DISTRIBUTED SYSTEMS CS6421
ADVANCED RESOURCE MANAGEMENT

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Slides Credit:

Prof. Tim Wood and Prof. Roozbeh Haghnazar

FINAL PROJECT

- Groups of 3-4 students
- **Research-focused**: Reimplement or extend a research paper
- **Implementation-focused**: Implement a simplified version of a real distributed system

- Course website has sample ideas
  - But don't feel limited by them!
  - You don't have to use go!

- Timeline
  - Milestone 0: Form a Team
  - Milestone 1: Select a Topic
  - Milestone 2: Literature Survey
  - Milestone 3: Design Document
  - Milestone 4: Final Presentation

https://gwdistsys2023.github.io/DistributedSystem/project/

THIS WEEK…

- Case studies
  - Map reduce
  - DevOps
- Resource Optimization
  - Np-Hard problems
  - Many-Objective Optimization Problems
- Migration
  - Code
  - Processes
  - VMs
- Final Project

The future of distributed systems…

SCHEDULING IN MAP REDUCE

- Researchers have considered many factors when designing big data scheduling algorithms:
    - What types of factors might we care about for MR scheduling?

SCHEDULING IN MAP REDUCE

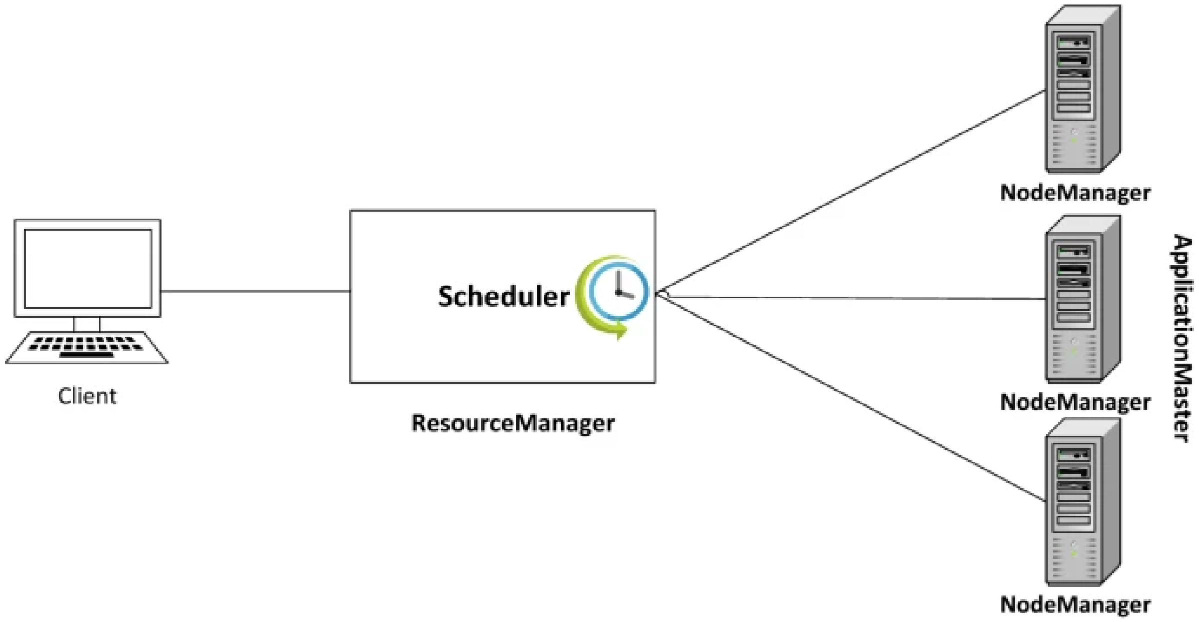
- Researchers have considered many factors when designing big data scheduling algorithms:
  - Resource Efficiency
  - Data Locality
  - Deadlines
  - Hardware and Task Heterogeneity
  - Nature of jobs (dependencies, discreet or continues problem space)
  - Energy consumption
  - Latency of short tasks vs throughput of big tasks

BASIC MAP REDUCE TASK SCHEDULING

- **FIFO** - Assigns resources to jobs based on arrival time.
  - Fully complete one job before starting the next
- **Fair** - Assigns resources to jobs so that all jobs get an equal share of resources over time
  - Splits up cluster to run multiple jobs simultaneously
  - Jobs are grouped into pools (e.g., all jobs from one user are in the same pool)
  - Fairness is provided across pools; jobs within a pool can be FIFO or Fair
- **Capacity** - Assigns resources to jobs based on its organization's capacity
  - Each organization contributes resources to the cluster, guaranteeing its minimum share
  - If an organization is not using all resources, others can use them in a fair manner
  - Supports priorities, security ACLs, and resource requirements (only RAM)

YARN MAP REDUCE TASK SCHEDULING

- Hadoop Yarn is a framework, which provides a management solution for big data in distributed environments.
- Provides support for:
  - multi-tenant environment
  - cluster utilization
  - high scalability
  - implementation of security controls
- Yarn consists of two main components which are:
  - Resource Manager
  - Application master



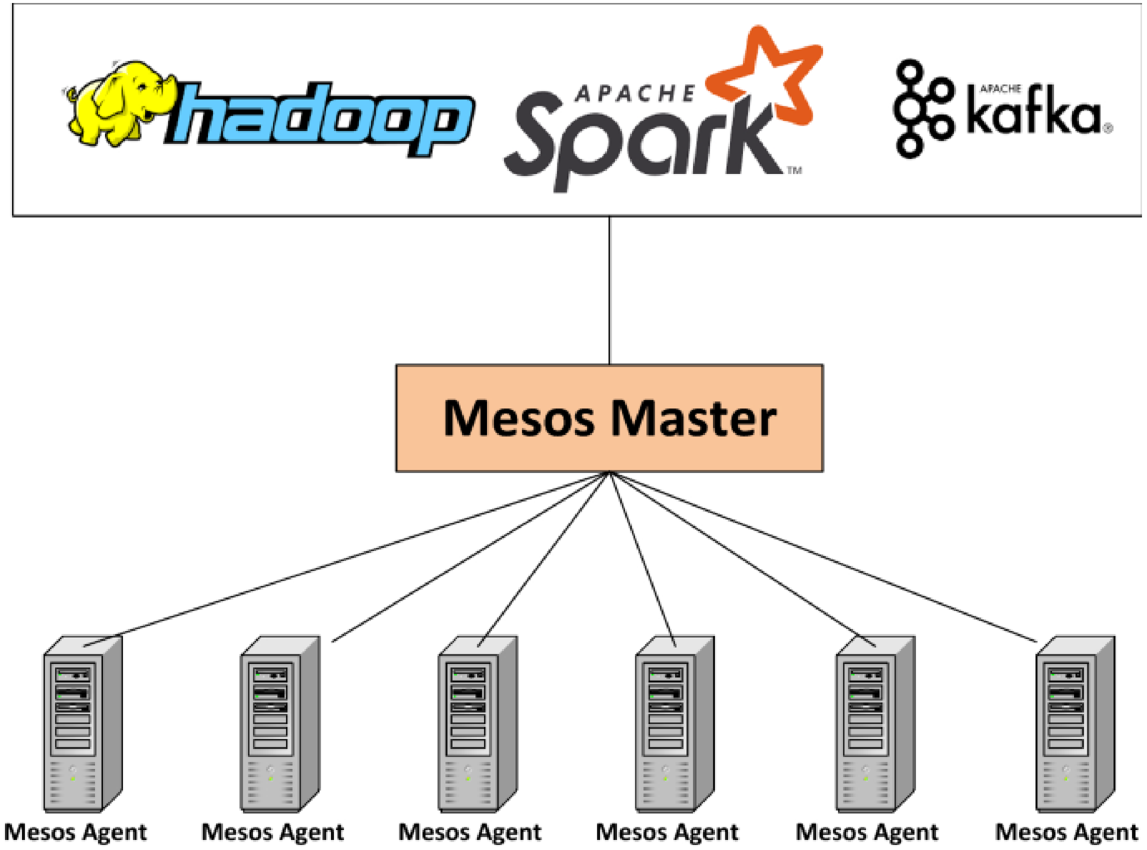
CORONA

- Corona is an extension of the MapReduce framework from Facebook
- It provides high scalability and cluster utilization for small tasks.
- This extension was designed to overcome some of the important Facebook challenges, such as:
  - Scalability
  - Low latency for small jobs (pull-model)
  - Resource requirements
  - Dynamic software updates
- Introduces more scalable job tracking and scheduling components

More info: https://www.facebook.com/notes/facebook-engineering/under-the-hood-scheduling-mapreduce-jobs-more-efficiently-with-corona/10151142560538920/

APACHE MESOS

- Cluster manager to offer effective heterogeneous resources isolation and allocation for distributed applications
  - Originally developed at UC Berkeley, extended at Twitter/AirBnB/others
- Defines an abstraction of computing resources (CPU, storage, network, memory, and file system)
- Supports customizable schedulers that match requests from applications to cluster resources
  - Not MapReduce/Hadoop specific



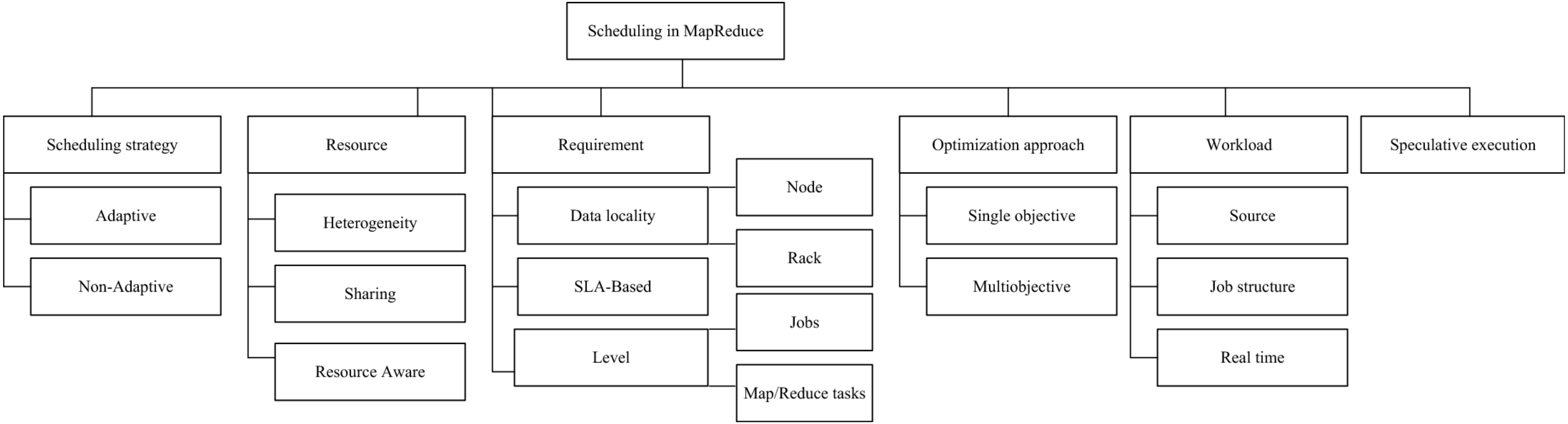
RESOURCE SCHEDULING FRAMEWORKS

Features	MapReduce default [21]	Yarn [22]	Mesos [23]	Corona [24]
Resources	Request based	Request based	Offer based	Push based
Scheduling	Memory	Memory	Memory/CPU	Memory/CPU/Disk
Cluster utilization	Low	High	High	High
Fairness	No	Yes	Yes	Yes
Job latency	High	Low	Low	Low
Scalability	Medium	High	High	High
Computation model	Job/task based	Cluster based	Cluster based	Slot based
Language	Java	Java	C++	–
Platform	Apache Hadoop	Apache Hadoop	Cross-platform	Cross-platform
Open source	Yes	Yes	Yes	Yes
Developer	ASF	ASF	ASF	Facebook

From *MapReduce scheduling algorithms: a review*
https://link-springer-com.proxygw.wrlc.org/article/10.1007/s11227-018-2719-5

TAXONOMY OF MAPREDUCE SCHEDULING

A **taxonomy** helps us structure our comparisons of different categories of MapReduce Schdulers



MAP REDUCE SCHEDULING

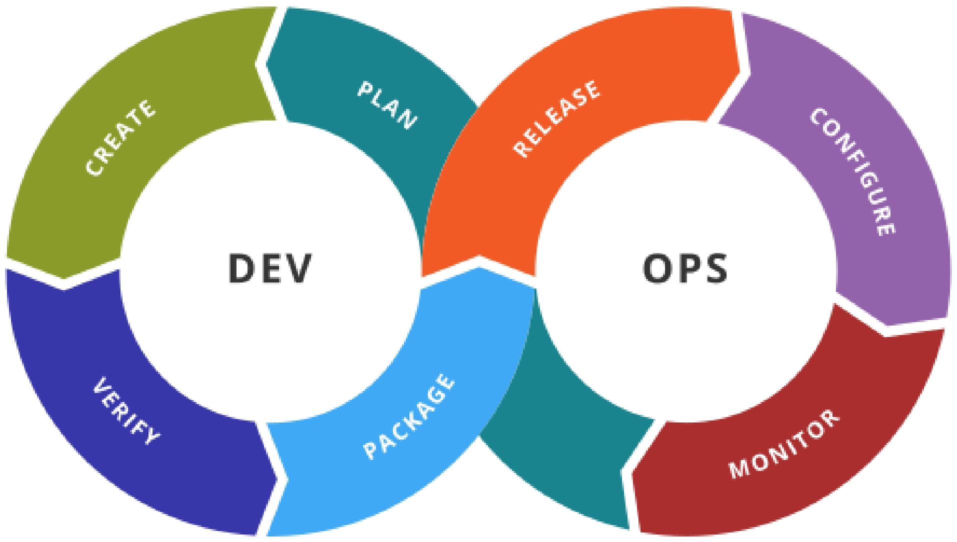
- Continues to evolve over time as needs change
  - Scale of MR clusters
  - Diversity of users and workloads
  - Size of data to process
  - Hardware accelerators

  - Might be a good area for a Final Project!

CASE STUDY: DEV OPS

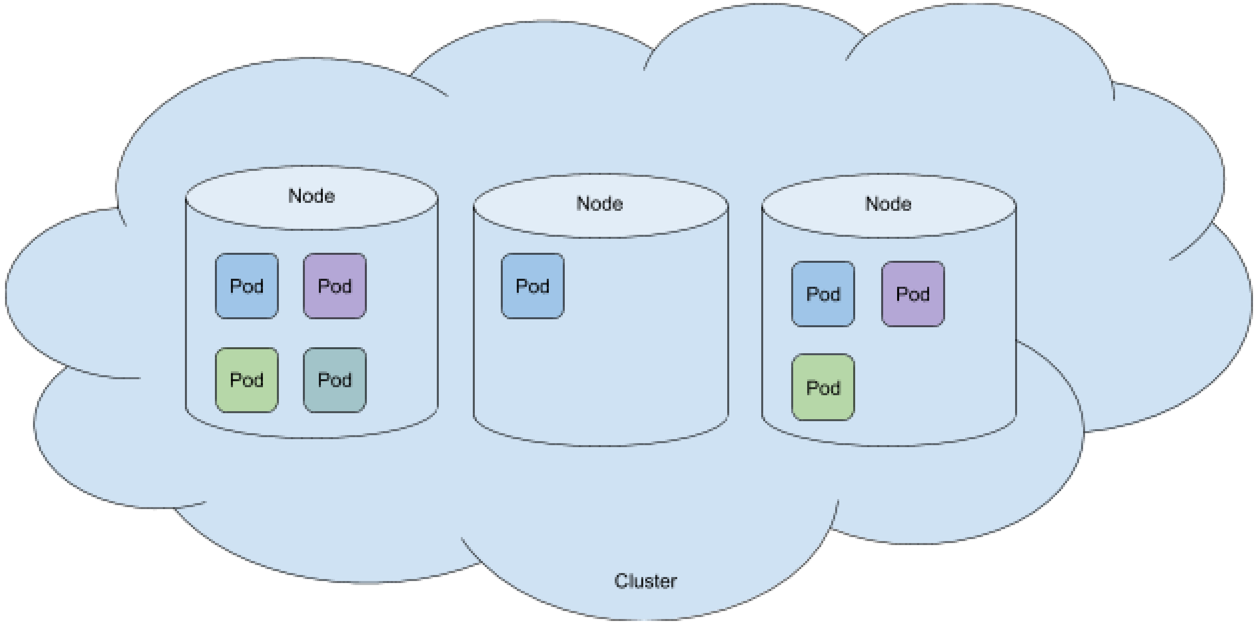
- Dev Ops combines **application development** and **deployment and operations** into a single management process
- Allows companies to more quickly update and deploy applications
  - Integrates the roles of dev and ops
  - Potentially could just break things faster…

- Load Balancers have become a tool for Dev Ops to handle:
  - Service discovery
  - Health checking
  - Load balancing
  - Release management
  - …



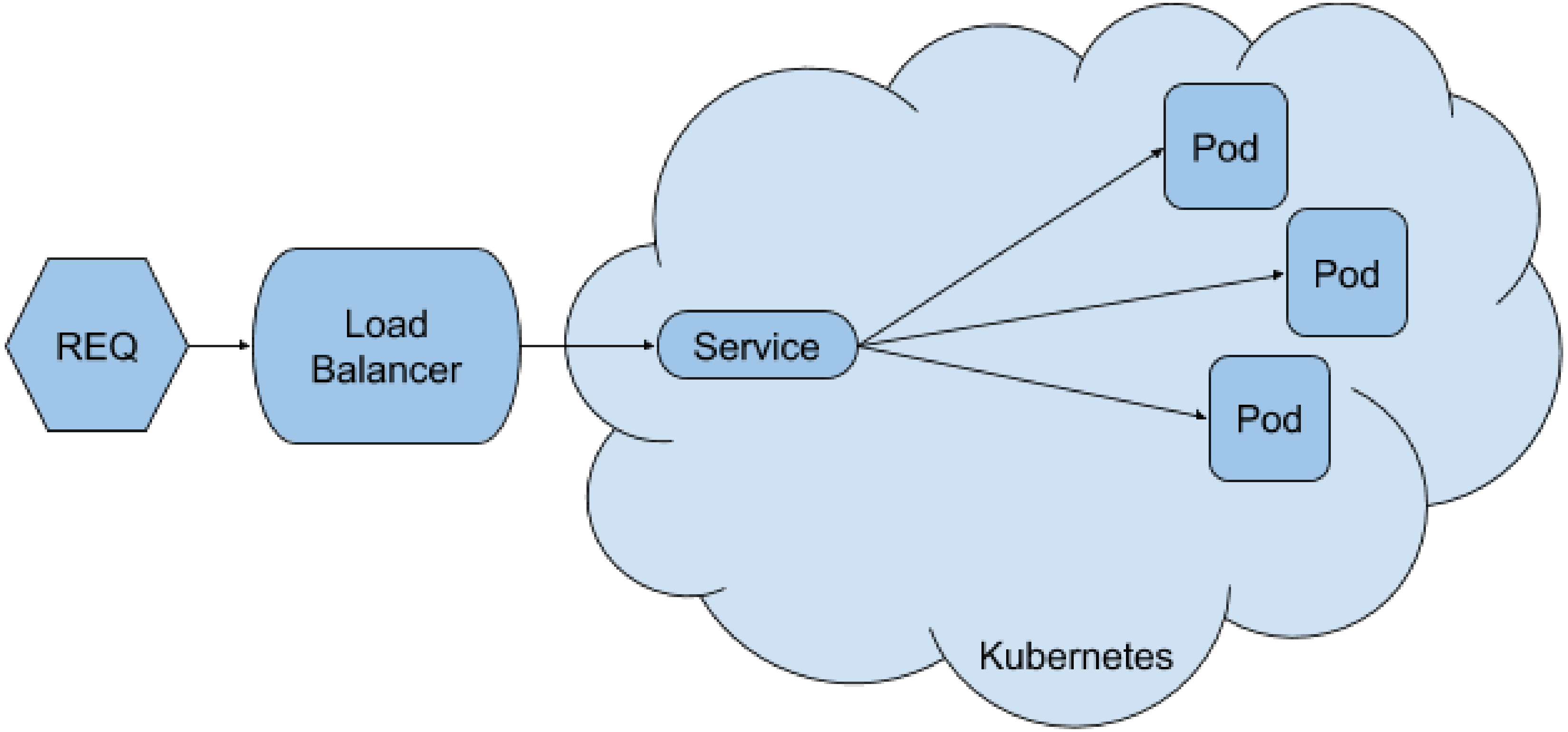
DEV OPS LB

- Kubernetes consists of physical or virtual machines—called nodes—that together form a cluster.
- Within the cluster, Kubernetes deploys pods.
- Each pod wraps a container (or more than one container) and represents a service that runs in Kubernetes. Pods can be created and destroyed as needed.
- A service is an abstraction that allows you to connect to pods in a container network without needing to know a pod's location (i.e. which node is it running on?) or to be concerned about a pod's lifecycle.

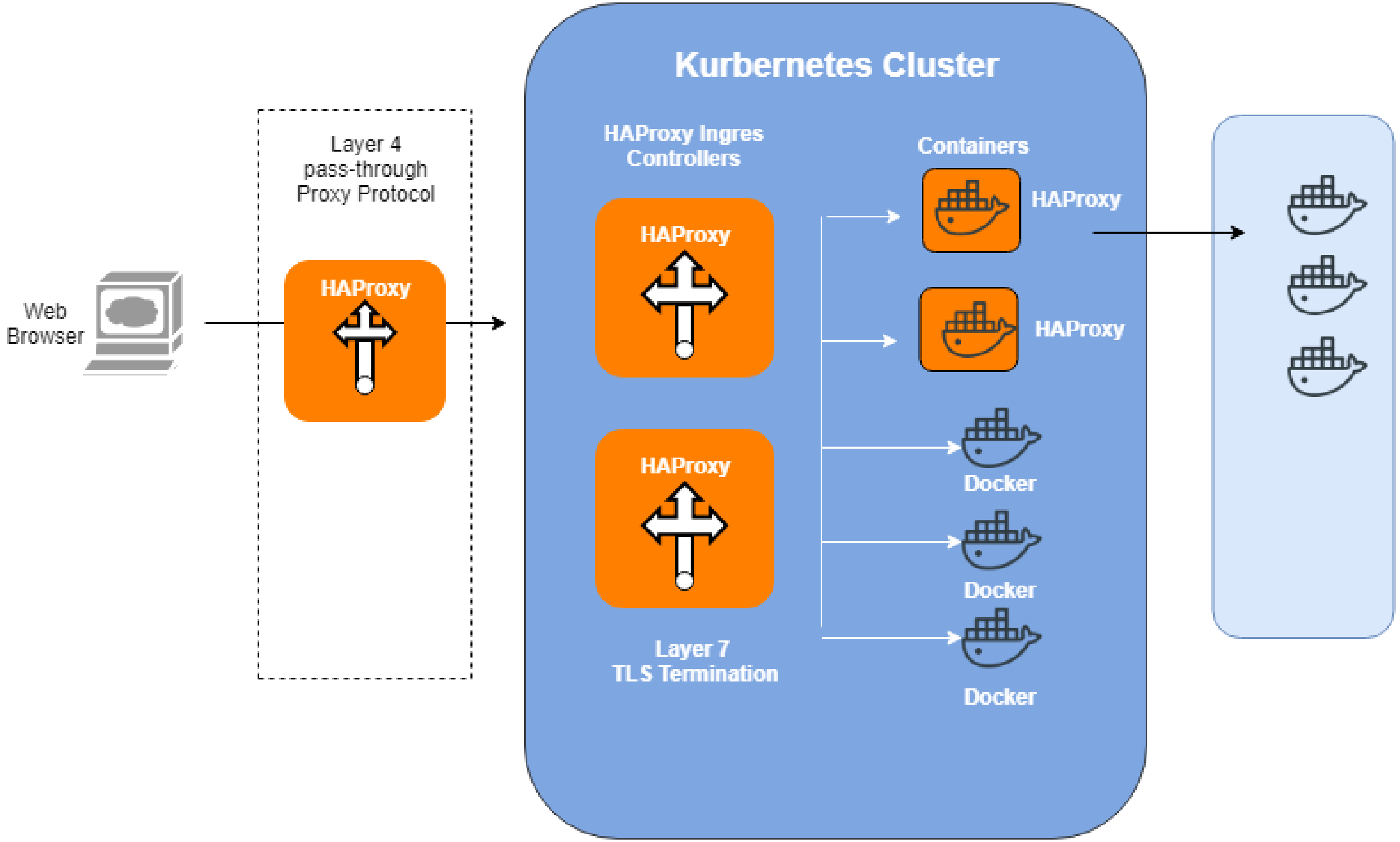


A Kubernetes cluster

DEV OPS LB



DEV OPS LB



Kurbernetes Cluster
Web Browser
Layer 4 pass-through Proxy Protocol
HAProxy
HAProxy Ingres Controllers
HAProxy
HAProxy
Layer 7 TLS Termination
Containers
HAProxy
HAProxy
Docker
Docker
Docker

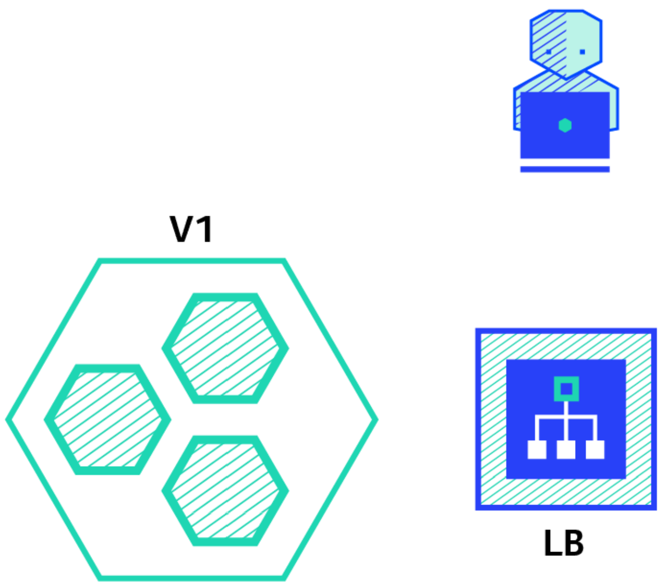
DEV OPS LB FOR DEPLOYMENT STRATEGY

- Load Balancer is just a flexible way to distribute requests
- Distribution policy doesn't need to be based on resources!

  - **Recreate**: Version A is terminated then version B is rolled out.
  - **Ramped** (also known as rolling-update or incremental): Version B is slowly rolled out and replacing version A.
  - **Blue/Green**: Version B is released alongside version A, then the traffic is switched to version B.
  - **Canary**: Version B is released to a subset of users, then proceed to a full rollout.
  - **A/B testing**: Version B is released to a subset of users under specific condition.
  - **Shadow**: Version B receives real-world traffic alongside version A and doesn't impact the response.

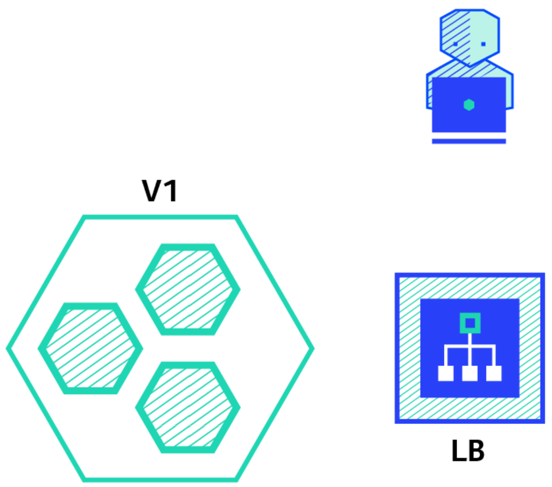
RECREATE DEPLOYMENT

- Pros:
  - Easy to setup.
  - Application state entirely renewed.
- Cons:
  - High impact on the user, expect downtime that depends on both shutdown and boot duration of the application.



RAMPED

- When an instance of pool B is deployed and its service would be ready, one instance from pool A would be shut down.
- Depending on the system taking care of the ramped deployment, you can tweak the following parameters to increase the deployment time:
    - Parallelism, max batch size: Number of concurrent instances to roll out.
    - Max surge: How many instances to add in addition of the current amount.
    - Max unavailable: Number of unavailable instances during the rolling update procedure.



BLUE/GREEN

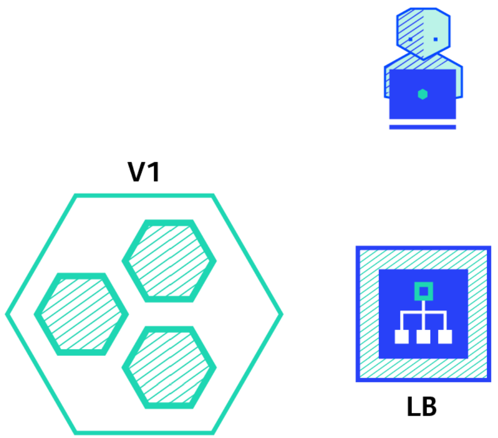
- The blue/green deployment strategy differs from a ramped deployment, version B (green) is deployed alongside version A (blue) with exactly the same amount of instances. After testing that the new version meets all the requirements the traffic is switched from version A to version B at the load balancer level.

Pros:

- Instant rollout/rollback.
- Avoid versioning issue, the entire application state is changed in one go.

Cons:

- Expensive as it requires double the resources.
- Proper test of the entire platform should be done before releasing to production.
- Handling stateful applications can be hard.



CANARY

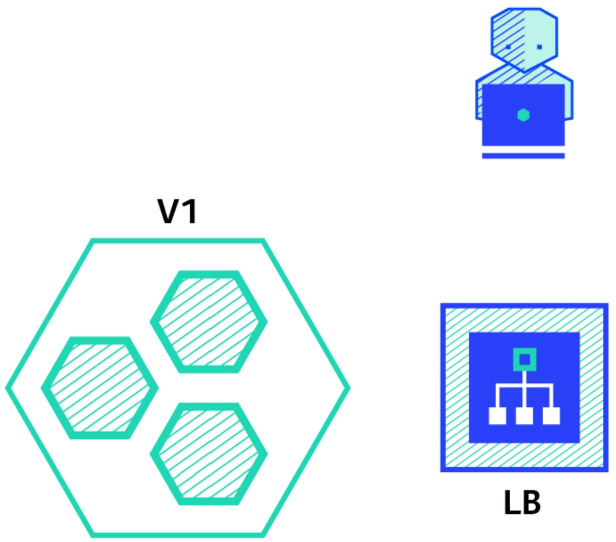
- A canary deployment consists of gradually shifting production traffic from version A to version B. Usually the traffic is split based on weight.

Pros:

- Version released for a subset of users. Convenient for error rate and performance monitoring.
- Fast rollback.

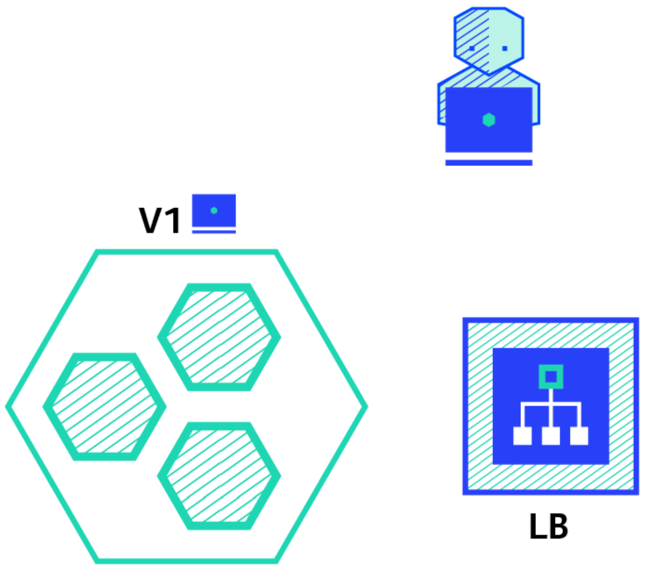
Con:

- Slow rollout.



A/B TESTING

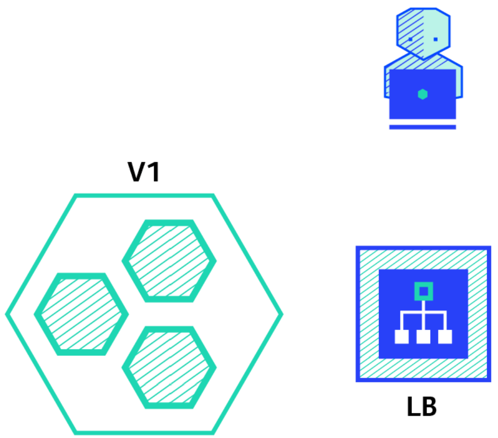
- A/B testing deployments consists of routing a subset of users to a new functionality under specific conditions. It is usually a technique for making business decisions based on statistics, rather than a deployment strategy.
- Here is a list of conditions that can be used to distribute traffic amongst the versions:
  - By browser cookie
  - Query parameters
  - Geolocalisation
  - Technology support: browser version, screen size, operating system, etc.
  - Language



SHADOW

- A shadow deployment consists of releasing version B alongside version A, fork version A's incoming requests and send them to version B as well without impacting production traffic.
- This is particularly useful to test production load on a new feature. A rollout of the application is triggered when stability and performance meet the requirements.

For example, given a shopping cart platform, if you want to shadow test the payment service you can end-up having customers paying twice for their order.



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ADVANCED RESOURCE MANAGEMENT ALGORITHMS

PROBLEM DEFINITIONS

- O(1) – constant-time
- O($\log_2(n)$) – logarithmic-time
- O(n) – linear-time
- O(n^2) – quadratic-time
- O(n^k) – polynomial-time
- O(k^n) – exponential-time
- O($n!$) – factorial-time

POLYNOMIAL ALGORITHMS

- $T(n) = \left(C * n^k\right)$ where $C > 0$ and $k > 0$ where C, k are constant and n is input size
- In general, for polynomial-time algorithms k is expected to be less than n.
- Many algorithms complete in polynomial time:
  - All basic mathematical operations; addition, subtraction, division, multiplication
  - Testing for primacy
  - Hash-table lookup, string operations, sorting problems
  - Shortest Path Algorithms; Djikstra, Bellman-Ford, Floyd-Warshall
  - Linear and Binary Search Algorithms for a given set of numbers

NP ALGORITHMS

- Cannot be solved in polynomial time. However, they can be verified (or certified) in polynomial time. (verification can be done by Turing machine)
- We expect these algorithms to have an exponential complexity, which we'll define as:
- $T(n) = (C_1 * k^{C_2 * n})$ where $C_1 > 0$, $C_2 > 0$ and $k > 0$ where C_1, C_2, k are constant and n is input size
- complexity is $O(k^n)$ for some k and their results can be verified in polynomial time.

- Salesman Problem
- Integer Factorization
- Graph Isomorphism

NP-COMPLETE ALGORITHMS

- What makes them different from other NP problems is a useful distinction called completeness.
  - Traveling Salesman
  - Knapsack
  - Graph Coloring

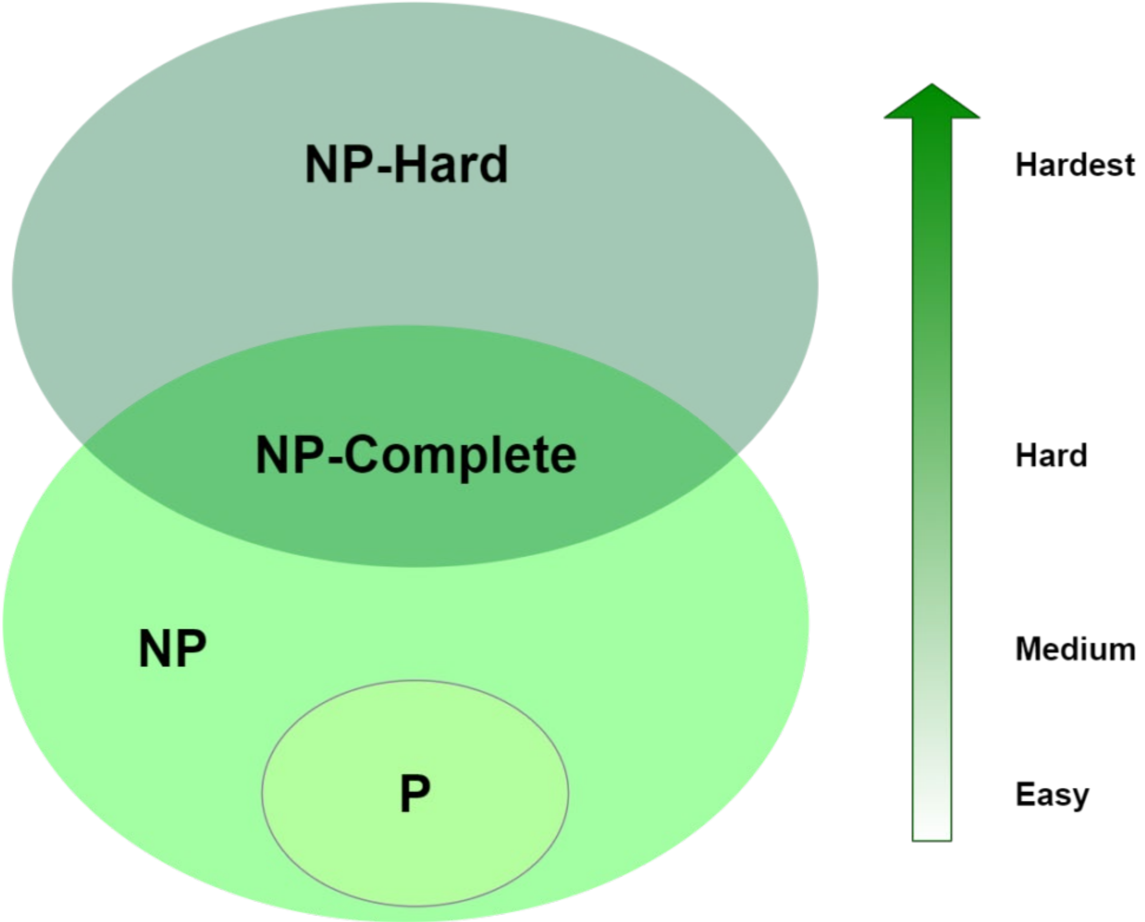
- Prove P=NP or P≠ NP

https://www.claymath.org/millennium-problems/p-vs-np-problem

https://en.wikipedia.org/wiki/Millennium_Prize_Problems

NP-HARD ALGORITHMS

- Non-deterministic Polynomial-time hard
- Most complex problems in computer science.
- They are not only hard to solve but are hard to verify as well.
  - K-means Clustering
  - Traveling Salesman Problem,
  - Graph Coloring
  - maximum clique problem
- These algorithms have a property similar to ones in NP-Complete – they can all be reduced to any problem in NP



MANY OBJECTIVE OPTIMIZATION PROBLEM

- Many objective problems are the problems that have some objectives which should be satisfied by the solutions.

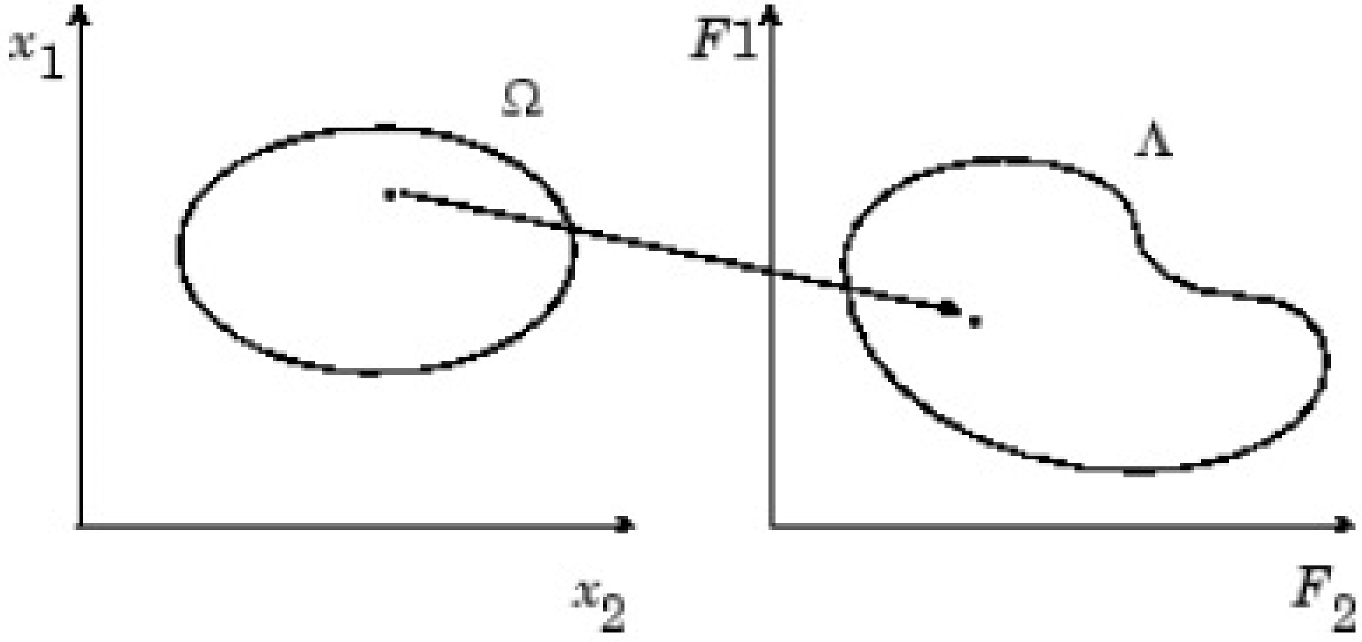
$$find\ x \in \phi: f(x) \le f(y), \forall\ y \in \phi$$

$$\min_{x} f(x) \in R, x \in \phi$$

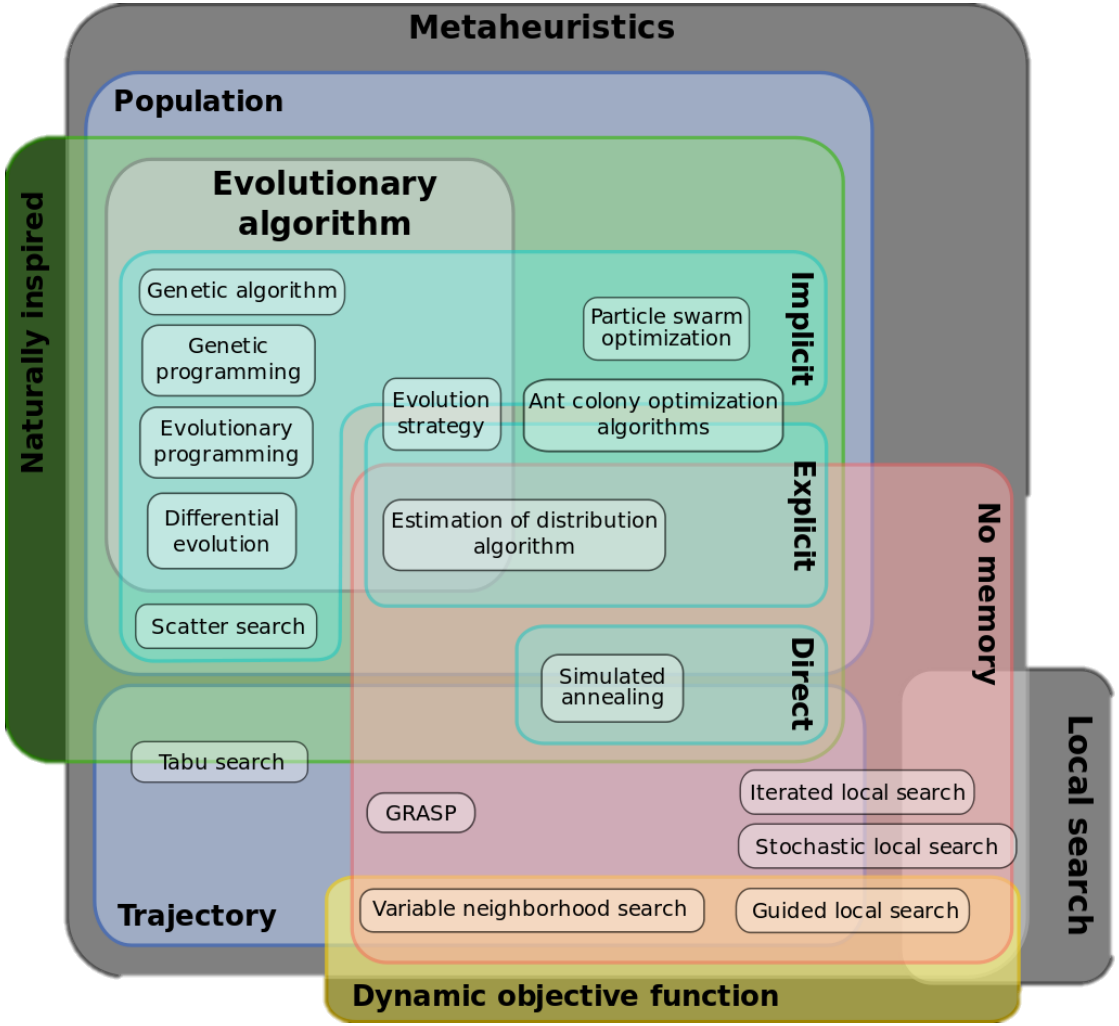
$$f: X \subset R^n \ \rightarrow Y \subset R$$

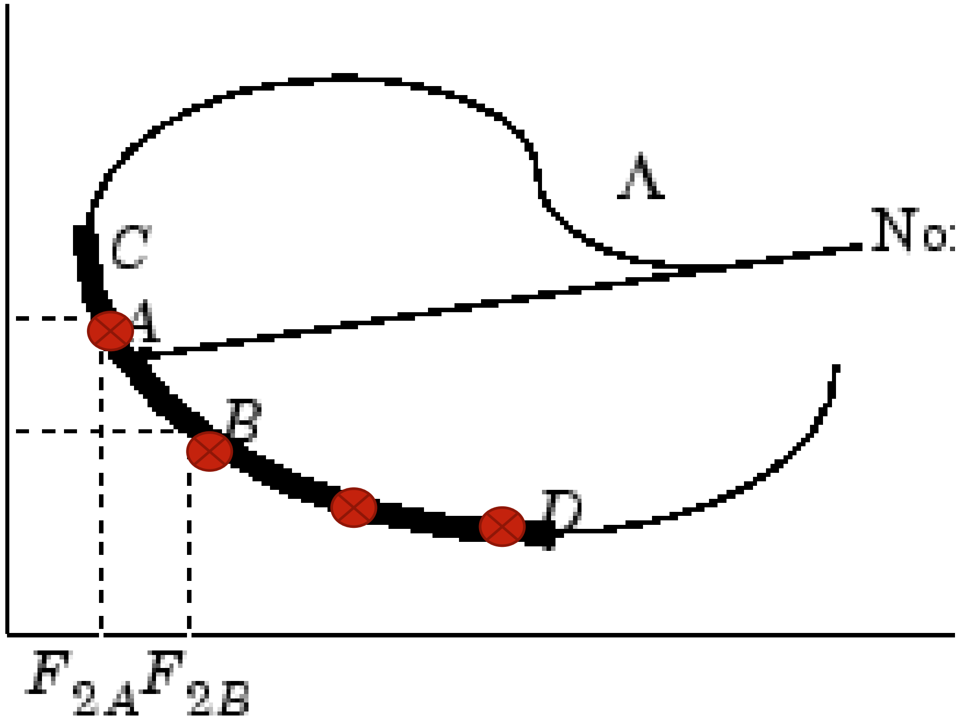
$$X = \{x = (x_1 \dots x_n), x_i \in D_i\}$$

$$\phi = \begin{cases} g_i(x) \le 0 \\ h_j(x) = 0 \\ x \in X \end{cases}$$



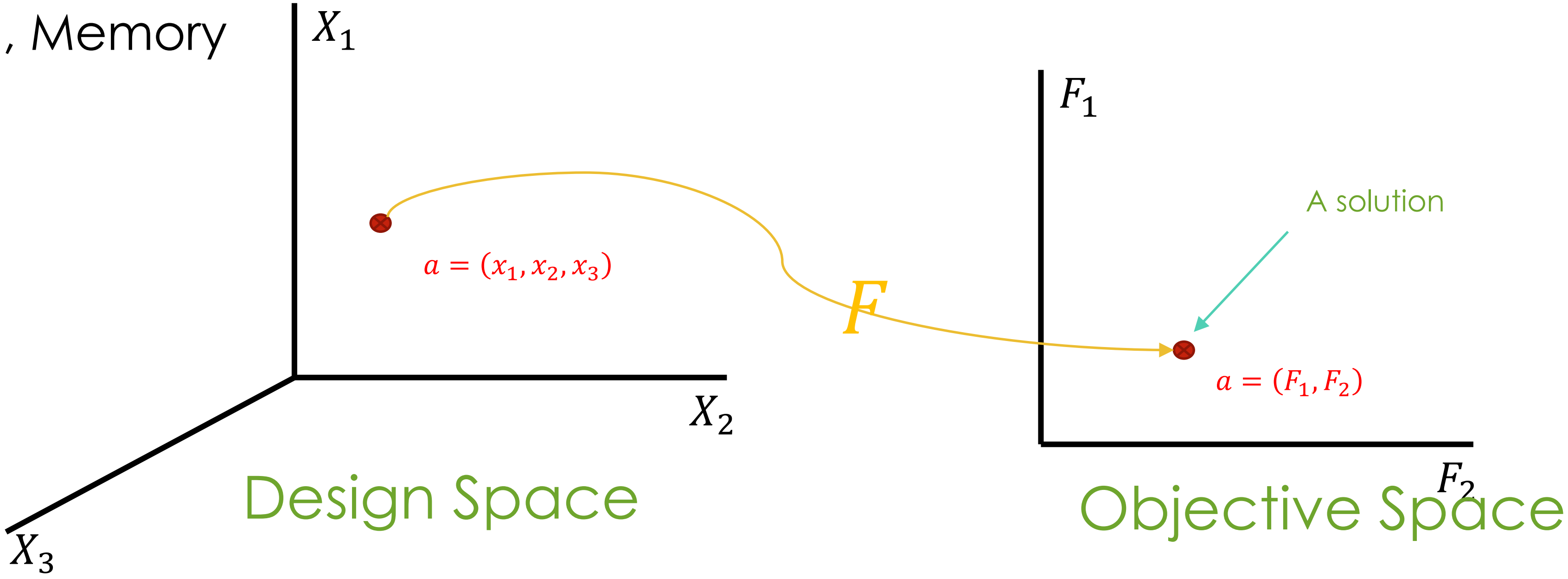
FINDING THE PARETO FRONT





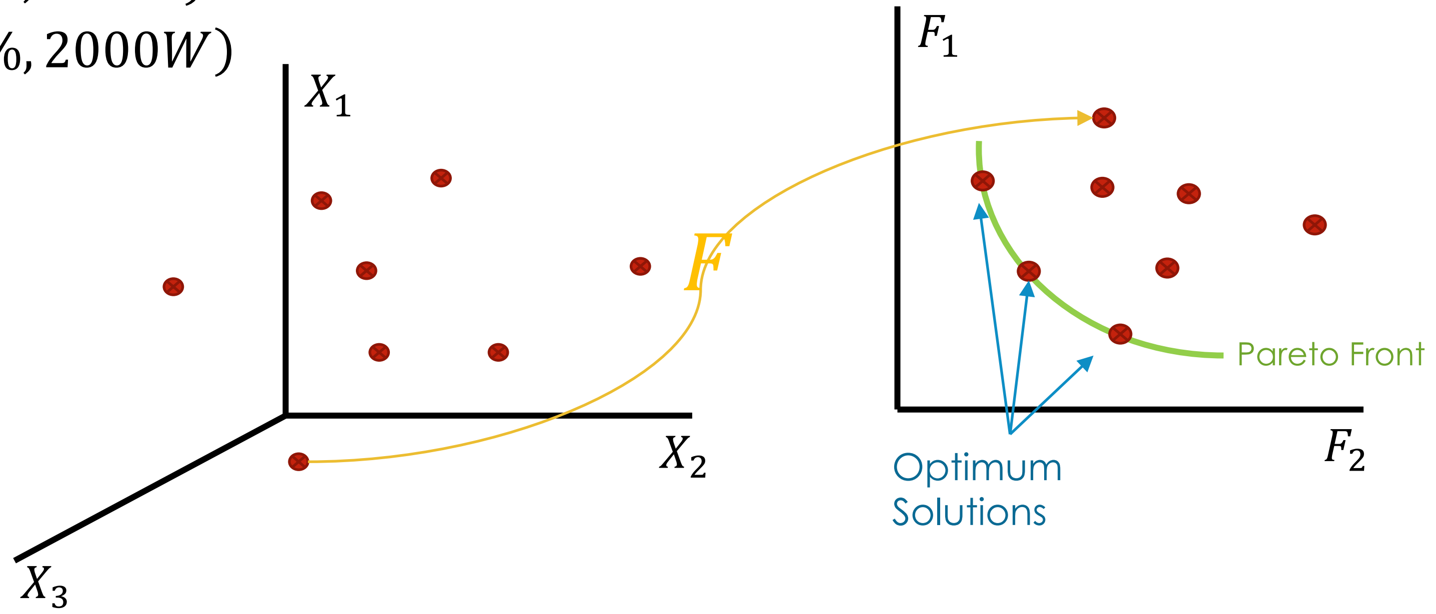
PLACEMENT AS AN OPTIMIZATION PROBLEM

- $f: X \subset R^n \rightarrow Y \subset R$
- $X = \{X_1: VM1, X_2: VM2, X_3: VM3\}$
- $Y = \{F_1: Utilization, F_2: Power\ Consumption\}$
- Constrains: CPU, RAM, Memory



PLACEMENT AS AN OPTIMIZATION PROBLEM

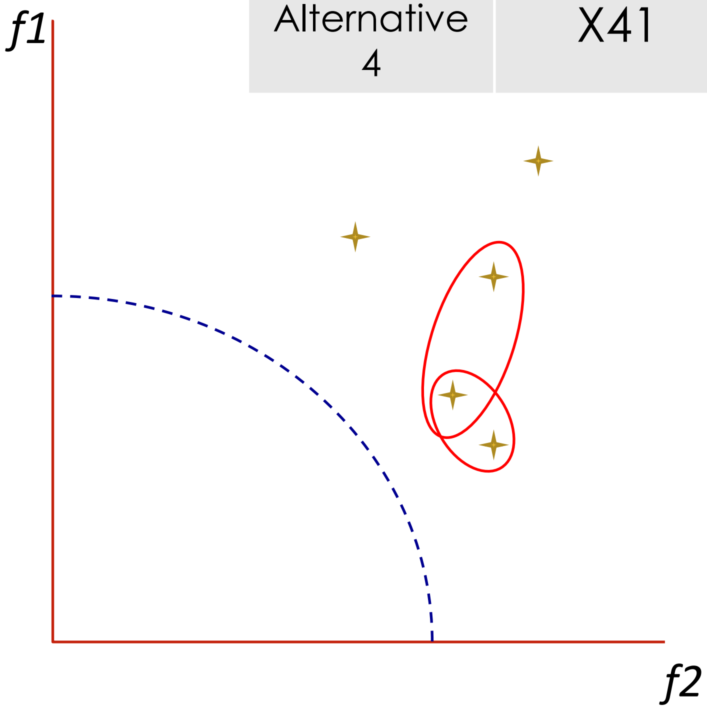
- For example we can see solutions like this when we aim to find the best placement of our VMs among $VM_1..VM_{10}$:
  - $a_1 = (VM_1, VM_5, VM_6) \rightarrow (30\%, 900W)$
  - $a_2 = (VM_1, VM_3, VM_7) \rightarrow (70\%, 1100W)$
  - $a_3 = (VM_2, VM_8, VM_1) \rightarrow (50\%, 950W)$
  - $a_4 = (VM_2, VM_8, VM_1) \rightarrow (85\%, 2000W)$
  - …



MULTI CRITERIA DECISION MAKING

- Choose the best option among the alternatives
- Strategies
  - Pair-wise Comparison
    - AHP, ANP, ELECTRE...
  - Reference Distance
    - VIKOR, TOPSIS, ….

	Crierion 1	Crierion 2	Crierion 3	Crierion 4
Alternative 1	X11	X12	X13	X14
Alternative 2	X21	X22	X23	X24
Alternative 3	X31	X32	X33	X34
Alternative 4	X41	X42	X43	X44



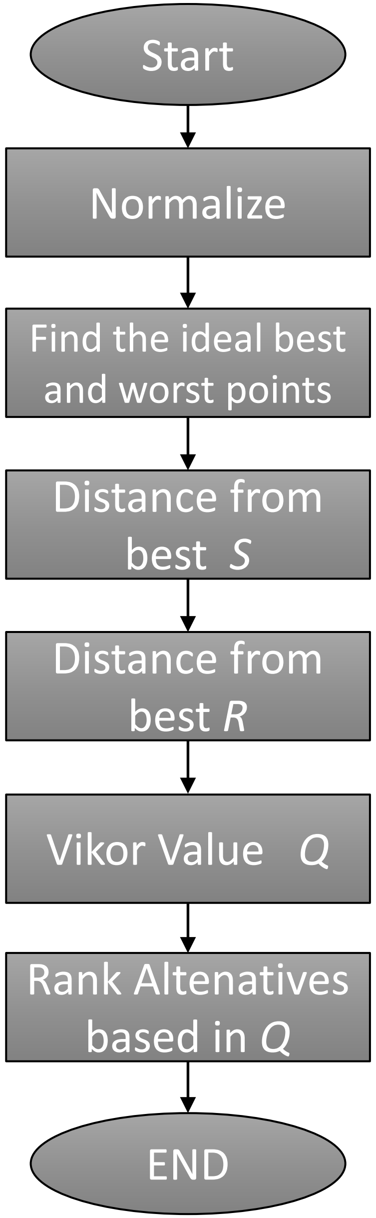
MCDM

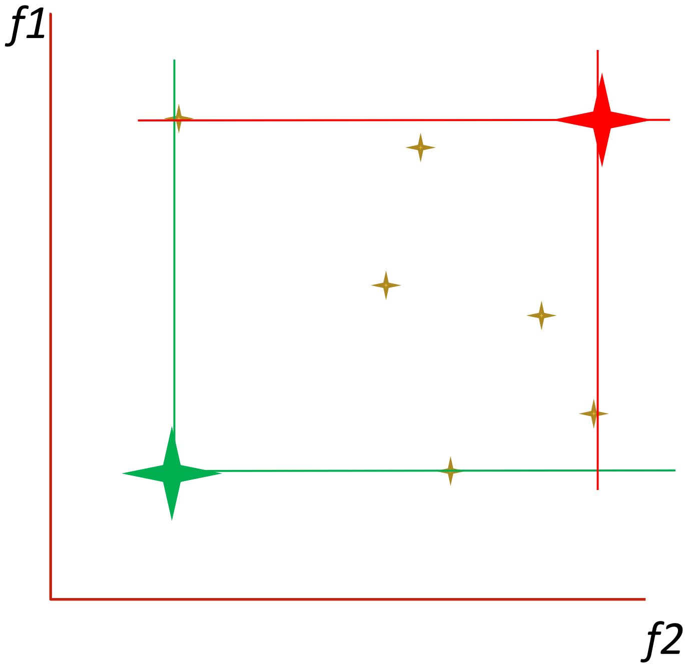
- For example: VIKOR is one of the MCDM methods which:
  - The complexity of the algorithm is low
  - Selection is based on the distance to the best point

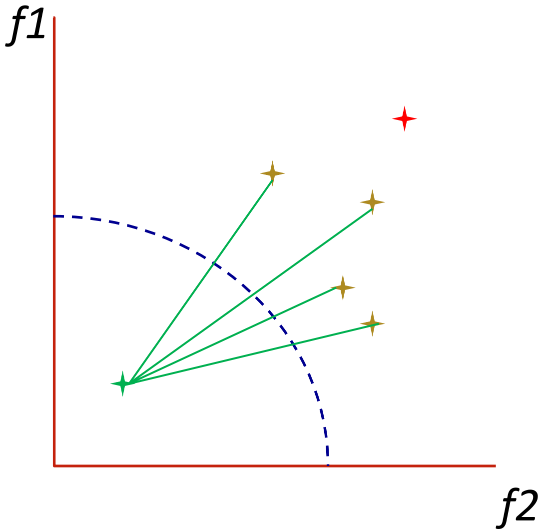
$$S_i = \sum_{j=1}^{n} w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)}$$

$$R_i = MAX[w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)}]$$

$$Q_i = v[\frac{S_i - S^*}{S^- - S^*}] + (1 - v)[\frac{R_i - R^*}{R^- - R^*}]$$

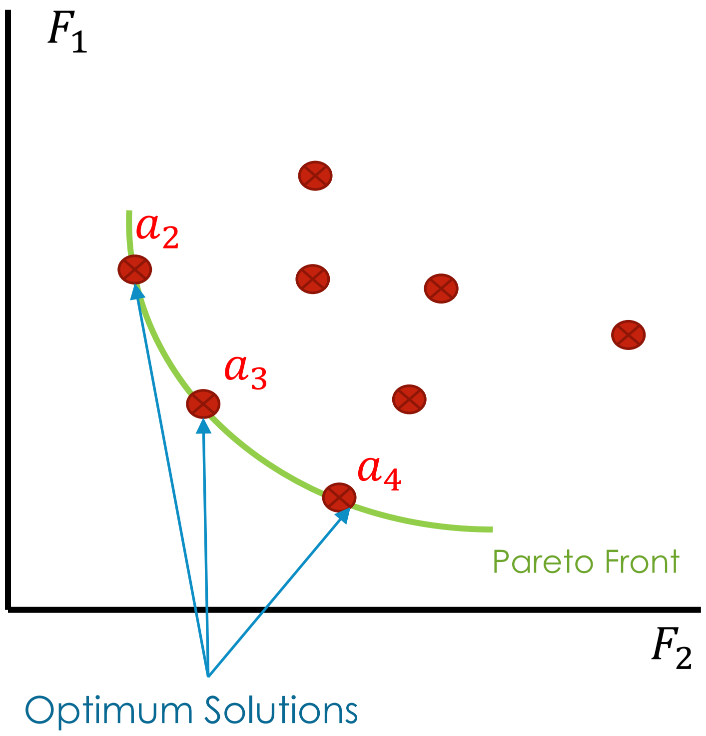






PLACEMENT AS A DECISION MAKING PROBLEM

	Crierion1	Crierion2	Crierion3	Crierion4
a_4	X11	X12	X13	X14
a_3	X21	X22	X23	X24
a_2	X31	X32	X33	X34



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DYNAMIC PLACEMENT WITH CODE MIGRATION

CODE MIGRATION

Placement doesn't need to be **static**

Migration allows us to move code between nodes on demand

Why? What? How?

YOU USE MIGRATION EVERY DAY!

- ________________ is the simplest and most common form of code migration
  - You probably use this hundreds of times every day…
- **What is it?**
- **Why is it used?**
- **What problems does it cause?**

YOU USE MIGRATION EVERY DAY!

- __JavaScript__ is the simplest and most common form of code migration
  - You probably use this hundreds of times every day…
- JavaScript files (source code) are migrated from the server to your web browser for execution
  - More responsive UI, local error checking
  - Takes advantage of client processing power
  - Can open security vulnerabilities
  - Adds complexity to software

WHY MIGRATE?

- The ability to move where code is executed provides flexibility

- Performance
  - Reduced perceived latency by having JS update a GUI locally
- Resource efficiency
  - Move VMs to a different server for consolidation
- Security
  - Move processing to data for compliance reasons

MIGRATION CHARACTERISTICS

- **Weak Mobility**: just the code is moved and restarted
  - e.g., JavaScript.
  - Simple implementation, but limited flexibility
- **Strong Mobility**: code & state is moved and execution continues seamlessly
  - e.g., VM migration
  - Very powerful, but hard to implement
- Which side of the communication starts the migration?
  - The machine currently executing the code (**sender-initiated**)
  - The machine that will ultimately execute the code (**receiver-initiated**).

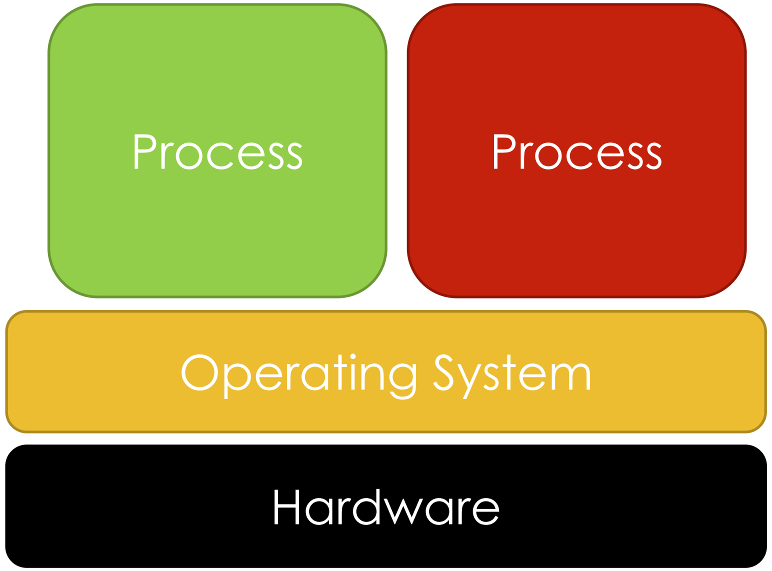
WHAT TO MIGRATE?

- A running component consists of three “segments”:
    1. Code – instructions
    2. Resources – external references
    3. Execution – current state

JavaScript code migration?

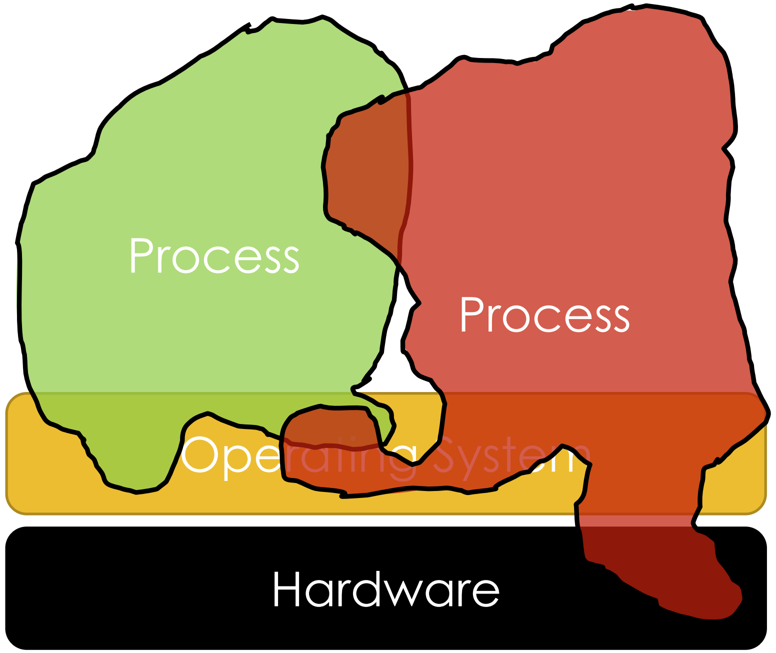
Process migration?

HOW TO MIGRATE A PROCESS?



- How cleanly isolated is a process?

HOW TO MIGRATE A PROCESS?



- Code, libraries, data/image files
- Stack/Heap/registers
- OS state: file descriptors, sockets, scheduler information, permissions

- IP address?
- HW devices like GPUs, printers?
- Inter-process communication?
- Requirements for destination?

WHAT ABOUT RESOURCES?

- What makes code migration difficult is the requirement to migrate resources.
- Resources are the external references that a process is currently using, and includes (but is not limited to):
  - Variables, open files, network connections, printers, databases, etc...

- Not all resources can be migrated
- What if source and destination hosts are heterogenous?

PROCESS MIGRATION WITH CRIU

Pronounced Kree-ew

- CRIU = Checkpoint/Restore in Userspace
  - Libraries supported by Linux to enable checkpointing and migration
  - “In userspace” meaning it requires limited kernel support
- Checkpoint + Restore = Migration!

- Saves all process and OS state to a file
  - Can operate on a tree of processes (containers!)
- Restore process(es) from a checkpoint file

- Based on old research like [*Zap*, OSDI 2002]

https://criu.org

VM MIGRATION

Supported by Xen, Vmware, KVM

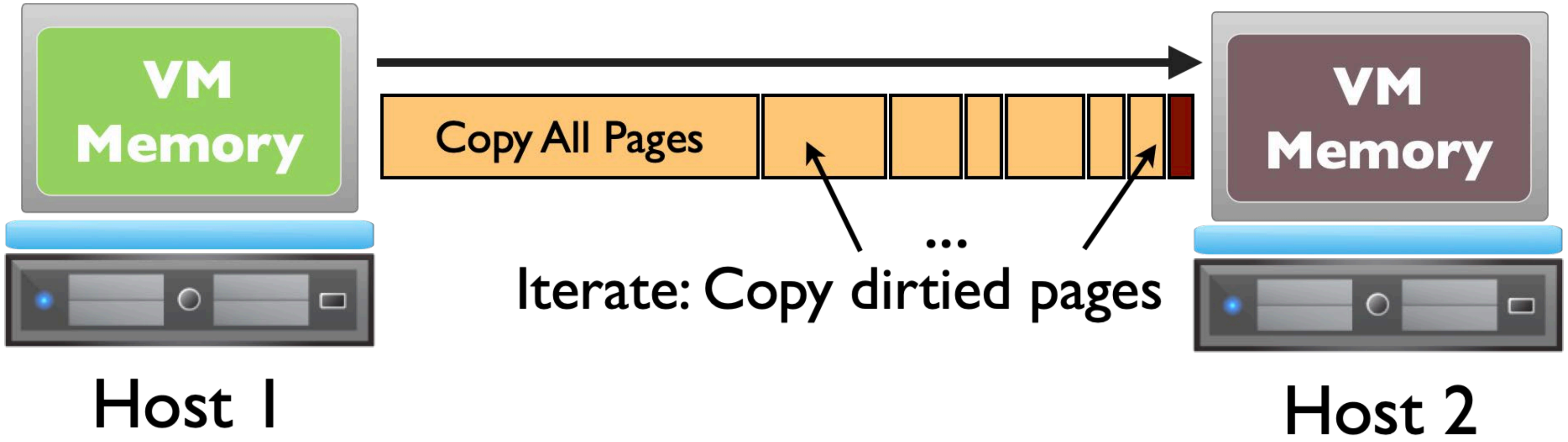
- Moving an entire VM is actually a lot simpler!
- Virtual machine cleanly encapsulates all processes and OS
  - Simple, well defined interfaces are very useful in systems!
- Migrate VM's memory and CPU state
- Update network configuration (ARP message)

Trade-offs?

VM MIGRATION TECHNIQUES

- **Stop and Copy**: pause VM and copy all of its data, then resume on host 2
- **Iterative**: Copy pages as VM runs, track what gets "dirtied" and resend

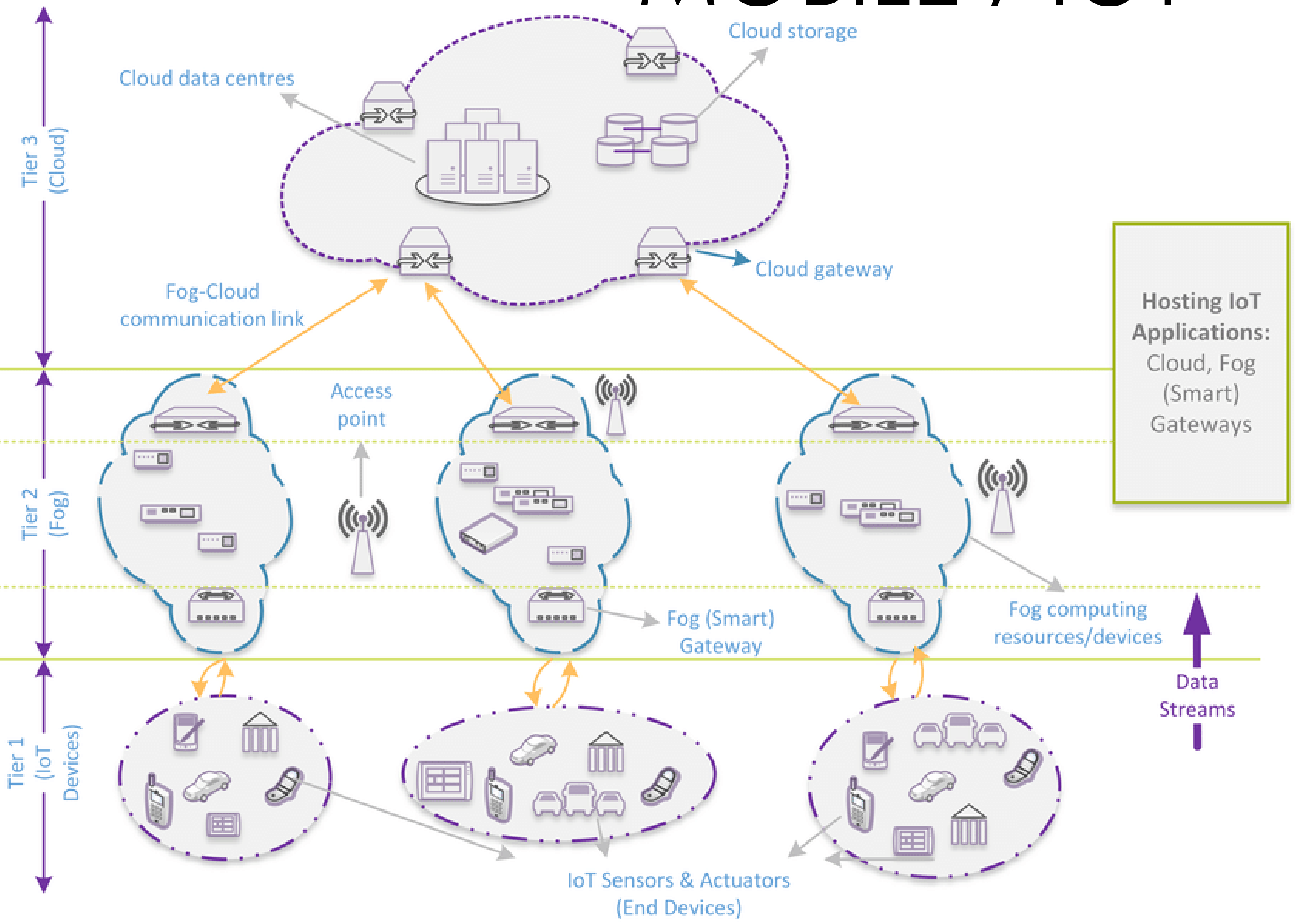
- **Pull**: Start running on destination immediately and pull missing pages over network on demand



See [Clark, Usenix 2005], [Wood VEE 2011], etc

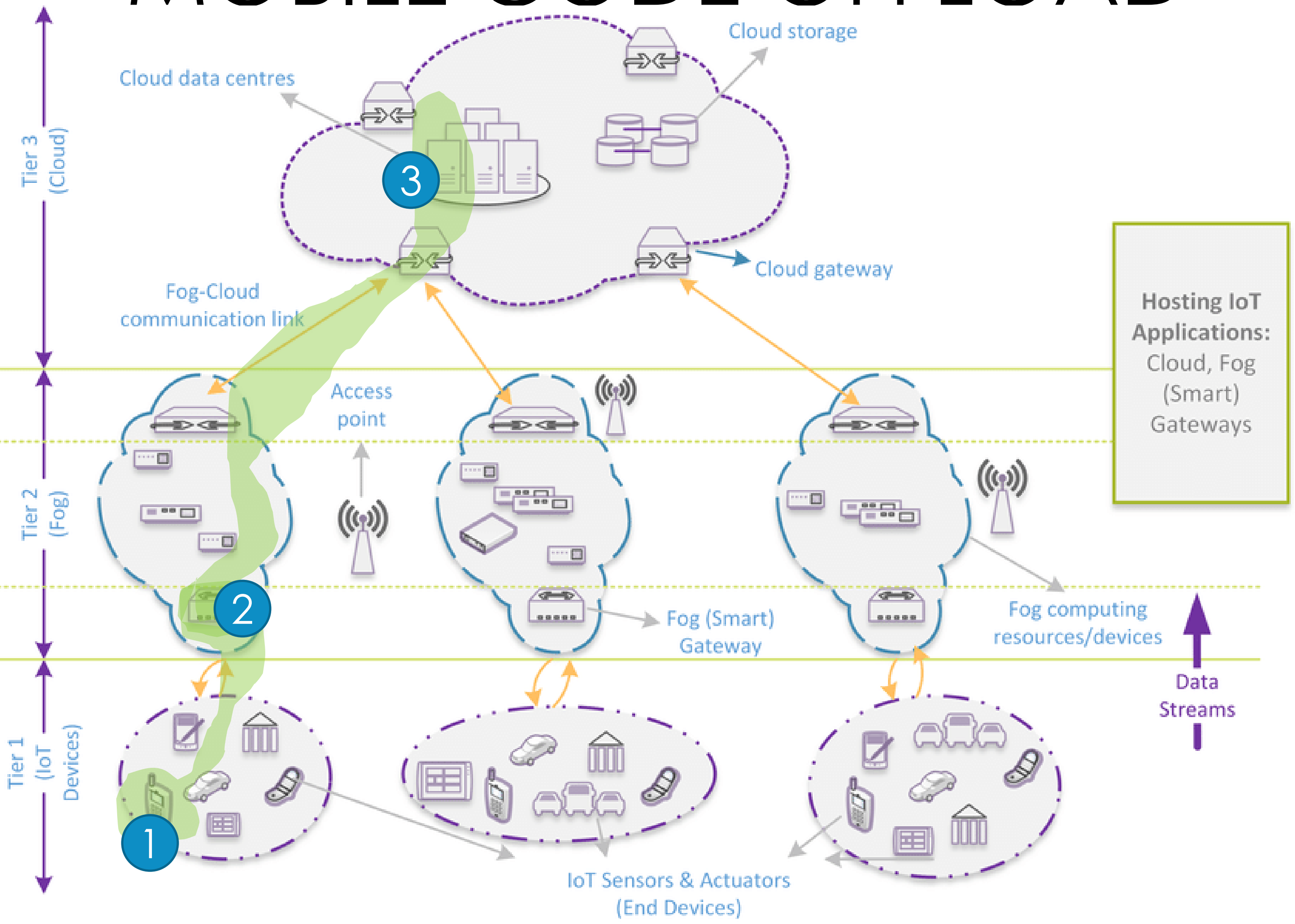
MOBILE / IOT

How can we use migration in a mobile / IoT environment?



MOBILE CODE OFFLOAD

- Mobile Code Offload
  - Migrate components of an application between phone and cloud
- Decide what to migrate based on available resources
  - Network latency to cloud?
  - Battery life on device?
- See [Maui, MobiSys 2010] and others



SOFTWARE AGENTS

- What is a software agent?
  - “An **autonomous** unit capable of performing a task in collaboration with other, possibly remote, agents”.
- Software agents are a software architecture that focuses on dynamic, flexible software components that can make their own decisions
  - Can involve dynamic migration driven by the software component itself

- Autonomic Computing
  - Self-configuring, Self-managing, Self-healing, Self-optimizing, Self-organizing…
  - Goal is to reduce the complexity of distributed systems by building intelligence and automated control into the components

FINAL PROJECT

- Groups of 3-4 students
- **Research-focused**: Reimplement or extend a research paper
- **Implementation-focused**: Implement a simplified version of a real distributed system

- Course website has sample ideas
  - But don't feel limited by them!
  - You don't have to use go!

- Timeline
  - Milestone 0: Form a Team
  - Milestone 1: Select a Topic
  - Milestone 2: Literature Survey
  - Milestone 3: Design Document
  - Milestone 4: Final Presentation

https://gwdistsys2021.github.io/gwDistSys2021/project/

WHICH LB ARCHITECTURE IS BETTER?