COMP 150-SEN
Software Engineering Foundations

Software Architecture

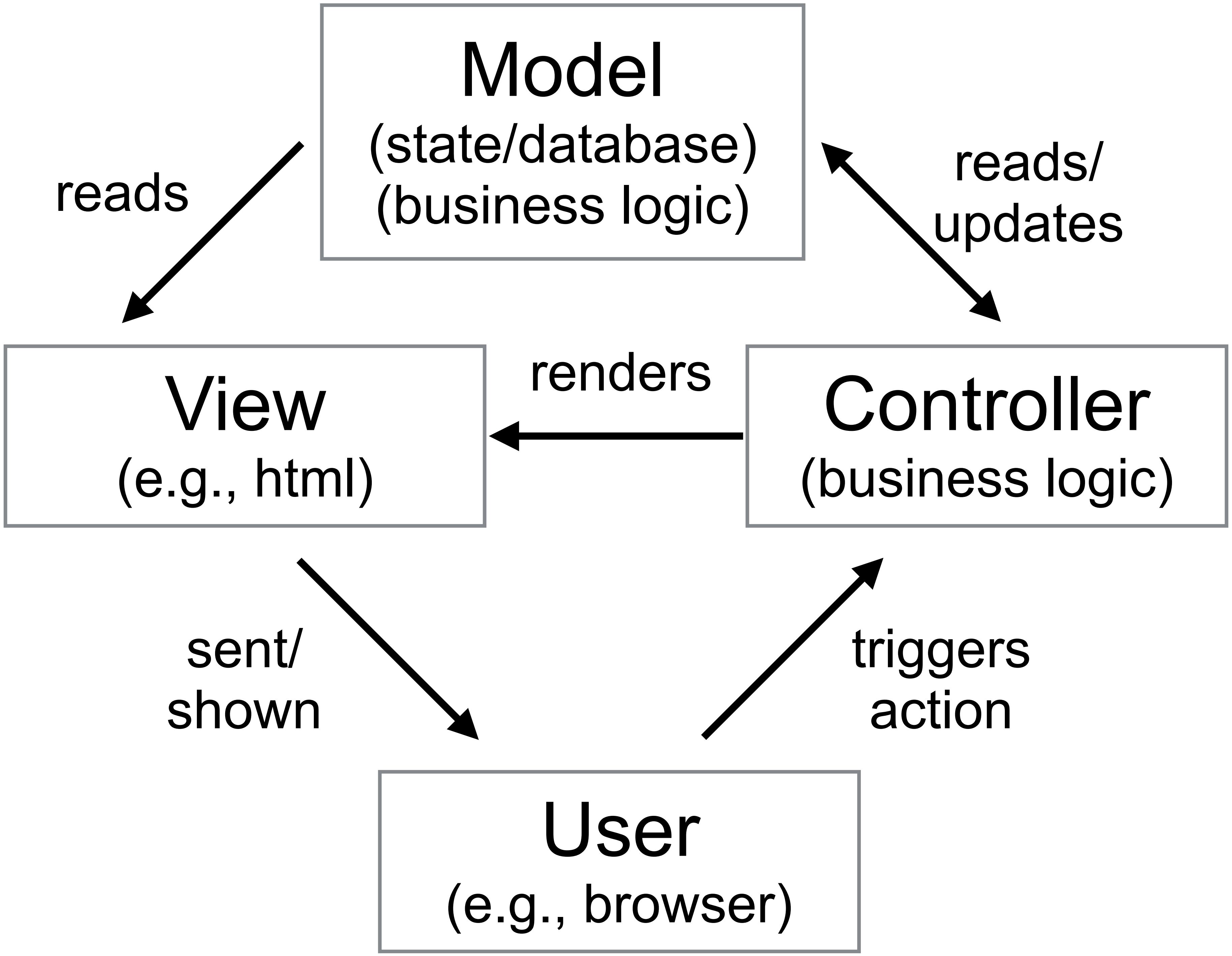
Spring 2019

(Some slides from Ben Liblit, UWisc CS 506)

Introduction

- *Software architecture* is the high-level structure and organization of a software system
  - The "big picture" or the "blueprint": What are the components of the system, and how they fit together
- Useful reading on software architecture
  - Garlan and Hall, *An Introduction to Software Architecture*. Technical Report CMU-CS-94-166, January 1994.
- Let's learn about one example architecture
  - Model-view-controller, a way of separating user interface from app's domain logic
- Then we'll talk more about architecture in general, and examine several more architectural styles

Model-View-Controller (MVC) Arch.



Key Features: Model

- Model separate from user interface (view + controller)
  - Model need not concern itself with presentation
  - The core business rules can go into a model
    - Username cannot be null; email address must be well-formed; a credit to one bank account must correspond to a debit from another; etc
  - Ensures that the data always “makes sense”
- The app data is *at rest* in the model
  - One or more views will always see data consistently
  - One or more controller can access the model, transactionally
  - The model can be backed up!

Key Features: View

- View decides which data to show and how to show it
  - But view should *not* change the model!
- Can have many different views
  - Might vary based on user perspective, e.g., student sees their grade record one way, faculty sees it another way
  - Might vary based on localization or customization, e.g., Fahrenheit vs. Celsius
  - Might be shown simultaneously, e.g., individual slide view vs. thumbnail view in PowerPoint
- Views often linked to controller
  - What the user can see informs them about what choices they have next, e.g., a student on a grade screen might be able to navigate to a courses screen

Key Features: Controller

- The input to the app
  - Provides actions that the user can invoke
  - Selects next view to display
- Business logic split between model and controller
  - E.g., checking whether current user has permission to read/write data could be done in controller or in model
  - Or, model could provide a method that includes the check, and then the controller calls that method
  - General design choice: include something in the model if multiple controller methods will reuse it
- Controllers often have a broad interface
  - E.g., in a web app, user could visit many URLs
  - E.g., in a desktop app, user could click many buttons

Example: Ruby on Rails

- Rails is a web app framework written in Ruby
  - Developed by David Heinemeier Hansson as part of Basecamp; released separately as Rails in 2004
- MVC framework
  - Model = database (sqlite, mysql, postgres, etc)
  - View = `.html.erb` files, i.e., html with embedded Ruby
  - Controller = methods that handle web requests
- Side note: real-world apps include many languages
  - Ruby, HTML, CSS, JavaScript, SQL, …
- Very quick tour of Rails next, with some code
  - Learn more at https://guides.rubyonrails.org

Sending a Web Request

- Browser sends a request for a web page

```
$ nc -c www.cs.tufts.edu 80
GET / HTTP/1.1

HTTP/1.1 200 OK
Date: Mon, 18 Feb 2019 20:57:47 GMT
Server: Apache/2.2.15 (Red Hat)
X-Powered-By: PHP/5.3.3
Content-Length: 848
Content-Type: text/html; charset=UTF-8
Connection: close

<html>
<head>
<title>Tufts University ECE and CS Departments</title>
```

} (Type these three lines)

Rails Server Internal Sequence

- Server receives a request
- It first *routes* the request to a *controller* method
- That method accesses the db using *models*
- When the controller is done, it *renders* a view
- The view file is sent back to the web browser

- Note: HTTP is *stateless*
  - Each request connects, gets result, drops connection
  - Web server stores state in db and in browser cookies
  - Servers and OSes play a lot of tricks to avoid making so many connections

Rails Models

- Examples from *talks*, a web site for displaying a list of talks in the department

```
# db/schema.rb
create_table “talks" do |t|
    t.text     "title"
    t.text     "abstract"
    t.text     “speaker"
    t.integer  “owner_id"  # talk creator
end
```

```
# app/models/talk.rb
class Talk < ActiveRecord::Base
  validates_presence_of :owner  # an invariant!
end
```

Rails Routing: URLs to Methods

```
# config/routes.rb
Talks::Application.routes.draw do
  resources :talks
end
```

```
$ rake routes
    talks GET    /talks(.:format)              talks#index
          POST   /talks(.:format)              talks#create
 new_talk GET    /talks/new(.:format)          talks#new
edit_talk GET    /talks/:id/edit(.:format)     talks#edit
     talk GET    /talks/:id(.:format)          talks#show
          PATCH  /talks/:id(.:format)          talks#update
          PUT    /talks/:id(.:format)          talks#update
          DELETE /talks/:id(.:format)          talks#destroy
```

- A route maps an HTTP verb and URL to a method
  - Example: `GET /talks/12` calls T`alksController#show`

Rails Controllers

- Receive a request

```ruby
# app/controllers/talks_controller.rb
class TalksController < ApplicationController
  def show
    # params maps :id to the id in the URL
    # Talk.find does a db query
    # @f for any f is a field (instance variable)
    @talk = Talk.find(params[:id])
    # notice the method just returns nothing!
  end
end
```

Rails Views

```
# app/views/talks/show.html.erb
<div class="center-header">
 <div class="talk">
  <div class="title"><%= @talk.title %></div>
  <div class="speaker"><%= @talk.speaker %></div>
</div>
<div class="abstract">
 <% if @talk.abstract == "" %>
  <span class="title">No abstract</span>
 <% else %>
  <span class="title">Abstract</span>
  <div class="abstract-body"><%= @talk.abstract %></div>
  <% end %>
</div>
…
```

- Didn't need to def `Talk#title` and `Talk#speaker`
  - Implemented using reflection and knowledge of db!

MVC Pros and Cons

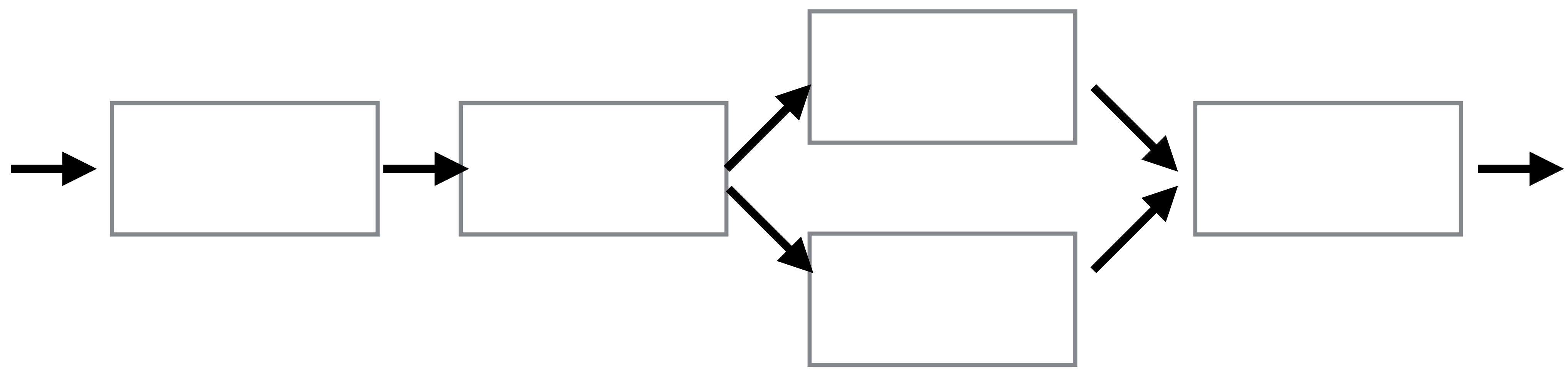
- Separation between data and interface is key
  - Views can be replaced, changed, customized, expanded
  - As db is read and written, changes reflected in all views
    - Centralized store of “truth” for the system state
  - Scalable deployment easier, e.g., multiple controller/view instances communicate with one db
    - System is quiescent when controller method returns
- Several potential drawbacks
  - Many kinds of changes to model require changing view and controller
    - E.g., removing a db column, changing the name of a table
  - Views and controllers are closely coupled
  - Added complexity
    - E.g., even simple Rails app has many files in many locations

What is Software Architecture?

- Tends to be more *abstract* than any coding feature
  - E.g., it may talk about things that are represented by sets of classes rather than a single class
- Is *hard to change* after building a system!
- Helps guide *division of work* by different developers
- Includes *decisions*, *principles*, and *vision* that led to the design
  - Informs later decisions as the system evolves
  - (Design patterns are smaller scale than architectures)

Pipe and Filter Architecture

- Each component has inputs and outputs
  - Component reads input stream, produces output stream



  - Components are *filters*, connections are the *pipes*
  - A *stream* is a sequence of data iof unknown length
- Key design properties/questions
  - Filters should not share internal state
    - Filters don't know how they're connected
  - At any joins, data rates from pipes need to sync up
  - Filters and pipes have to agree on input/output data types

Pipe and Filter: Unix Commands

- Ex: Count `httpd` instances running (off by one)

```
ps -ef | grep httpd | wc -l
```

- Commands take ASCII chars as input
  - What about unicode?
- Every command has *standard in* and *standard out*
  - But there's also *standard error*; where does that go?
  - Normally to stdout, but you can redirect it

```
# send both stdout and stderr to file.log
./script.sh > file.log 2>&1
```

- One command can launch another
  - See `pipe`, `fork`, and `exec*` C library functions
  - Most languages have a library to make these easier to use

Using Pipe and Filter in Java

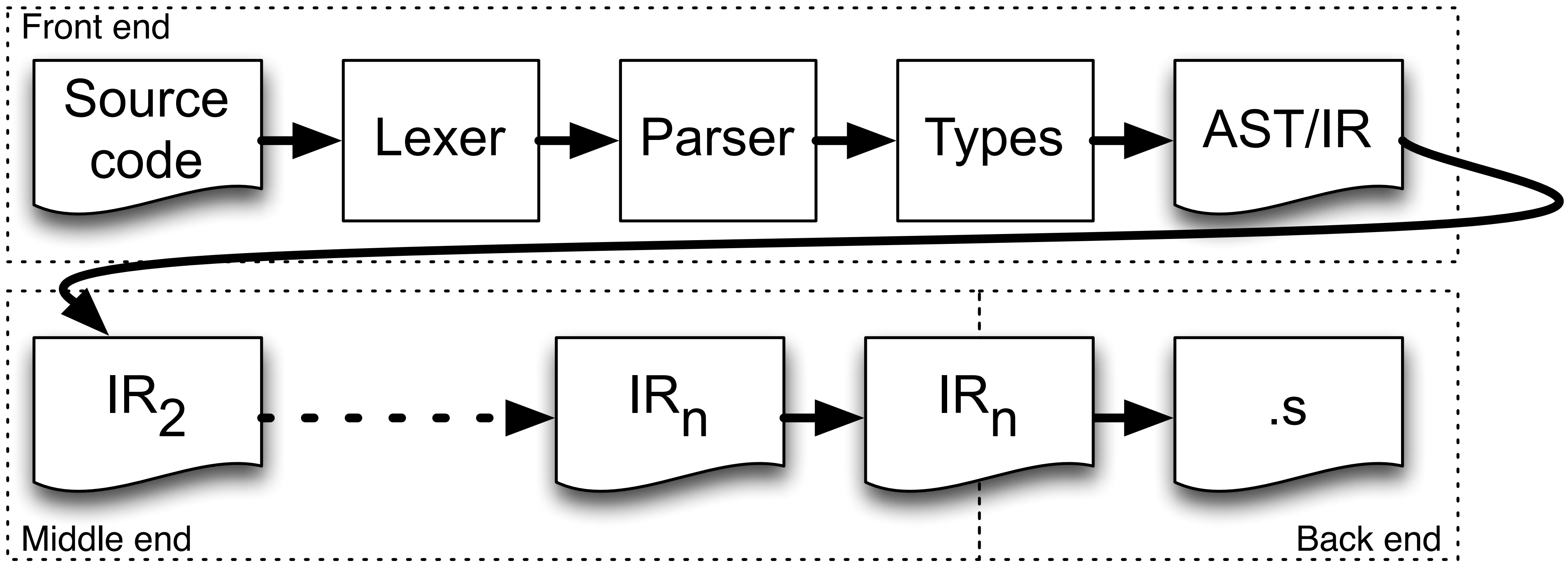
- Standard input, output, and error are standard

```
class System {
  static PrintStream out;  // stdout
  static InputStream in;   // stdin
  static PrintStream err;  // stderr
}
```

- To launch subprocesses, use `ProcessBuilder`

```
ProcessBuilder pb = new ProcessBuilder("ls");
Process p = pb.start();
p.waitFor();
InputStream is = p.getInputStream(); // output of p!
BufferedReader br =
 new BufferedReader(new InputStreamReader(is));
String line;
while ((line = br.readLine()) != null) {
 System.out.println(line);
}
```

Pipe and Filter? A Compiler



- A compiler is a sequence of transformations
  - Source text converted to *tokens* and then parsed to yield AST
  - The AST becomes a control-flow graph (CFG), which is successively simplified
  - Ultimately the CFG is simplified so much it can be output as an assembly or machine code file
- Except, all stages share state (e.g., symbol table)

Pipe and Filter Advantages

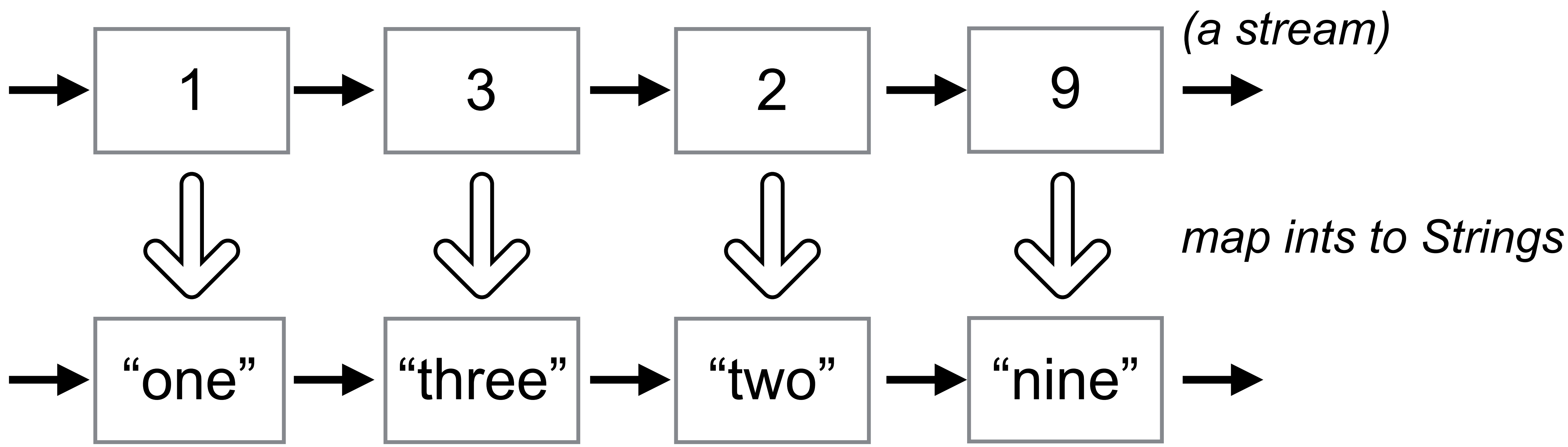
- Overall behavior is a composition of filter behaviors
  - Component connections are significant and obvious
- Potentially good reuse by creating different compositions of filters
- Can test each filter in isolation
- Filters can be replaced individually
- As we will see shortly, can support distributed execution

Pipe and Filter Disadvantages

- Not good for interactive use
  - Focused on converting inputs to outputs, not supporting user interactions
- Pipes are narrow; hard to pass complex data
  - E.g., compilers not really pipe-and-filter
- Overhead for parsing/unparsing data when read from/sent to a pipe
  - Though, components that are conceptually pipes could run as part of the same process
  - In which case they could pass data structures through "pipes"

Mapping a Stream

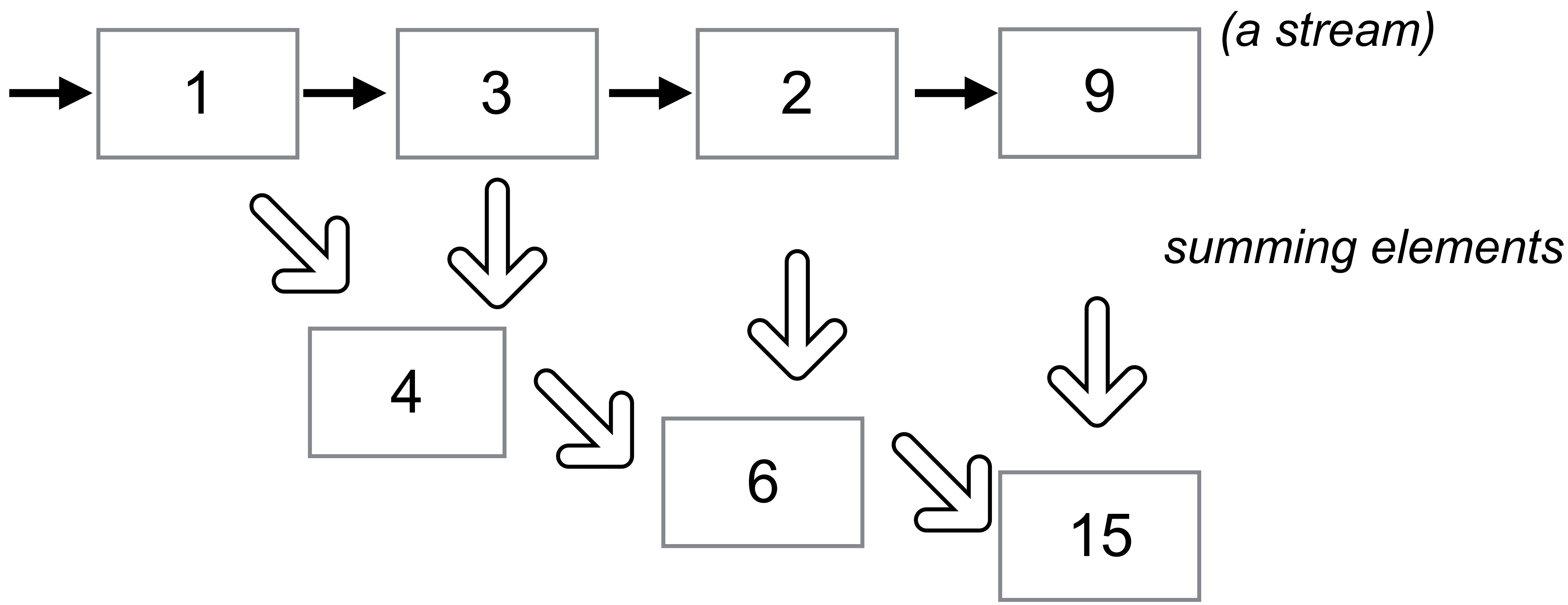
- A *map* operation transforms stream values



  - One-to-one correspondence between elements
  - Each element processed in isolation
  - Input and output types may differ

Reducing a Stream

- A *reduce* operation combines stream values



  - Many elements combined to yield a single value
  - Elements processed with reduction of other elements
  - Many possible reduction orders possible if operations are commutative and associative
  - Input and output types may differ
  - Stream must be finite to actually produce a value at the end

Google MapReduce

- Key challenge: Google data is BIG
  - Stored across vast number of machines in data centers
  - Need to process the data to do work
  - Can't move all the data to one place; it won't fit
  - Have to take machine failure into account
  - $\Rightarrow$ programming a data processing computation is hard!
- MapReduce idea:
  - System architecture: map and reduce components only
  - Parallelize and distribute them across a data center
    - Sophisticated plumbing maps this fast, robust, fault tolerant
- Pseudocode, pictures, examples shown next from Dean and Ghemawat, *MapReduce: Simplified Data Processing on Large Clusters*, OSDI 2004

MapReduce Pseudocode

- Count # word occurrences in documents

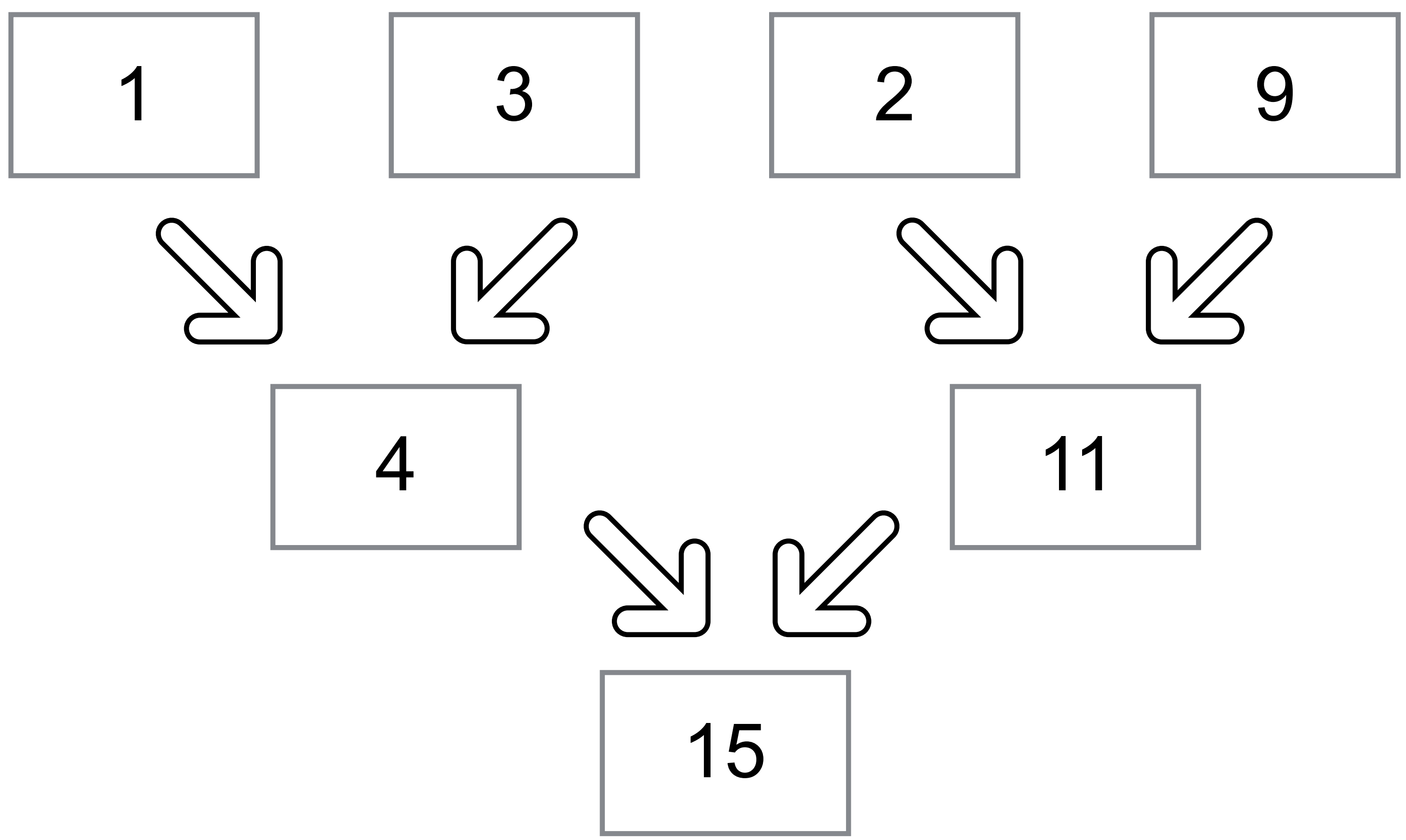
```
// map: (k1, v1) → List<(k2, v2)>
map(String key, String value) {
  // key: doc name, value: doc contents
  for (each word w in value) {
    EmitIntermediate(w, "1");
} }
// reduce: (k2, List<v2>) → List<v2>
reduce(String key, Iterator values) {
  // key: a word, values: list of counts
  int result = 0;
  for (each v in values) {
    result += ParseInt(v);
  }
  Emit(AsString(result));
}
```

MapReduce Types

- Slightly non-standard types for these operations
- Map input is key-value pairs, e.g., (doc, contents)
  - (“US Constitution”, “We the People…”)
  - (“Declaration of Independent”, “We hold these truths…”)
- Map output is a mapping written as a list
  - [(“We”, “2”), (“the”, “42”), (“People”, “1”), …] *(numbers made up)*
  - [(“We”, “5”), (“hold”, “3”), …] *(numbers also made up)*
- Reduce input is map output that is *grouped by key*
  - (“We”, [“2”, “5”])
- Reduce output is result list for that key
  - [“7”]
  - It’s a list so it can be input to reduce further down the line

MapReduce Distribution

- Original data starts on many machines
- Those machines, or others, map that data
  - Can be done massively in parallel, since mapping each piece of data is independent
- Reduce combines data across machines
  - Can be done as a tree to maximize parallelism



Fault Tolerance

- If a worker times out, its work can be passed to another machine
  - Will only stall part of the computation
  - In many cases, worker's result can just be ignored if it never finishes in time
  - After all, big data might have a lot redundancy and noise
- The Google File System stores reduce results
  - Large scale, robust, distributed file storage

Current State of MapReduce

- Open source tools available, e.g., Hadoop
- Programming model limited in many respects
- Google doesn’t use MapReduce any more

Layered Architecture

- Organized as a hierarchy
  - Layer provides services to layer above it
  - Layer is a client of the layer below it
- Example: running a Java program

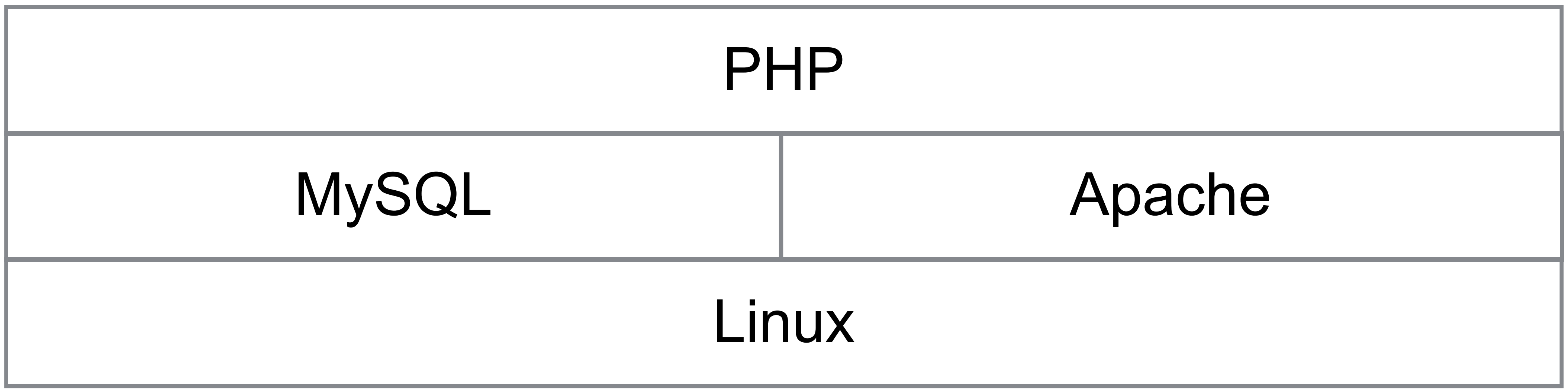
Java program
Java virtual machine
Operating system (kernel)
Hardware

Open Systems Interconnection (OSI)

- "Network stack" or "protocol stack"

Layer 7: Application (HTTP)	*(the actual application)*
Layer 6: Presentation	*(encoding, compression, crypto)*
Layer 5: Session	*(sequences of communication)*
Layer 4: Transport (TCP)	*(segmentation, acks, multiplex)*
Layer 3: Network (IP)	*(addressing, routing, etc)*
Layer 2: Data link (Ethernet)	*(sending data frames between nodes)*
Layer 1: Physical (IEEE 802.3u)	*(sending raw data over wires/radio/etc)*

LAMP Stack

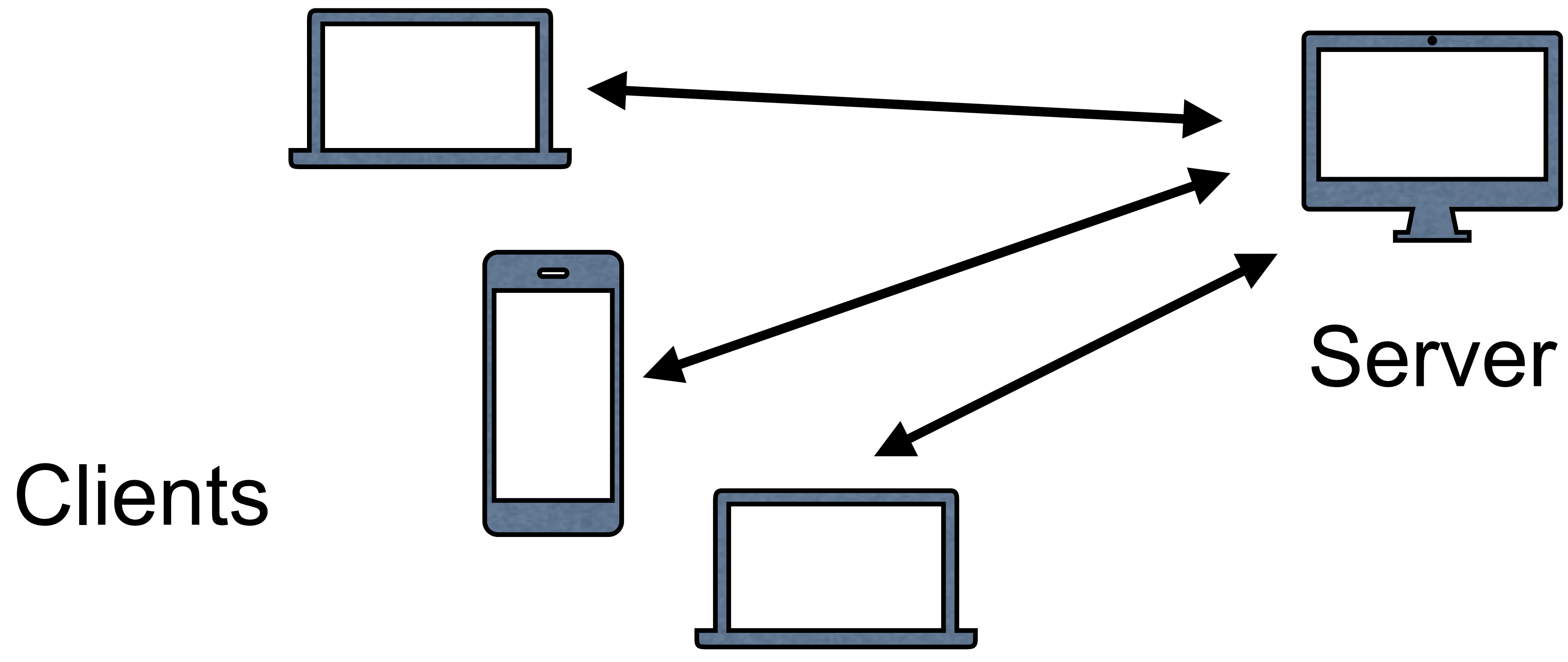


- Slightly old-school web server structure

Layered Architecture Tradeoffs

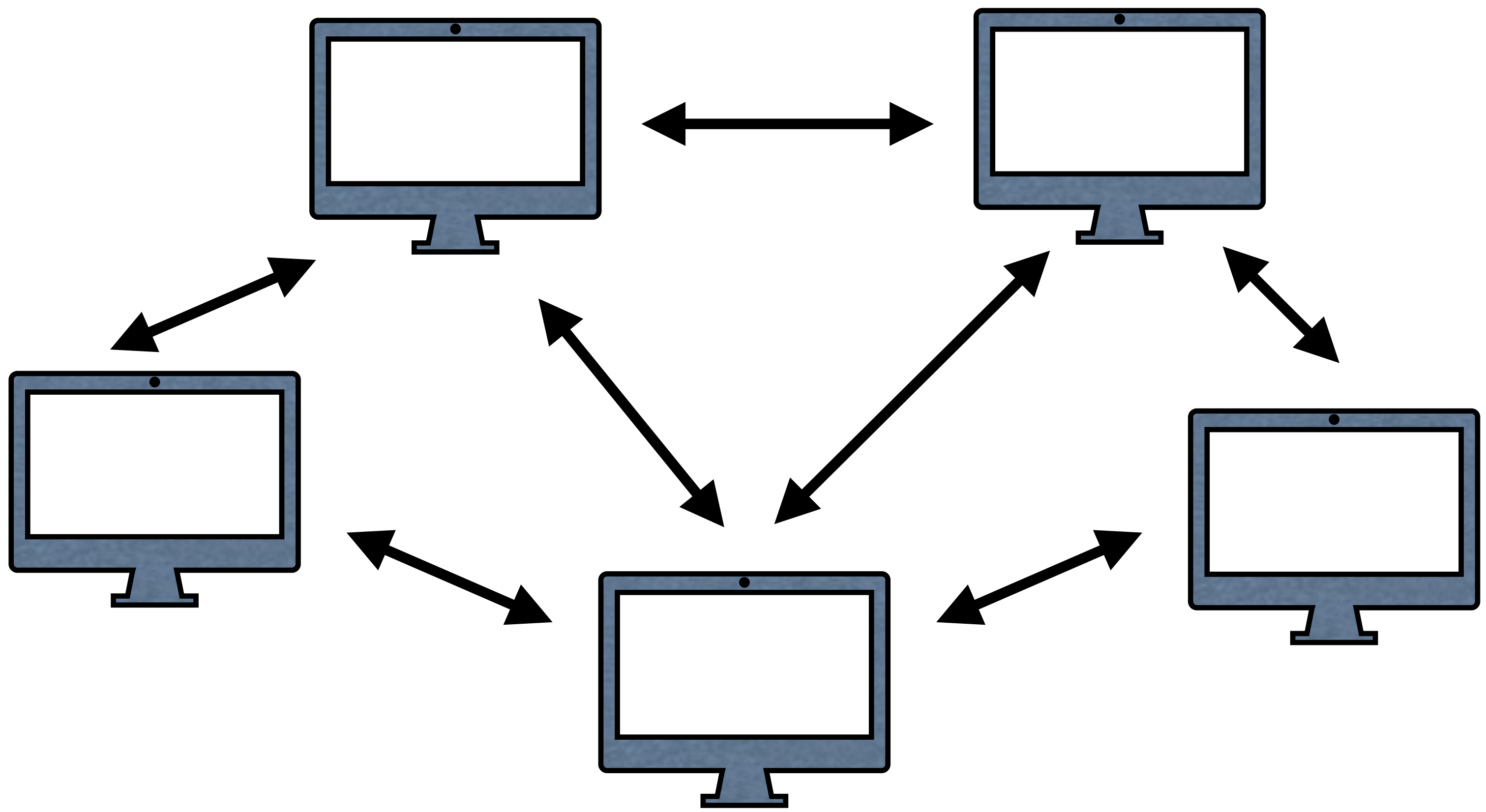
- Advantages
  - Good fit for system with increasing levels of abstraction
  - Changing one layer affects at most two others
  - Can interchange implementations of same layer interface
- Disadvantages
  - May not be able to identify clean layers
  - Might need to jump layers for performance or functionality

Client-Server Architecture



- Clients communicate with server, typically over network
- Tradeoffs
  - Server is central point of failure
    - Replication can help, but then consistency is
    - CAP theorem: Pick two of Consistency, availability, and partition tolerance
  - Any client-to-client communication must go through server

Peer-to-Peer Architecture



- Machines communicate with each other
  - Popularized by Napster (!), 1999
- Several challenges/tradeoffs
  - Trust between nodes
  - More equal upload/download volume compared to client server
  - Location of data on network not centralized

Software Architecture Activities

- Initial design/development/evaluation
  - Note architecture can have several different views
    - User perspective; development view (software modules); run-time view (processes etc); physical view (hardware, location in data center, etc)
- Maintain architecture over time
  - Architectural drift — implementation decisions that aren't encompassed by the architecture, but don't conflict with it
  - Architectural erosion — implementation decisions that actually violate the architecture
  - What to do?
    - Change the architecture or change the code!
- Evolve architecture as requirements change
- Key challenge: Architecture is not code, hence it will inevitably drift from the code