. Layered Systems



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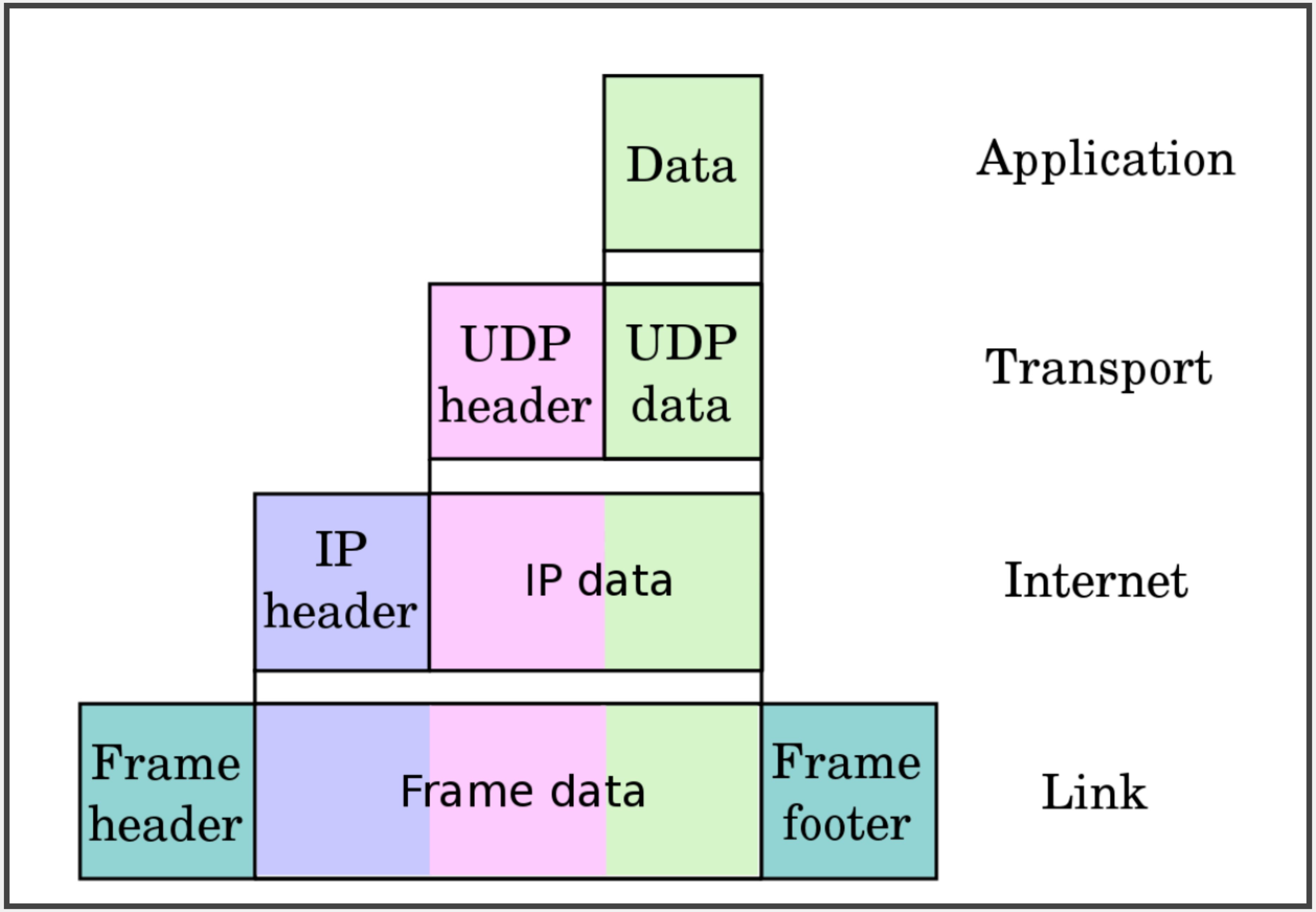
Example Internet Protocol Suite



Guidelines for Selecting a Notation

- Suitable for purpose
- Often visual for compact representation
- Usually boxes and arrows
- UML possible (semi-formal), but possibly constraining
  - Note the different abstraction level – Subsystems or processes, not classes or objects
- Formal notations available
- Decompose diagrams hierarchically and in views
- Always include a legend
- Define precisely what the boxes mean
- Define precisely what the lines mean
- Do not try to do too much in one diagram
  - Each view of architecture should fit on a page
  - Use hierarchy