Systems for Data-Intensive Cluster Computing

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ALMADA Summer School

Moscow, Russia

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About Myself

- http://budiu.info/work
- Senior Researcher at Microsoft Research in Mountain View, California
- Ph.D. in Computer Science from Carnegie Mellon, 2004
- Worked on reconfigurable hardware, compilers, security, cloud computing, performance analysis, data visualization

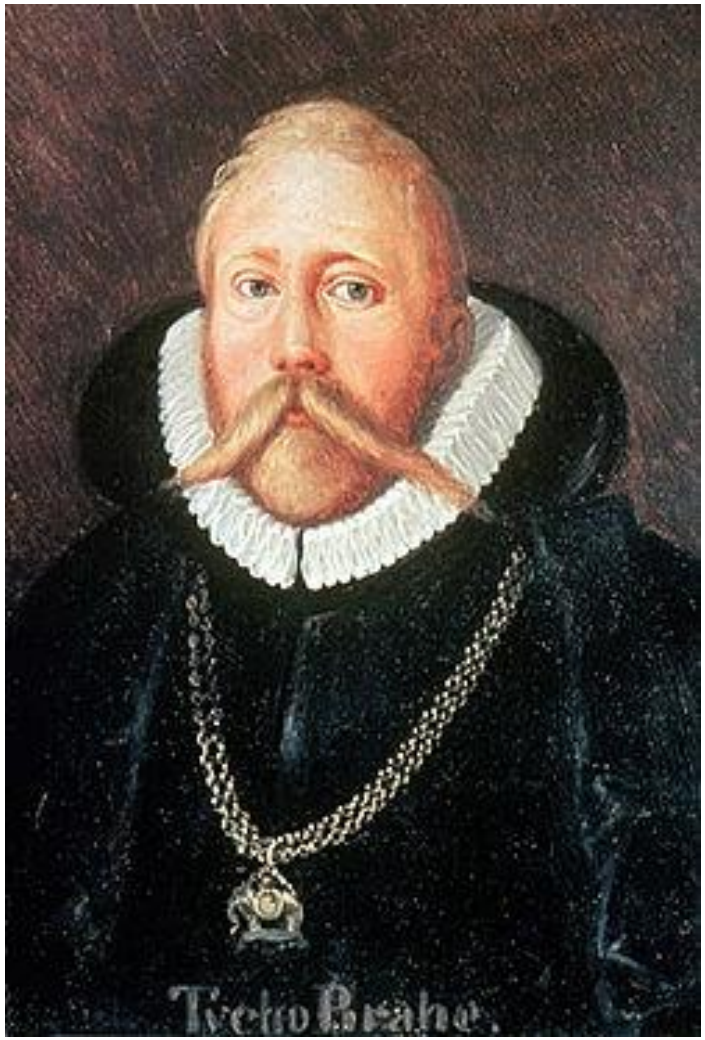
Lessons to remember

Will use this symbol throughout the presentation to point out fundamental concepts and ideas.

This talk is not about specific software artifacts. It is a talk about principles, illustrated with some existing implementations.

BIG DATA

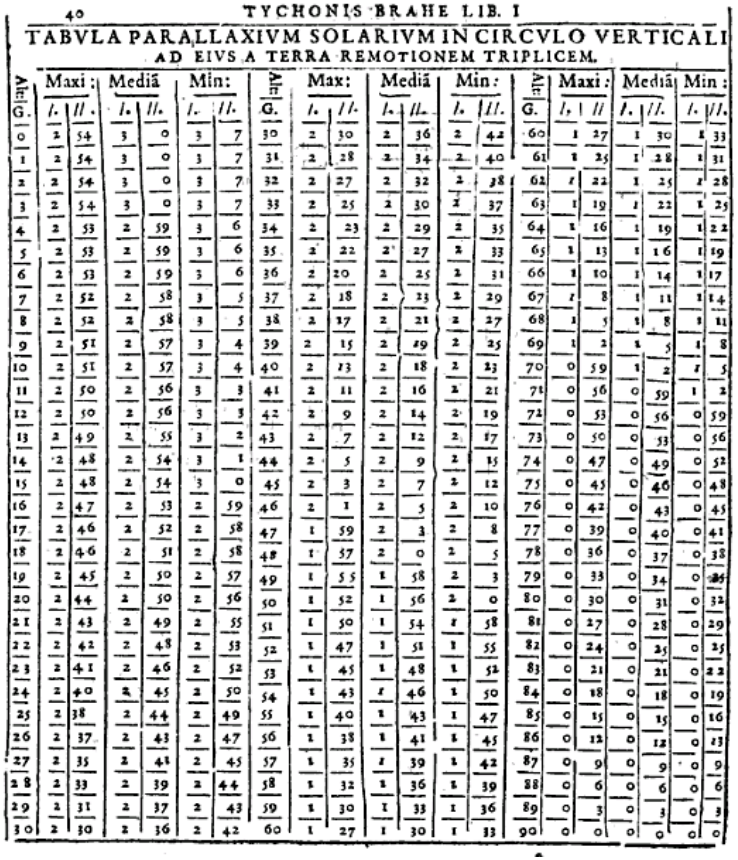
500 Years Ago



Tycho Brahe
(1546-1601)

Johannes Kepler
(1571-1630)

The Laws of Planetary Motion



40 TYCHONIS BRAHE LIB. I

TABVLA PARALLAXIVM SOLARIVM IN CIRCVLO VERTICALI AD EIVS A TERRA REMOTIONEM TRIPLICEM.

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0	2	54	3	0	3	7	30	2	30	2	36	2	42	60	1	27	1	30	1	33
1	2	54	3	0	3	7	31	2	28	2	34	2	40	61	1	25	1	28	1	31
2	2	54	3	0	3	7	32	2	27	2	32	2	38	62	1	22	1	25	1	28
3	2	54	3	0	3	7	33	2	25	2	30	2	37	63	1	19	1	22	1	25
4	2	53	2	59	3	6	34	2	23	2	29	2	35	64	1	16	1	19	1	22
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6	2	53	2	59	3	6	36	2	20	2	25	2	31	66	1	10	1	14	1	17
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10	2	51	2	57	3	4	40	2	13	2	18	2	23	70	0	59	1	2	1	5
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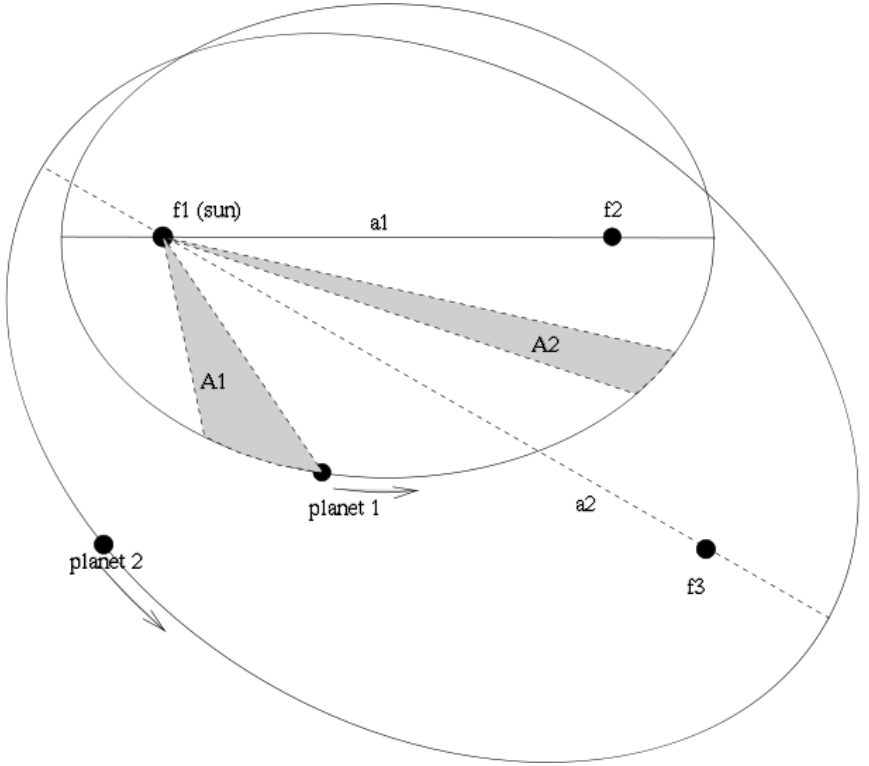
26	2	37	2	43	2	47	56	1	38	1	41	1	45	86	0	12	0	12	0	13
27	2	35	2	41	2	45	57	1	35	1	39	1	42	87	0	9	0	9	0	9
28	2	33	2	39	2	44	58	1	32	1	36	1	39	88	0	6	0	6	0	6
29	2	31	2	37	2	43	59	1	30	1	33	1	36	89	0	3	0	3	0	3
30	2	30	2	36	2	42	60	1	27	1	30	1	33	90	0	0	0	0	0	0

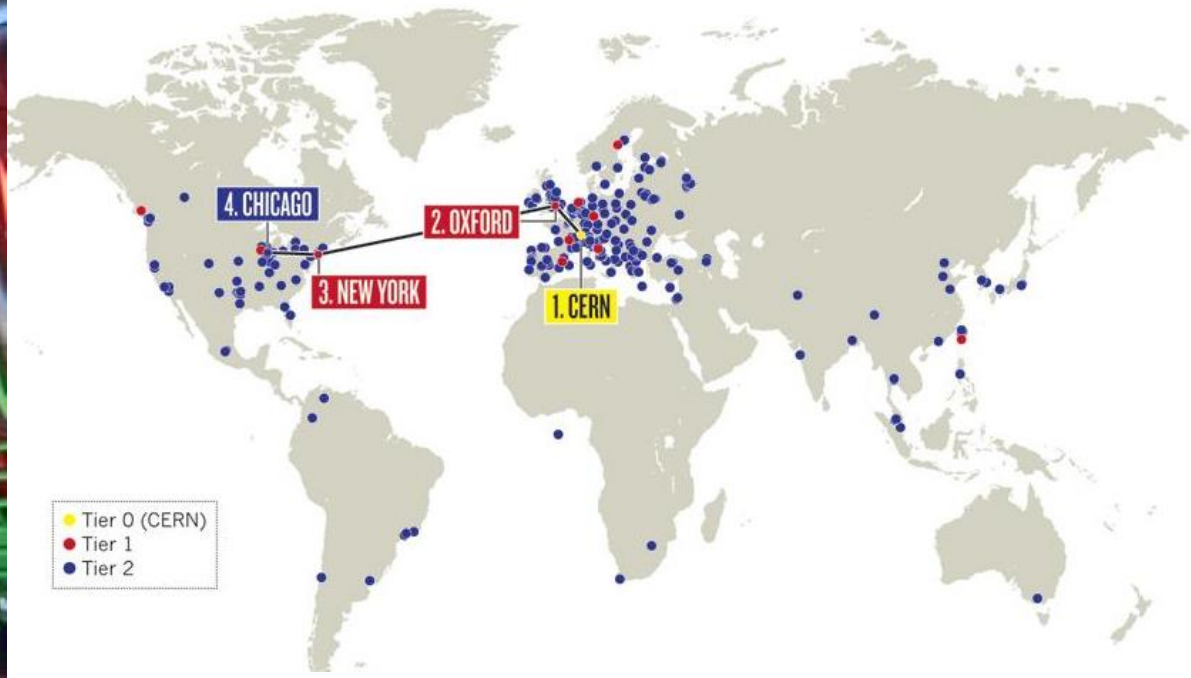
Tycho's measurements



Kepler's laws

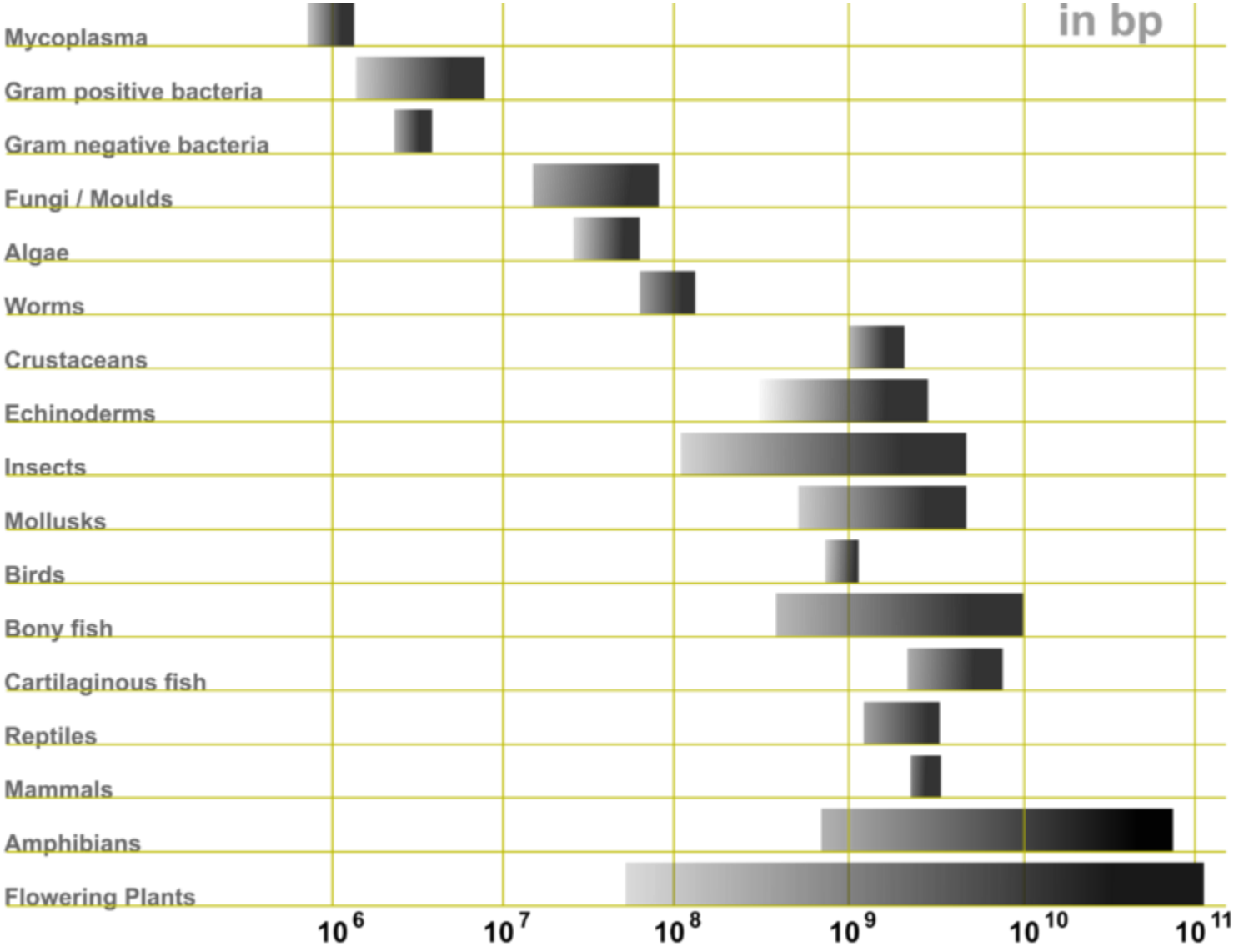
The Large Hadron Collider

25 PB/year

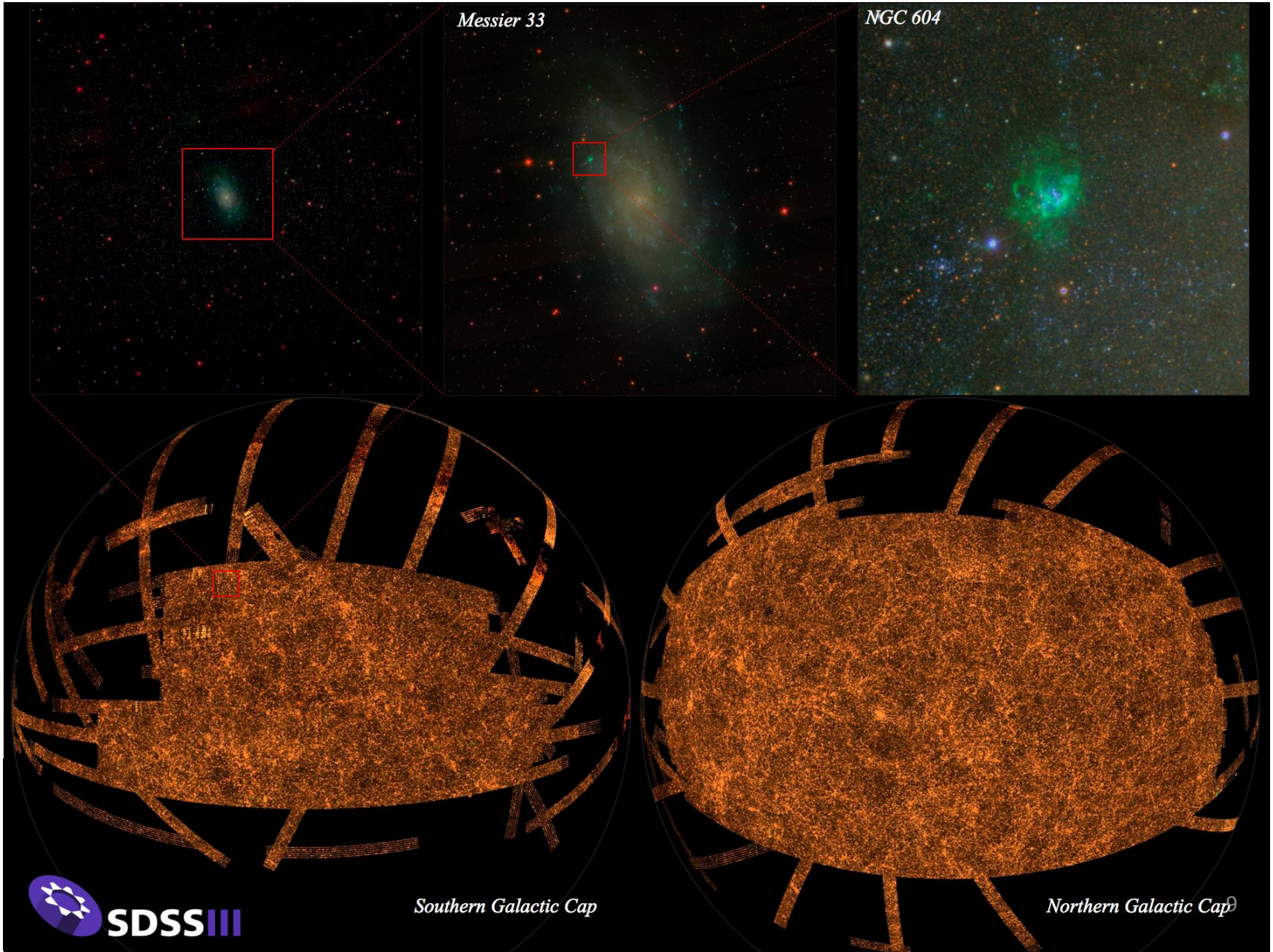


WLHC Grid:
200K computing cores

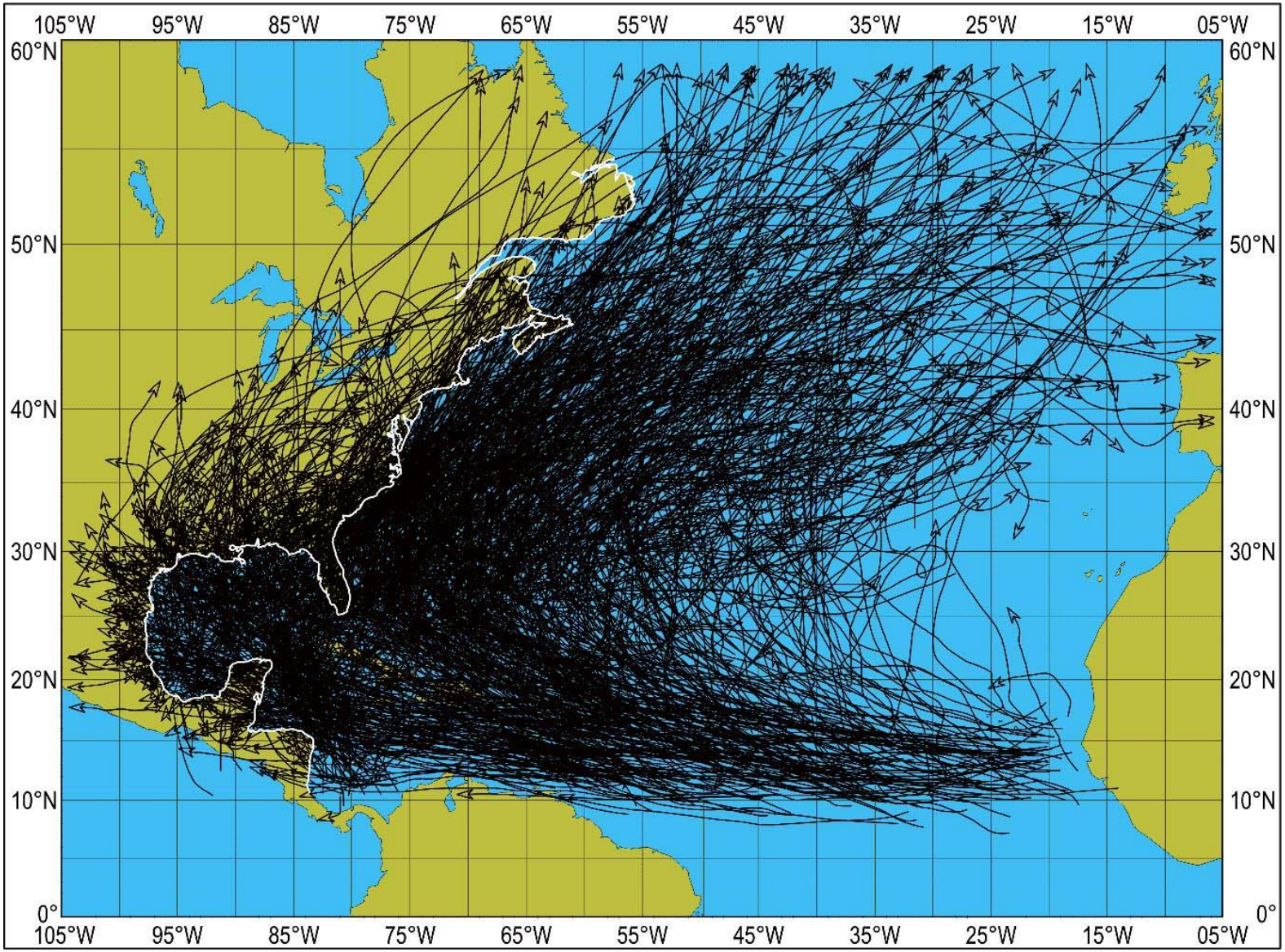
Genetic Code



Astronomy


Messier 33
NGC 604
SDSSIII
Southern Galactic Cap
Northern Galactic Cap

Weather


105°W
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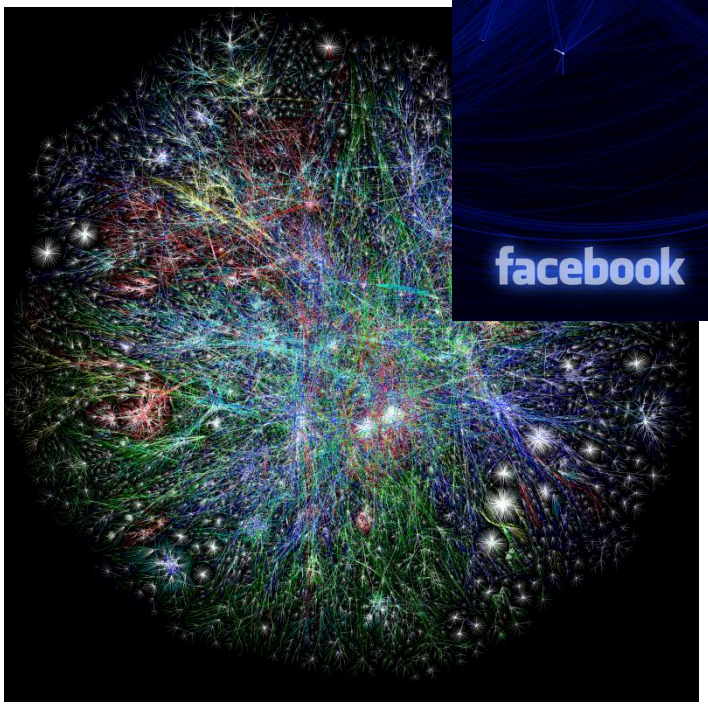
50°N
40°N
30°N
20°N
10°N
0°
NORTH ATLANTIC TROPICAL STORMS AND HURRICANES, 1851-2004 (1325 STORMS)
NOAA

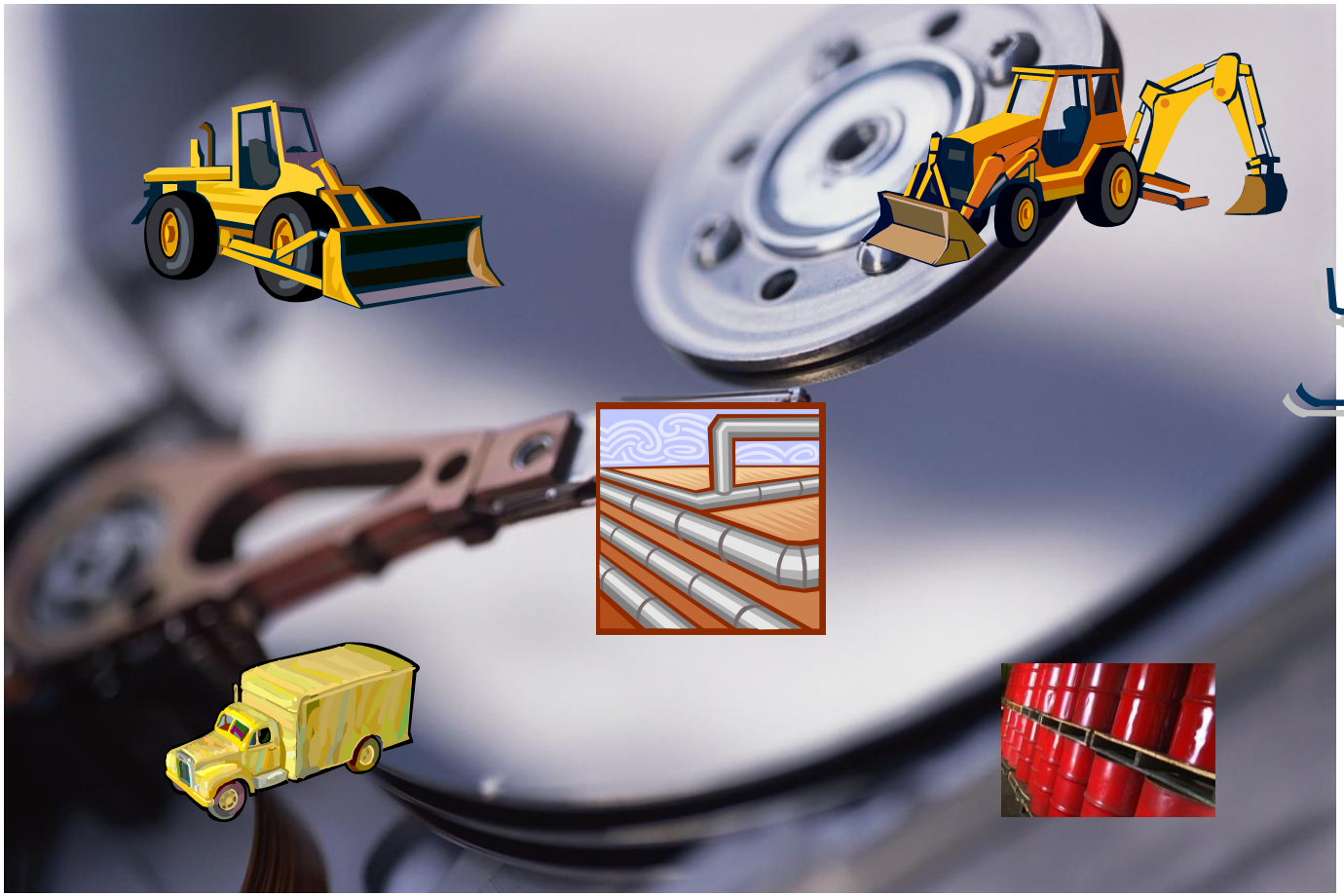
The Webs

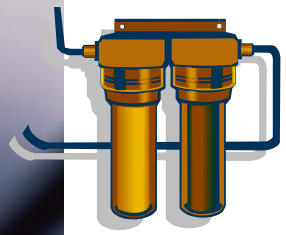
Facebook friends graph



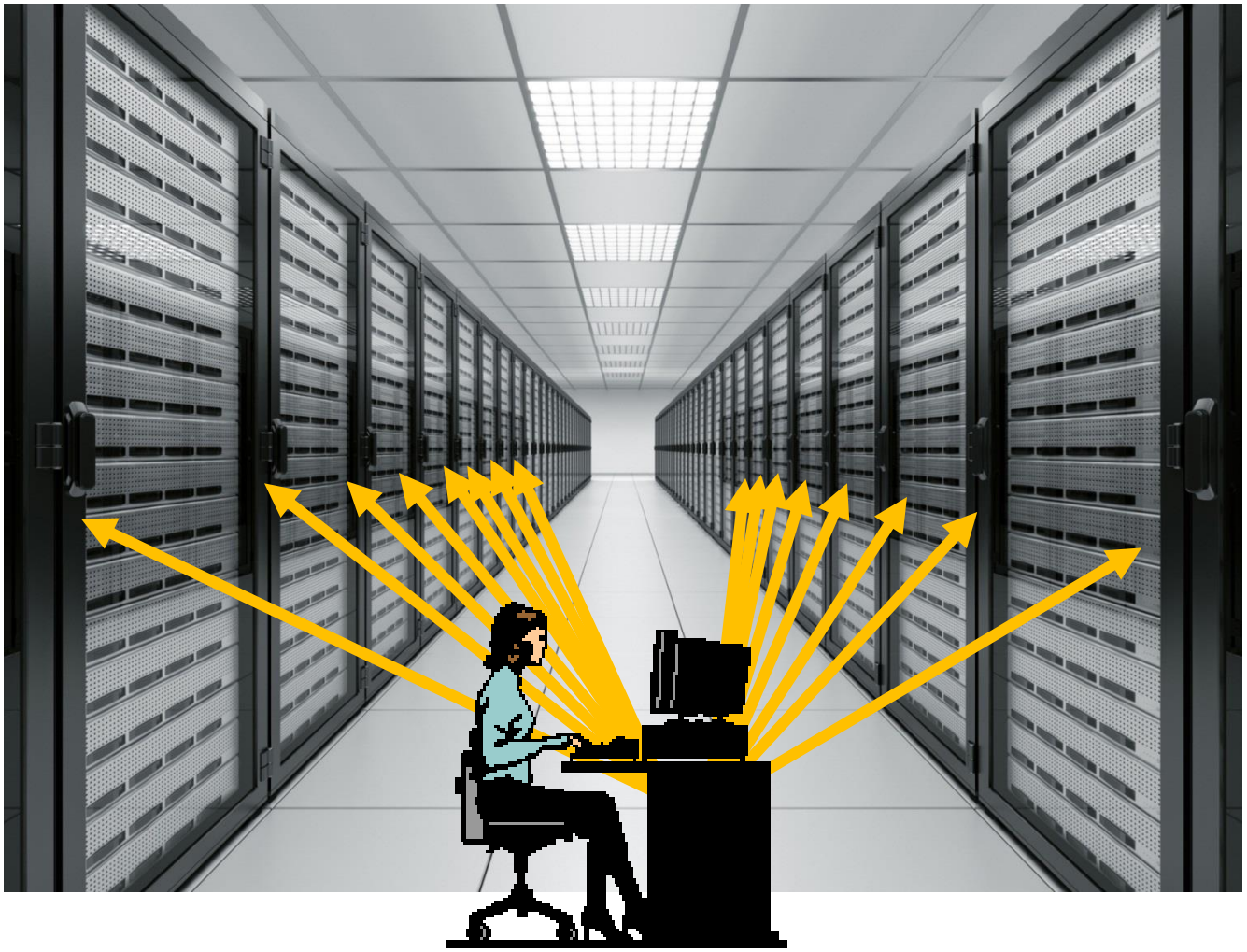
Internet

Big Data





Big Computers



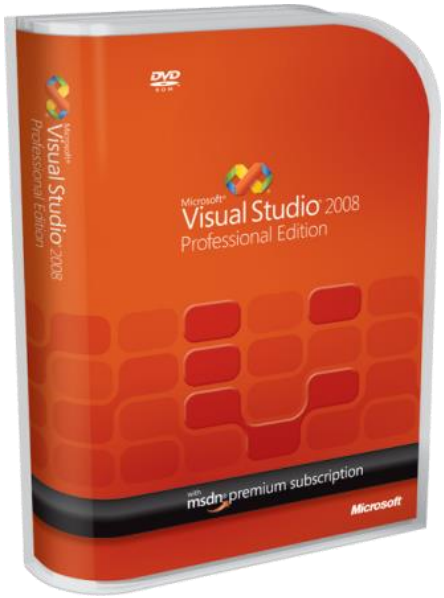
Presentation Structure

- Friday
  - Introduction
  - LINQ: a language for data manipulation; homework
  - A Software Stack for Data-Intensive Manipulation (Part 1)
    - Hardware, Management, Cluster, Storage, Execution
- Tuesday
  - Thinking in Parallel
  - A Software Stack for Data-Intensive Manipulation (Part 2)
    - Language, Application
  - Conclusions

LINQ: LANGUAGE-INTEGRATED QUERY

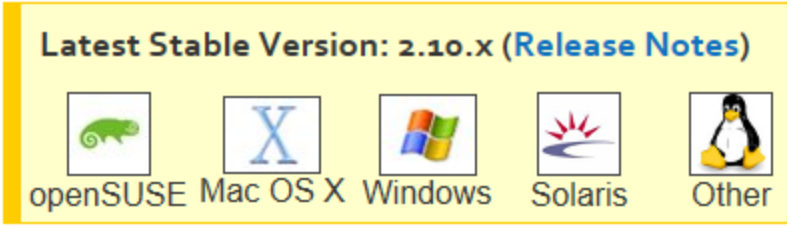
LINQ

- Language extensions to .Net
  - (We will use C#)
- Strongly typed query language
  - Higher-order query operators
  - User-defined functions
  - Arbitrary .Net data types



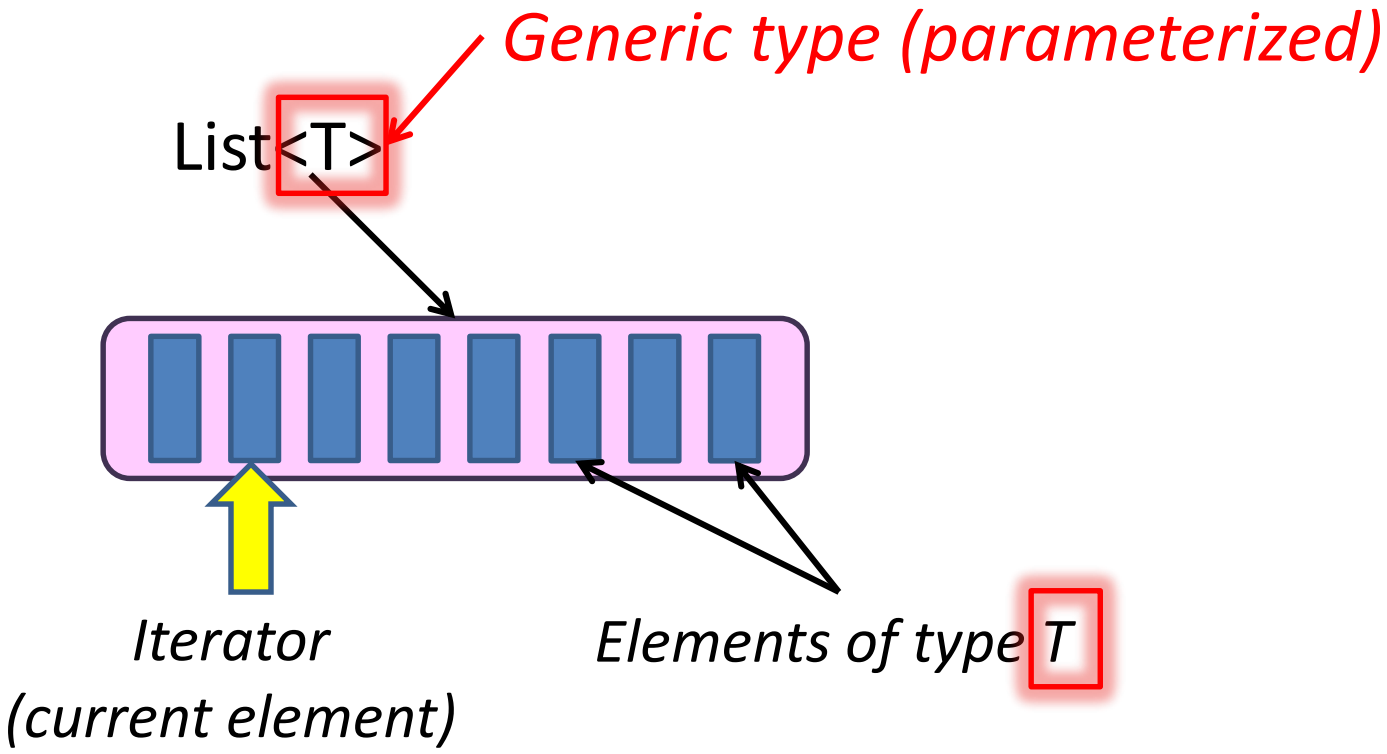
LINQ Availability

- On Windows: Visual Studio 2008 and later, including VS Express (free)
  - http://www.microsoft.com/visualstudio/eng/downloads#d-2012-editions
- On other platforms: open-source mono



  - http://mono-project.com/Main_Page
- Java Streams --- planned in Java 8 --- are similar

Collections



LINQ = .Net+ Queries

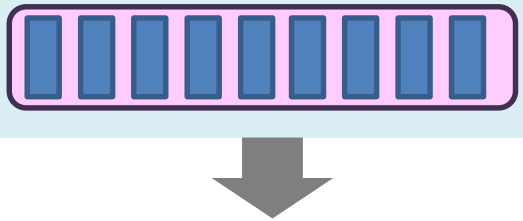
```
Collection<T> collection;
```

```
bool IsLegal(Key);
string Hash(Key);
```

```
var results = collection.
              Where(c => IsLegal(c.key)).
              Select(c => new { Hash(c.key), c.value});
```

Essential LINQ Summary

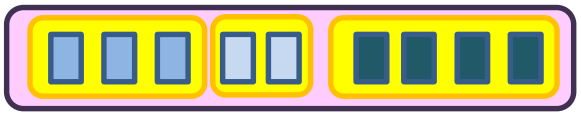
Input



Where (filter)

Select (map)

GroupBy



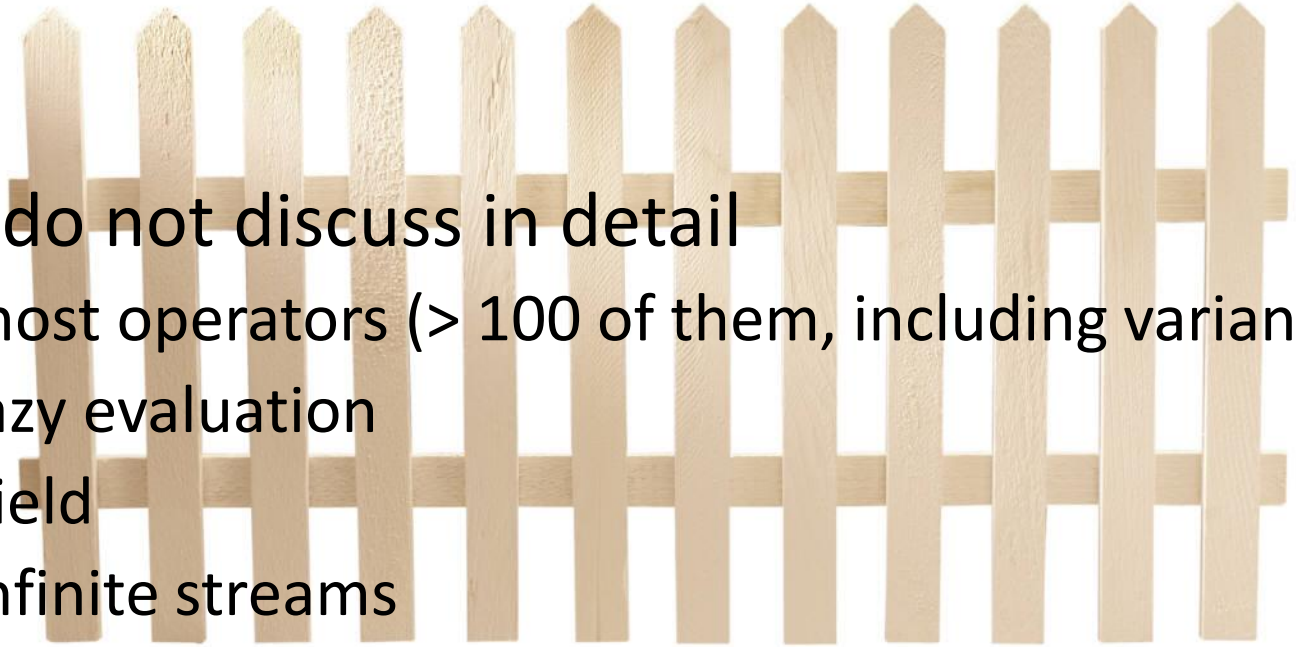
OrderBy (sort)

Aggregate (fold)

Join

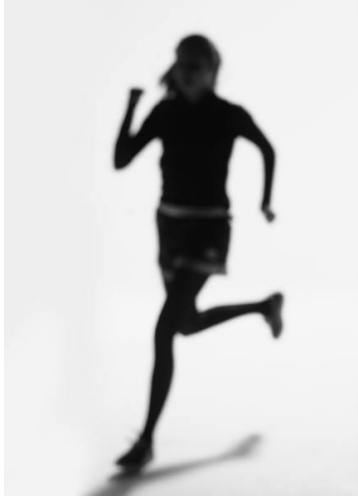
Tutorial Scope

- We only discuss essential LINQ



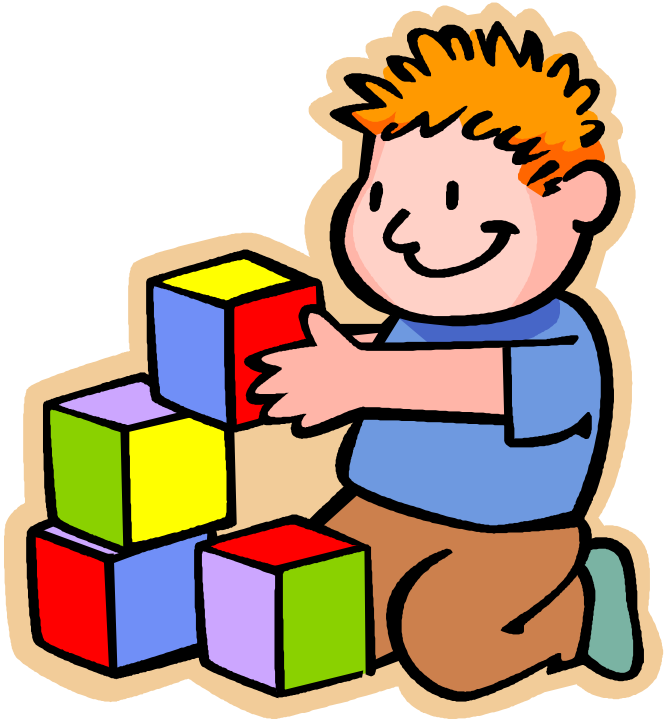
- We do not discuss in detail
  - most operators (> 100 of them, including variants)
  - lazy evaluation
  - yield
  - Infinite streams
  - IQueryable, IObservable

Running the Code



- Code can be downloaded at http://budiu.info/almada-code.zip
- Includes the code on all the following slides (file Slides.cs)
- Includes the homework exercises (details later)
- Includes testing data for the homework
- Contains a Visual Studio Solution file TeachingLinq.sln
- compileMono.bat can be used for Mono

Useful .Net Constructs



Tuples

```
Tuple<int, int> pair = new
    Tuple<int, int>(5, 3);
Tuple<int, string, double> triple =
    Tuple.Create(1, "hi", 3.14);

Console.WriteLine("{0} {1} {2}",
          pair, triple, pair.Item1);
```

Result: (5, 3) (1, hi, 3.14) 5

Anonymous Functions

- Func<I, O>
  - Type of function with
    - input type I
    - output type O
- x => x + 1
  - Lambda expression
  - Function with argument x, which computes x+1

Using Anonymous Functions

```
Func<int, int> inc = x => x + 1;
Console.WriteLine(inc(10));
```

Result: 11

Functions as First-Order Values

```
static T Apply<T>(
    T argument,
    Func<T, T> operation)
{
  return operation(argument);
}

Func<int, int> inc = x => x + 1;
Console.WriteLine(Apply(10, inc));
```

Result: 11

Multiple Arguments

```
Func<int, int, int> add =
        (x, y) => x + y;

Console.WriteLine(add(3,2));
```

Result: 5

Collections

IEnumerable<T>

```
IEnumerable<int> data =
        Enumerable.Range(0, 10);
foreach (int n in data)
    Console.WriteLine(n);

Program.Show(data);
```

Helper function I wrote to help you debug.

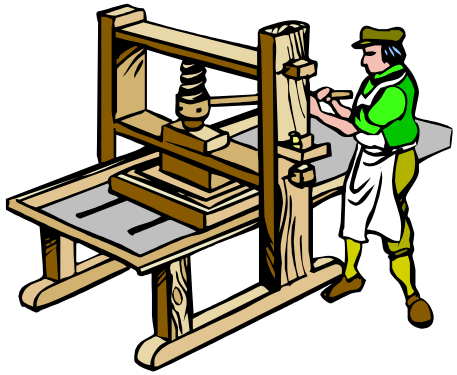
Result: 0,1,2,3,4,5,6,7,8,9

IEnumerables everywhere

- List<T> : IEnumerable<T>
- T[] : IEnumerable<T>
- string : IEnumerable<char>
- Dictionary<K,V> : IEnumerable<KeyValuePair<K,V>>
- ICollection<T> : IEnumerable<T>
- Infinite streams
- User-defined

Printing a Collection

```
static void Print<T>(
    IEnumerable<T> data)
{
    foreach (var v in data)
        Console.Write("{0} ", v);
    Console.WriteLine();
}
```



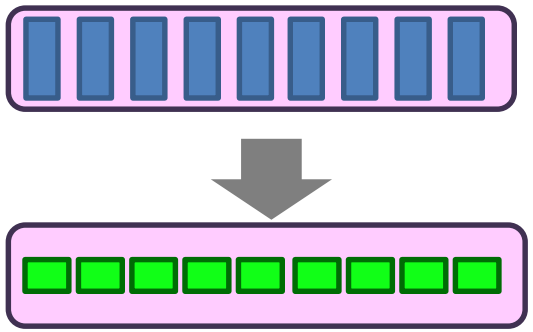
LINQ Collection Operations

Select

Input and output are both collections.

```
IEnumerable<int> result =
        data.Select(d => d + 1);
Show(result);
```

Note: everyone else calls this function "Map"



Data: 0,1,2,3,4,5,6,7,8,9

Result: 1,2,3,4,5,6,7,8,9,10

`Select` can transform types

```
var result = data.Select(
      d => d > 5);
Show(result);
```

```
Result: False,False,False,False,False,False,True,True,True,True
```

Separation of Concerns

```
var result = data.Select(d => d>5);
```

Operator applies to *any* collection

User-defined function (UDF)
Transforms the elements

Chaining operators

```
var result = data
        .Select(d => d * d)
        .Select(d => Math.Sin(d))
        .Select(d => d.ToString());
```

All these are collections.

Result: "0.00","0.84","-0.76","0.41","-0.29","-0.13","-0.99","-0.95","0.92","-0.63"

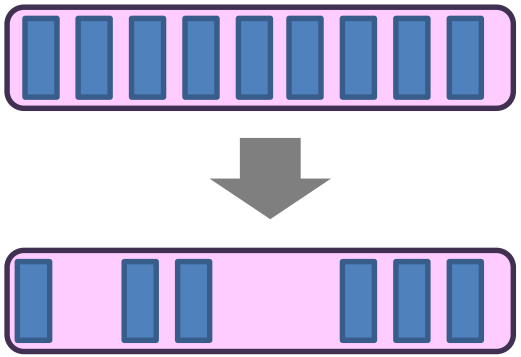
Generic Operators

```
IEnumerable<Dest>                                    Output type
    Select<Src,Dest>(
        this IEnumerable<Src>,                       Input type
        Func<Src, Dest>)                             Transformation function
```

Filtering with Where

```
var result = data.Where(
    d => d > 5);
Show(result);
```

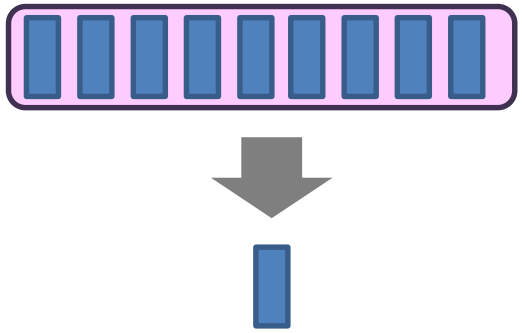
Result: 6,7,8,9



Aggregations

```
var ct = data.Count();
var sum = data.Sum();
Console.WriteLine("{0} {1}", ct, sum);
```

Result: 10 45



General Aggregations

```
var sum = data.Aggregate(
      (a, b) => a + b);
Console.WriteLine("{0}", sum);
```

Result: 45

(((((((0 + 1) + 2) + 3) + 4) + 5) + 6) + 7) + 8) + 9

Aggregations with Seeds

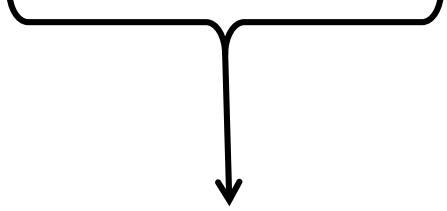
```
var sum = data.Aggregate(
    "X",  // seed
    (a, b) => string.Format(
            "({0} + {1})", a, b));

Console.WriteLine("{0}", sum);
```

Result: “((((((((((X + 0) + 1) + 2) + 3) + 4) + 5) + 6) + 7) + 8) + 9)”

Values can be Collections

```
var lines = new string[]
            { “First string”,
              “Second string” };
IEnumerable<int> counts =
     lines.Select(d => d.Count());
Show(counts);
```



(d as IEnumerable<char>).Count()

Result: 12,13

Flattening Collections with SelectMany

```
IEnumerable<string> words =
    lines.SelectMany(
        d => d.Split(' '));

IEnumerable<string[]> phrases =
    lines.Select(
        d => d.Split(' '));
```

SelectMany

```
var lines = new string[]
            { “First string”,
              “Second string” };
lines.SelectMany(d => d.Split(' '));
```

Result: { “First”, “string”, “second”, “string” }

```
lines.Select(    d => d.Split(' '));
```

Result: { {“First”, “string”}, {“second”, “string”} }

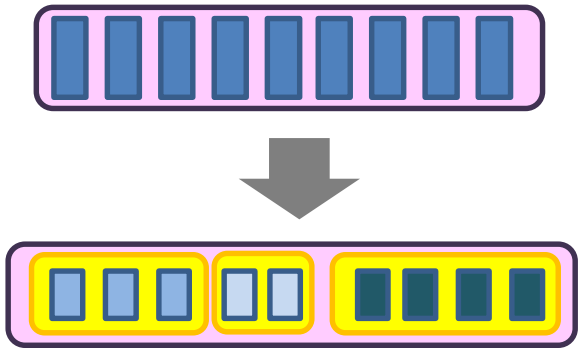
This is a collection of collections!

GroupBy

```
IEnumerable<IGrouping<int, int>> groups
    = data.GroupBy(d => d%3);
```

Key function

```
Result:0 => {0,3,6,9}
       1 => {1,4,7}
       2 => {2,5,8}
```



IGrouping

```
var result =
      data.GroupBy(d => d%3)
          .Select(g => g.Key);
```

Result: 0,1,2

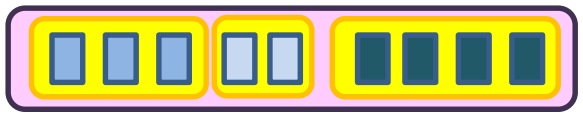
Groups are Nested Collections

IGrouping<TKey, TVals> : IEnumerable<TVals>

```
var result =
      data.GroupBy(d => d%3)
          .Select(g => g.Count());
```

LINQ computation on each group

Result: 4,3,3



Sorting

```
var sorted =
    lines.SelectMany(l=>l.Split(' '))
         .OrderBy(l => l.Length);
Show(sorted);
```

Sorting key

Result: "First","string","Second","string"

Joins

```
var L = Enumerable.Range(0, 4);
var R = Enumerable.Range(0, 3);
var result = L.Join(R, l => l % 2,
                       r => (r + 1) % 2,
                       (l, r) => l + r);
```

Left key

Right key

Join function

	L	0	1	2	3	4
R	keys	0	1	0	1	0
0	1		1+0=1		3+0=3	
1	0	0+1=1		2+1=3		4+1=5
2	1		1+2=3		3+2=5	
3	0	0+3=3		2+3=5		4+3=7

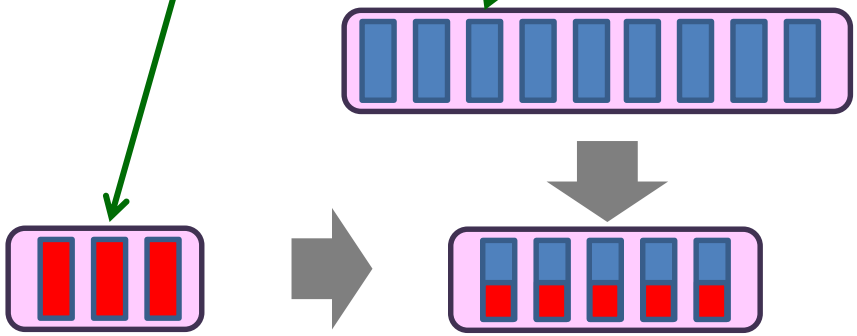
result

Join Example

```
var common =
    words.Join(data, s => s.Length, d => d,
                    (s, d) => new
                        { length = d, str = s });
```

Left input

Right input



Result: {
  { length = 5, str = First }
  { length = 6, str = string }
  { length = 6, str = Second }
  { length = 6, str = string }
}

Other Handy Operators

- collection.Max()
- left.Concat(right)
- collection.Take(n)

- Maximum element
- Concatenation
- First n elements

Take

First few elements in a collection

```
var first5 = data
      .Select(d => d * d)
      .Take(5);
```

Result: 0,1,4,9,16

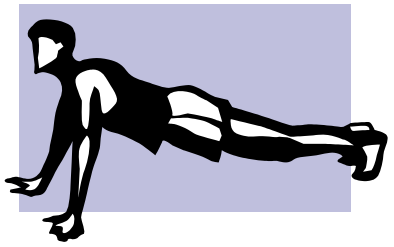
Homework

- http://budiu.info/almada-code.zip
- You only need the LINQ operations taught in this class
- Solutions should only use LINQ (no loops)
- Fill the 12 functions in class Homework, file Homework.cs
- Testing data given in Program.cs; Main is there
- Calling ShowResults(homework, data) will run your homework on the data (in Program.cs)
- You can use the function Program.Show() to debug/display complex data structures

- Slides.cs: code from all these slides
- Program.cs: main program, and sample testing data
- Tools.cs: code to display complex C# objects
- Homework.cs: skeleton for 12 homework problems

  You must implement these 12 functions.
- (Solutions.cs: sample solutions for homework)

Exercises (1)



1. Count the number of words in the input collection (use the supplied SplitStringIntoWords function to split a line into words)

2. Count the number of unique (distinct) words in the input collection. “And” = “and” (ignore case).

3. Find the most frequent 10 words in the input collection, and their counts. Ignore case.

Exercises (2)

4. From each line of text extract just the vowels (‘a’, ‘e’, ‘i’, ‘o’, ‘u’), ignoring letter case.

5. Given a list of words find the number of occurrences of each of them in the input collection (ignore case).

6. Generate the Cartesian product of two sets.

Exercises (3)

7. Given a matrix of numbers, find the largest value on each row. (Matrix is a list of rows, each row is a list of values.)

8. A sparse matrix is represented as triples (colNumber,rowNumber,value). Compute the matrix transpose. (Indexes start at 0.)

9. Add two sparse matrices.

Exercises (4)

10. Multiply two sparse matrices.

11. Consider a directed graph (V, E).
    Node names are numbers. The graph is given by the set E, a list of edges Tuple<int, int>.
    Find all nodes reachable in exactly 5 steps starting from node 0.

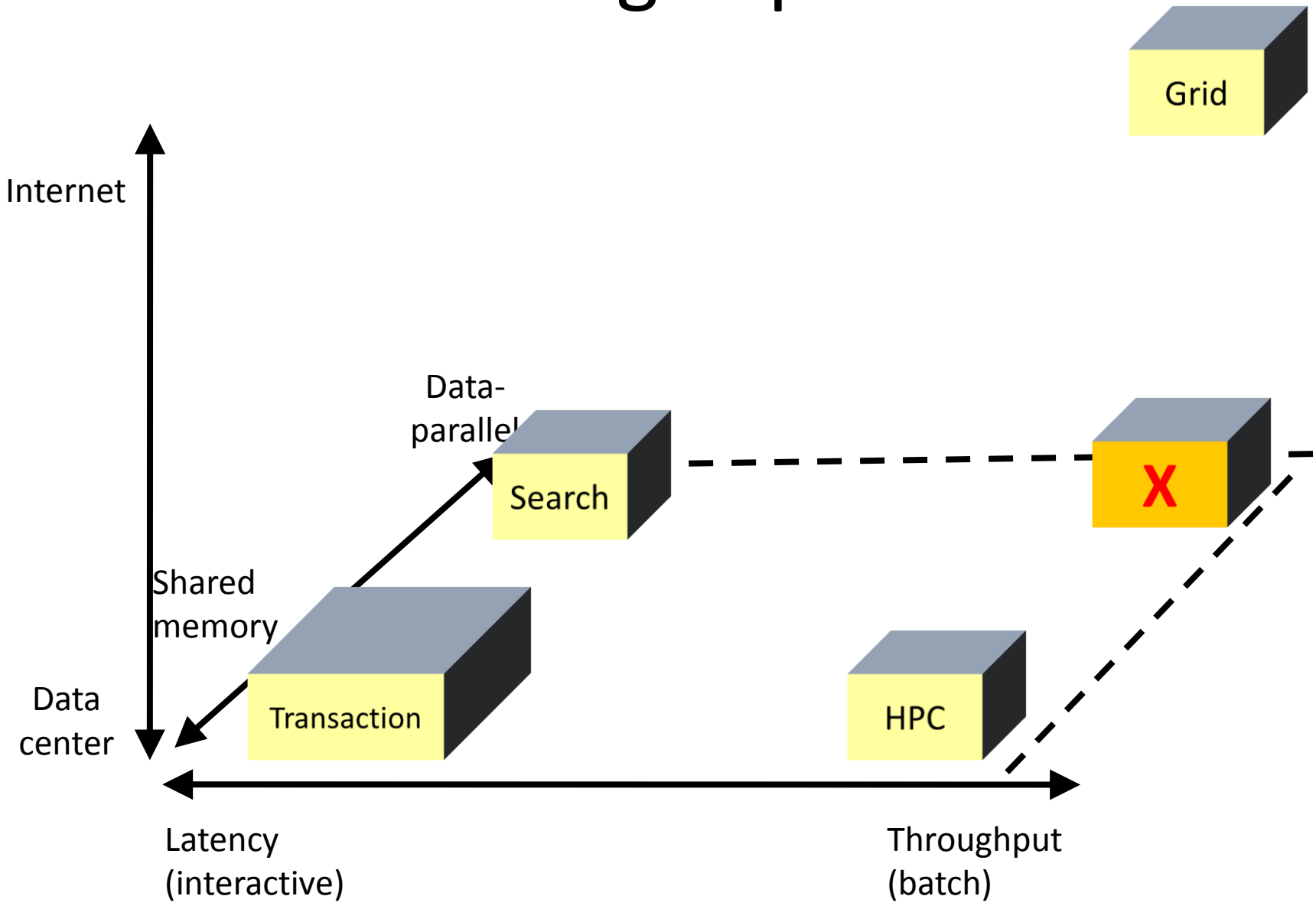
Exercises (5)

12. Compute two iteration steps of the pagerank of a directed graph (V, E). Each node n ∈ V has a weight W(n), initially 1/|V|, and an out-degree D(n) (the number of out-edges of n). Each algorithm iteration changes weights of all nodes n as follows:

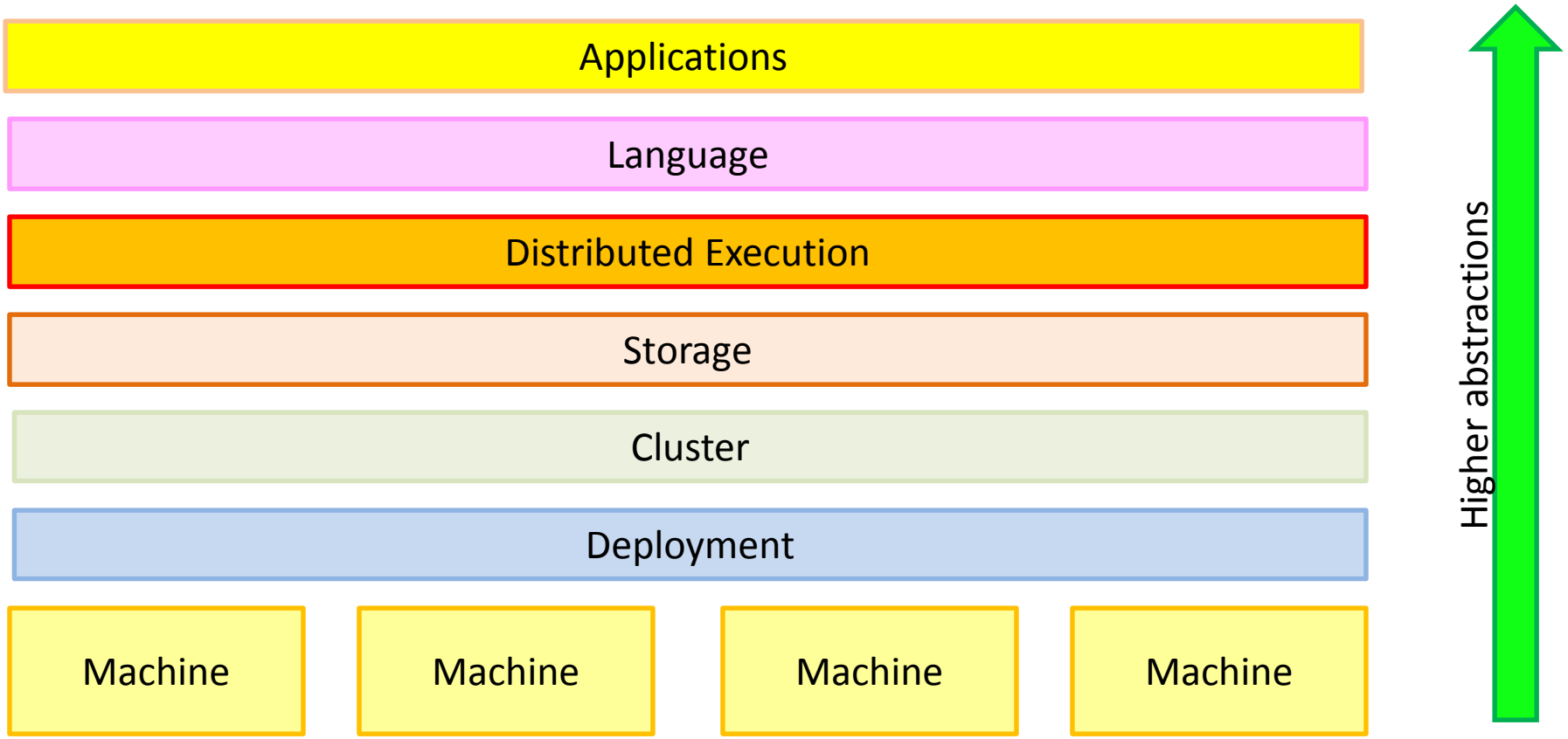
$$W'(n) = \sum_{(m,n)\in E} W(m)/D(m)$$

Crunching Big Data

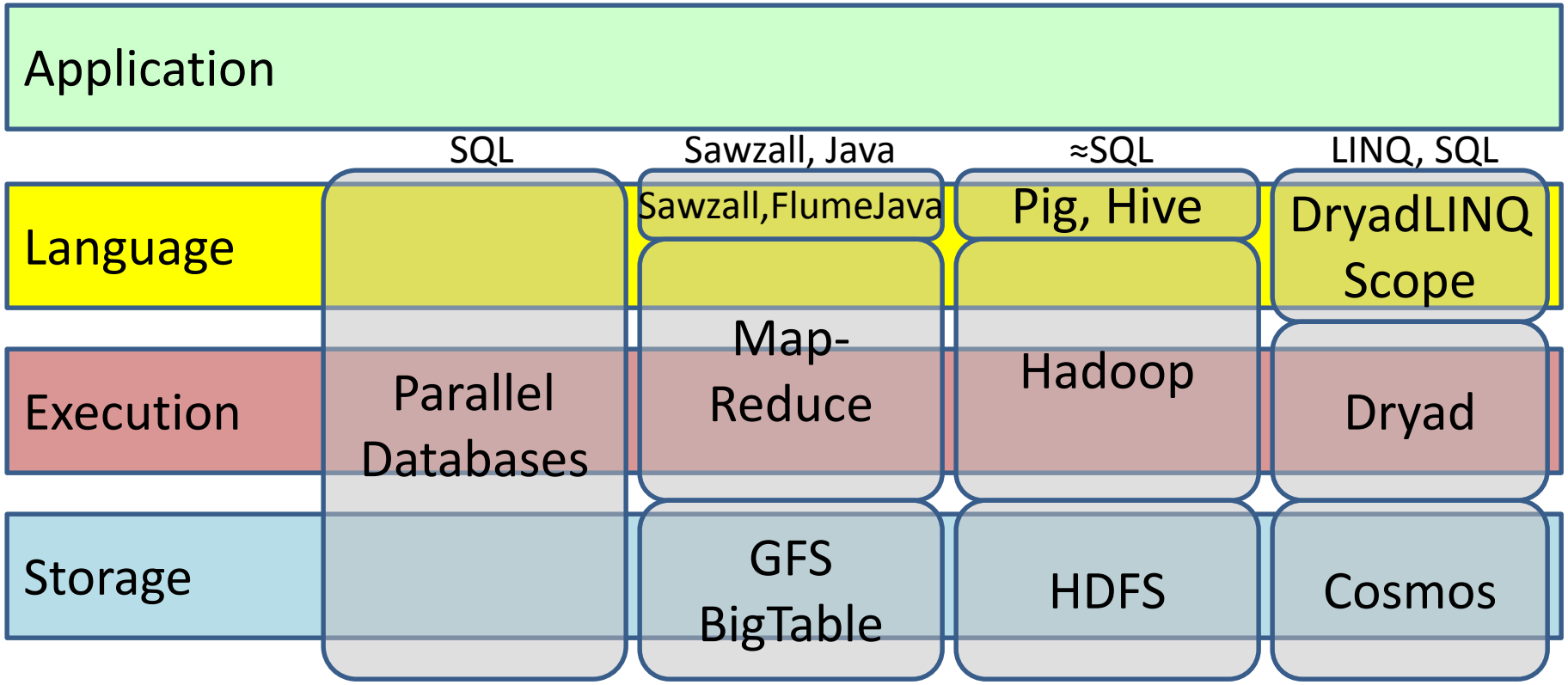
Design Space

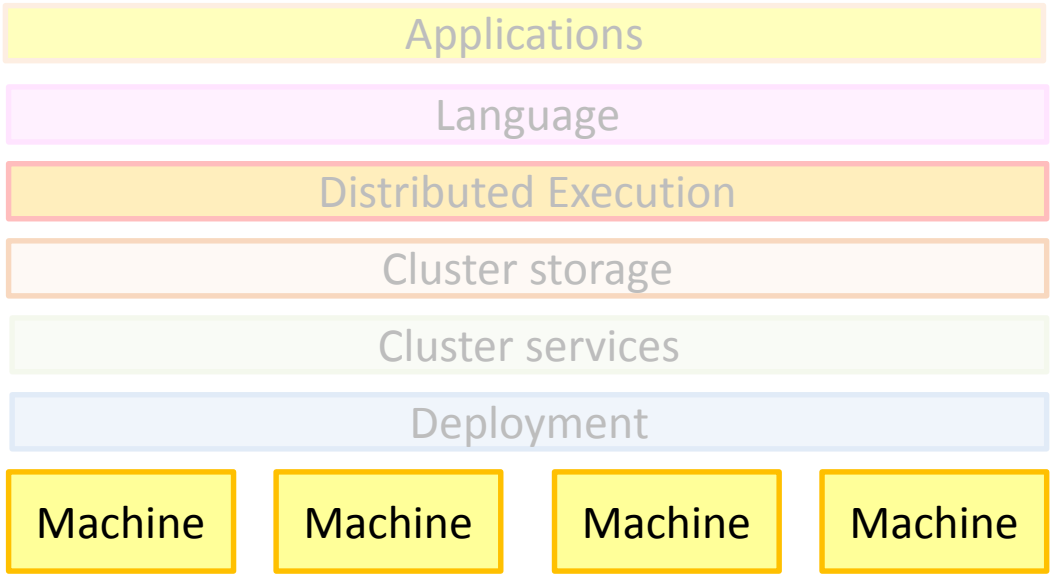


Software Stack



Data-Parallel Computation

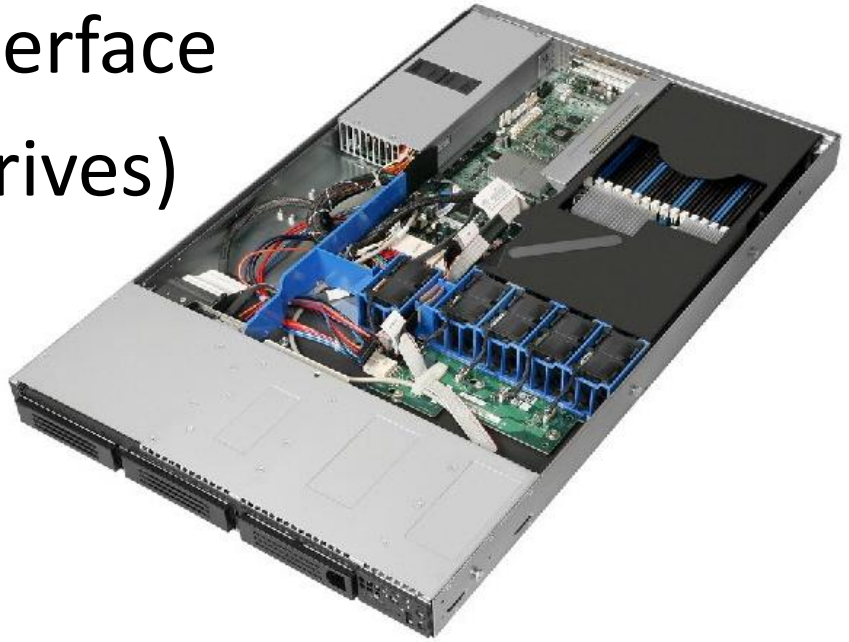




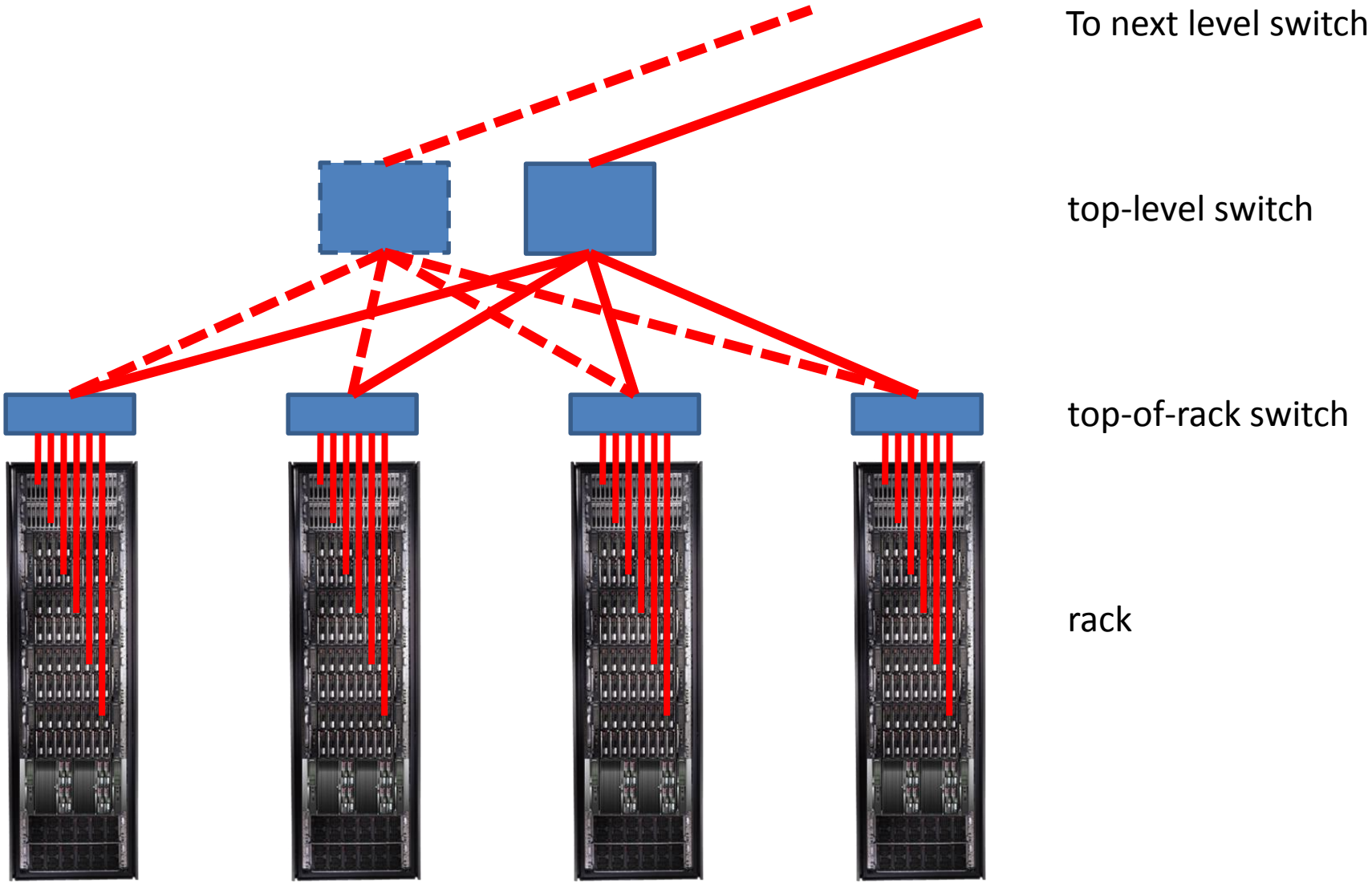
CLUSTER ARCHITECTURE

Cluster Machines

- Commodity server-class systems
- Optimized for cost
- Remote management interface
- Local storage (multiple drives)
- Multi-core CPU
- Gigabit+ Ethernet
- Stock OS

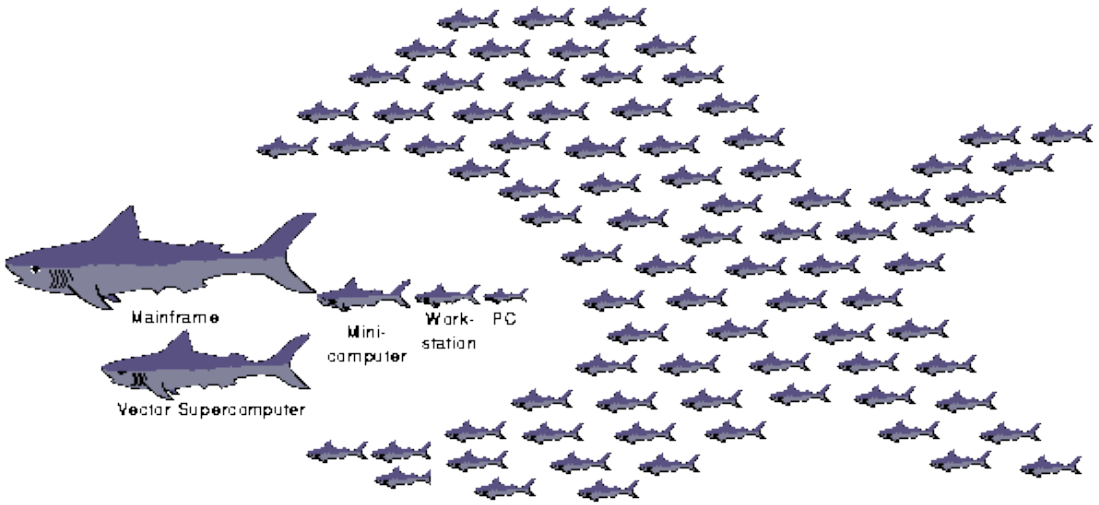


Cluster network topology

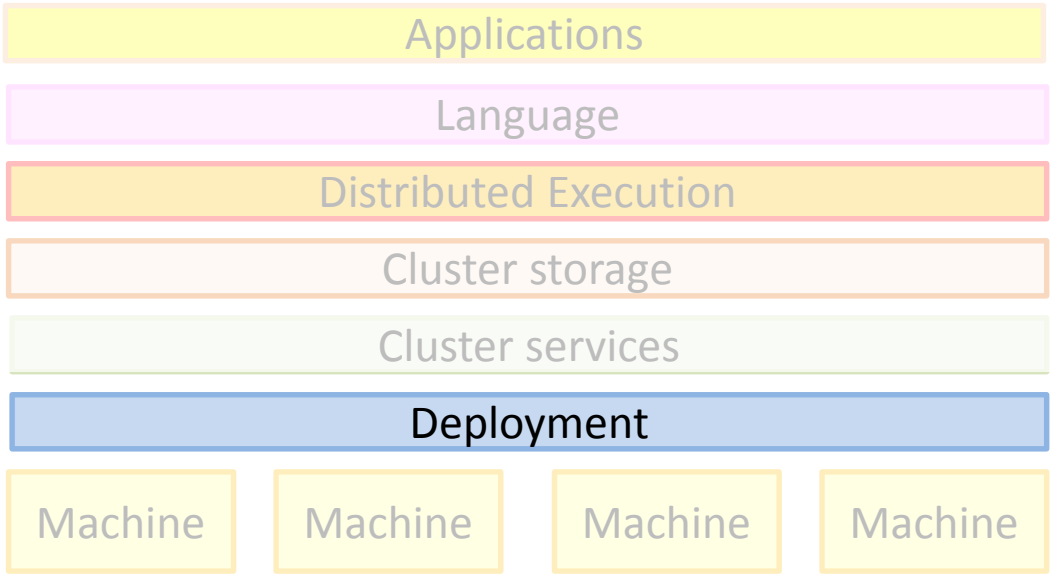


The secret of scalability

- Cheap hardware
- Smart software
- Berkeley Network of Workstations (’94-’98)
  http://now.cs.berkeley.edu



NOW



DEPLOYMENT: AUTOPILOT

Autopilot: Automatic Data Center Management, *Michael Isard*, in *Operating Systems Review*, vol. 41, no. 2, pp. 60-67, April 2007

Autopilot goal

- Handle automatically routine tasks
- Without operator intervention

Autopiloted System

Autopilot control

Application

Autopilot services

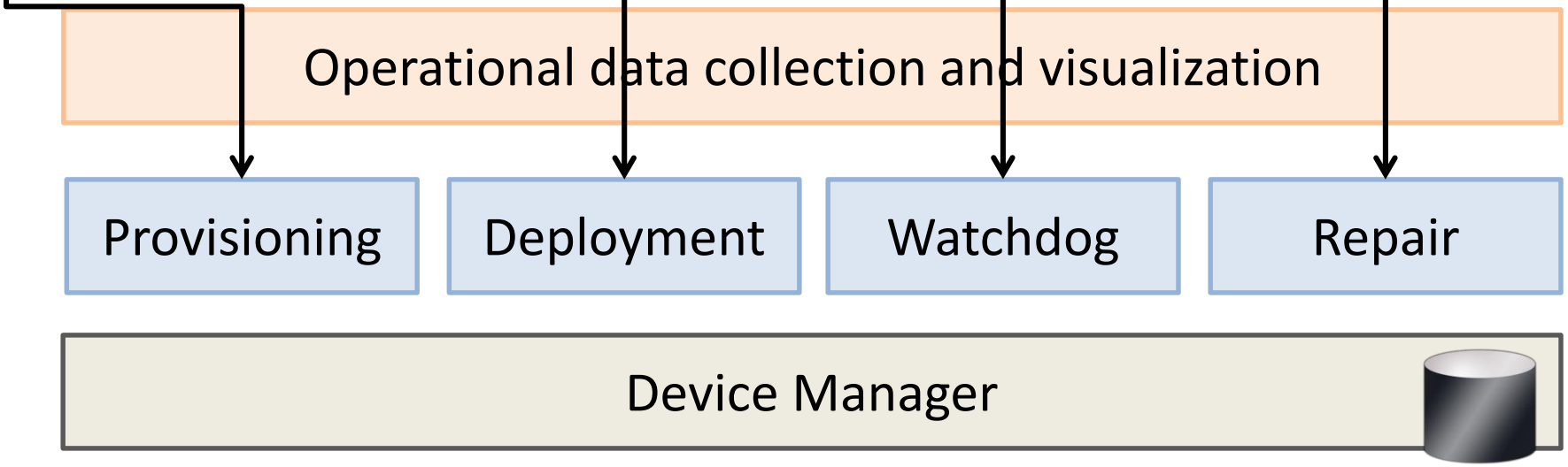
Recovery-Oriented Computing

- Everything will eventually fail
- Design for failure
- Crash-only software design
- http://roc.cs.berkeley.edu

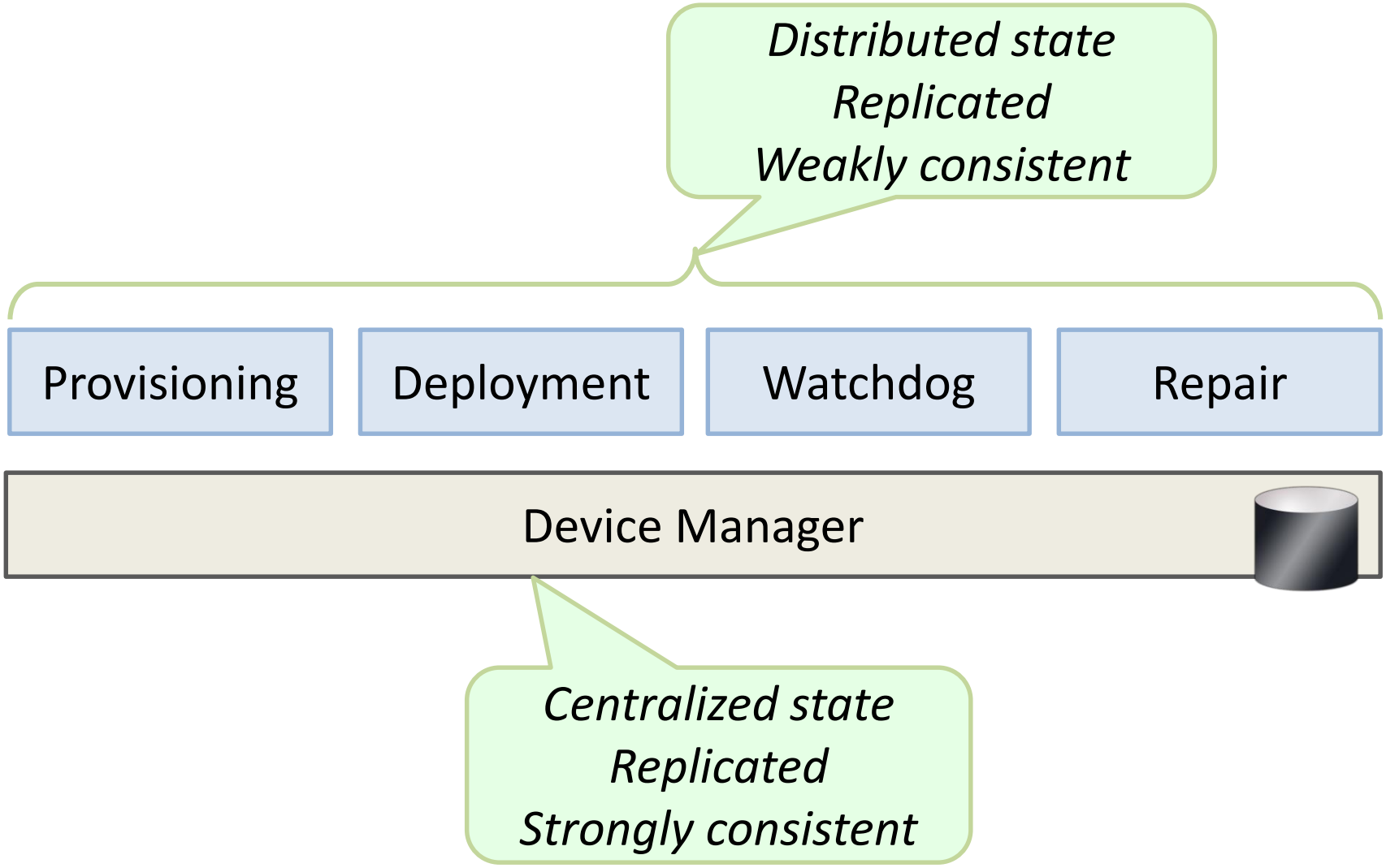
Brown, A. and D. A. Patterson. Embracing Failure: A Case for Recovery-Oriented Computing (ROC). *High Performance Transaction Processing Symposium*, October 2001.

Autopilot Architecture

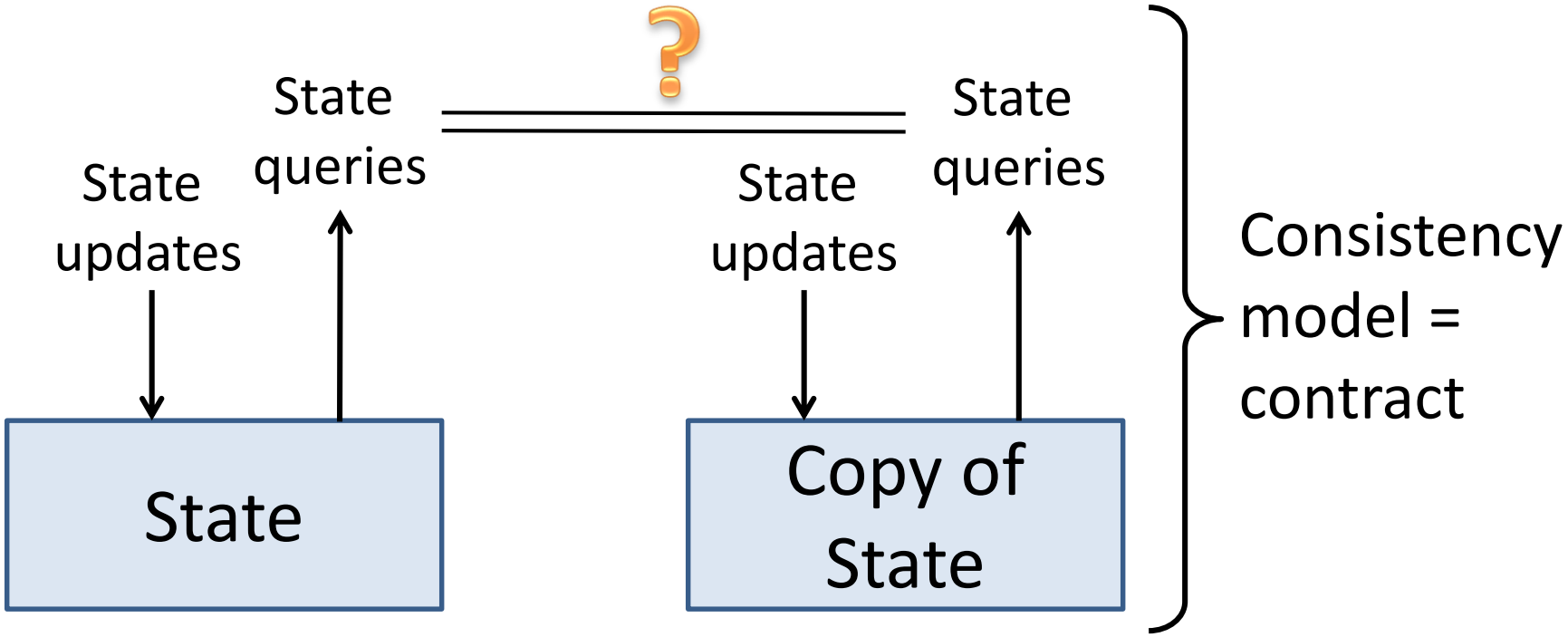
- Discover new machines; netboot; self-test
- Install application binaries and configurations
- Monitor application health
- Fix broken machines



Distributed State



Problems of Distributed State



Centralized Replicated Control

- Keep essential control state centralized
- Replicate the state for reliability
- Use the Paxos consensus protocol (Zookeeper is the open-source alternative)

Leslie Lamport. The part-time parliament. ACM Transactions on Computer Systems, 16(2):133-169, May 1998.

Consistency Models

Strong consistency

- Expensive to provide
- Hard to build right

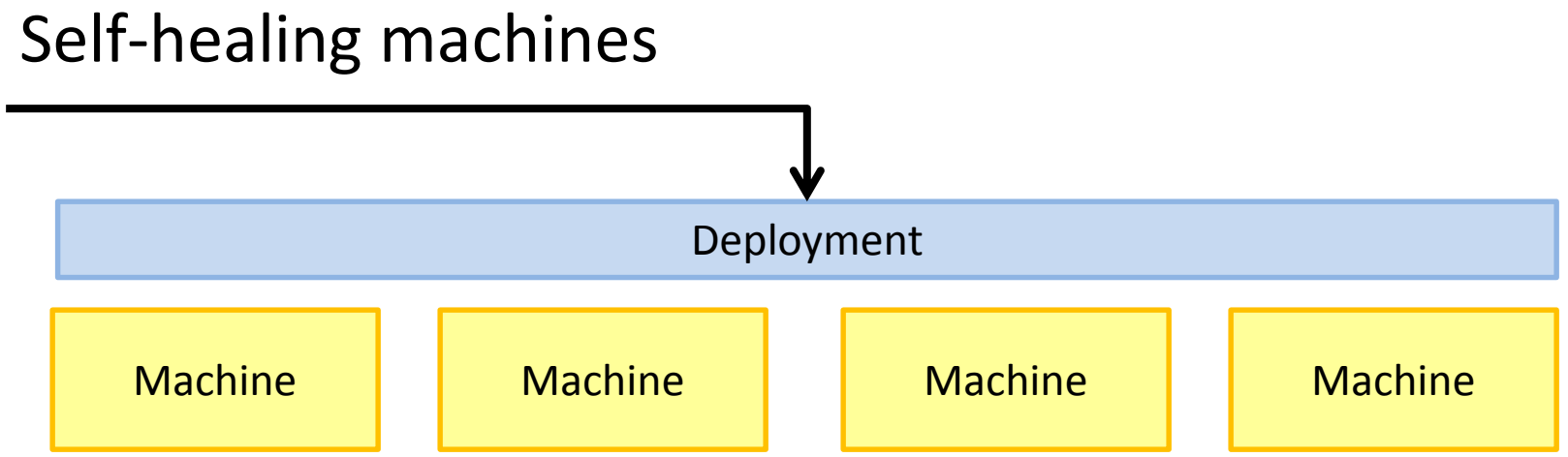
- Easy to understand
- Easy to program against
- Simple application design

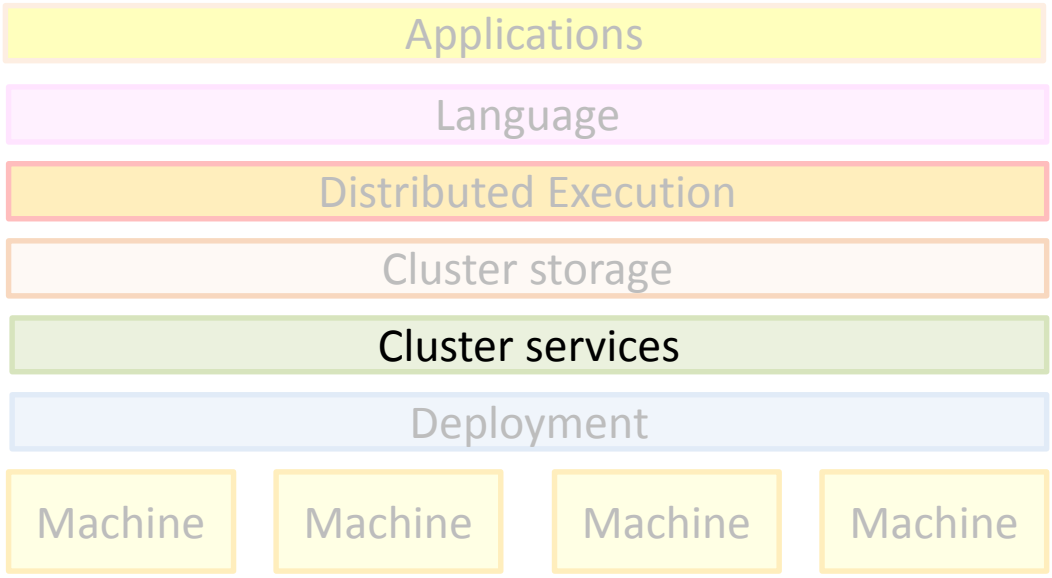
Weak consistency

- Increases availability

- Many different models
- Easy to misuse
- Very hard to understand
- Conflict management in application

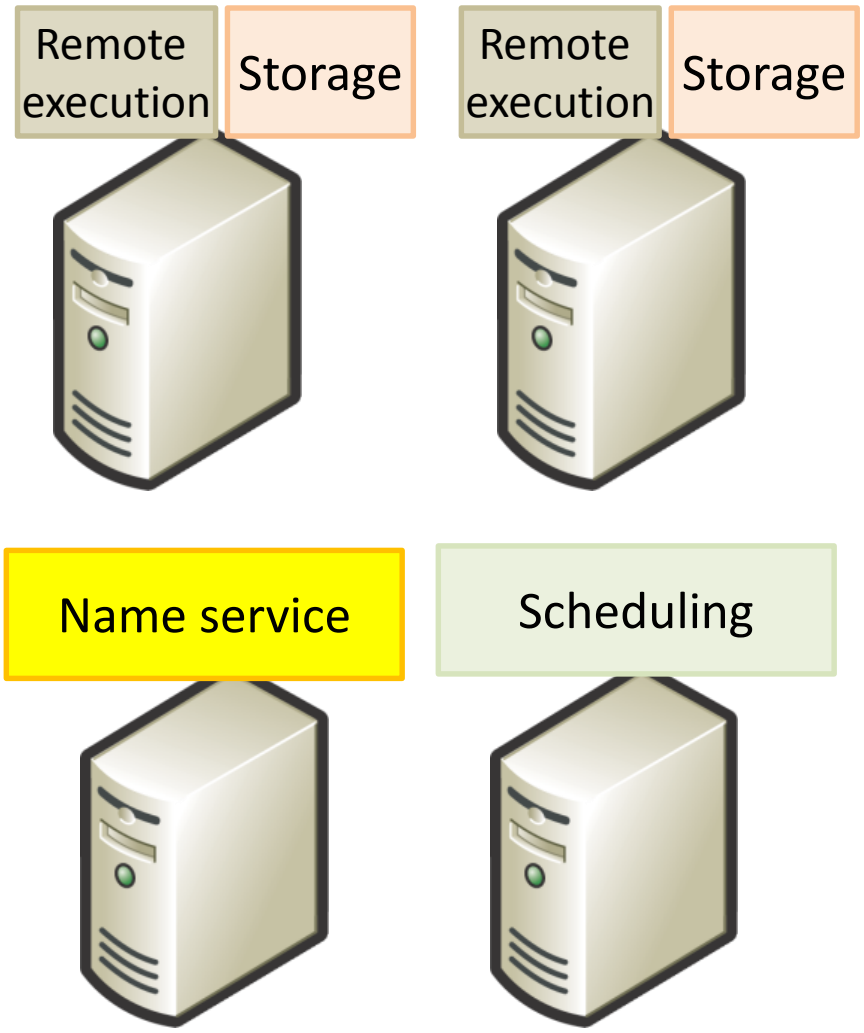
Autopilot abstraction





CLUSTER SERVICES

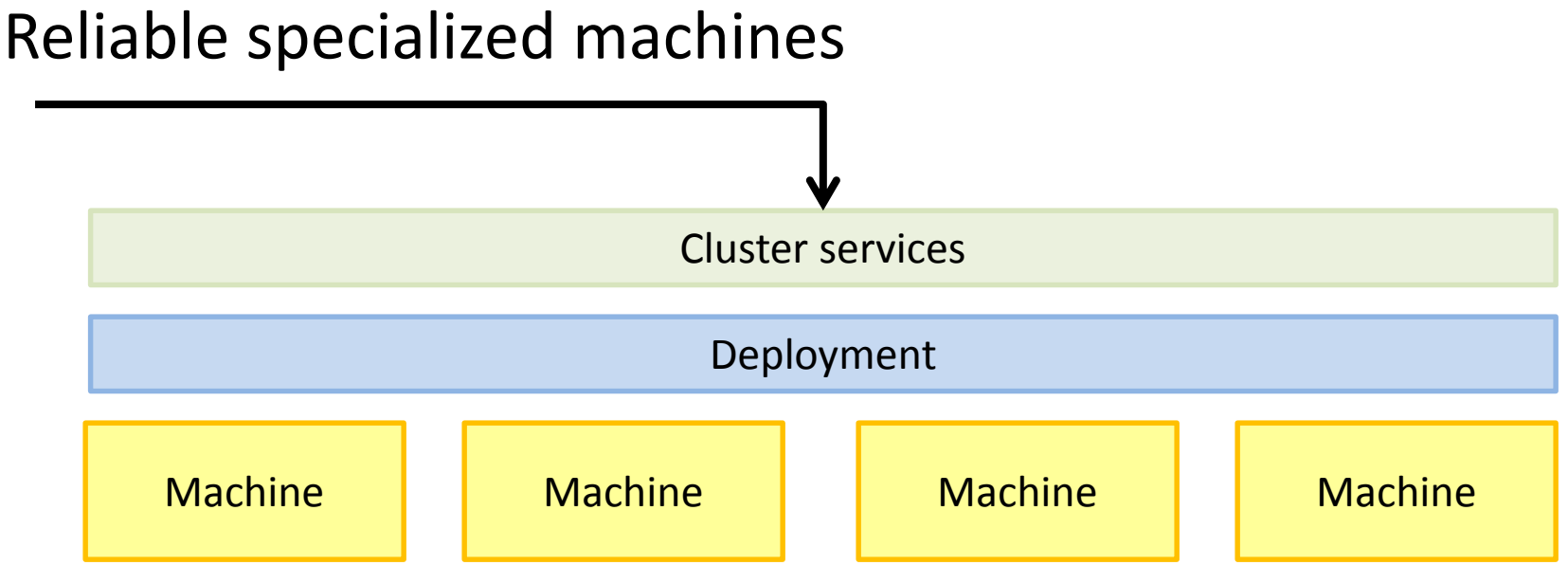
Cluster Machines



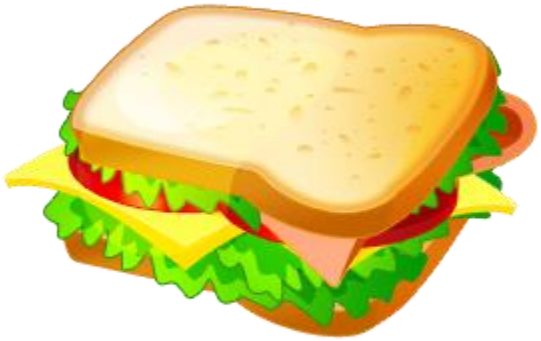
Cluster Services

- Name service: discover cluster machines
- Scheduling: allocate cluster machines
- Storage: file contents
- Remote execution: spawn new computations

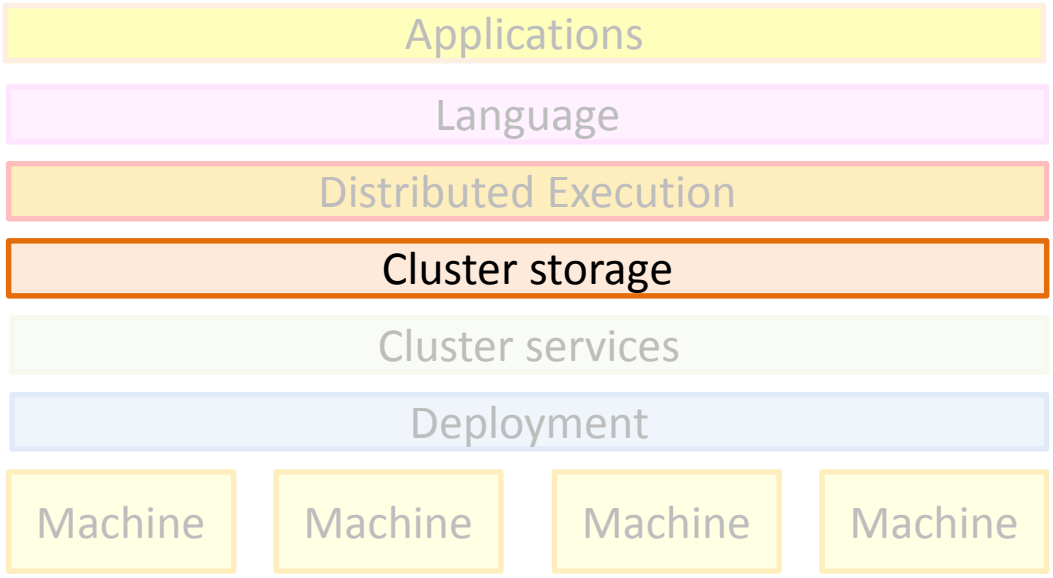
Cluster services abstraction



Layered Software Architecture



- Simple components
- Software-provided reliability
- Versioned APIs
- Design for live staged deployment

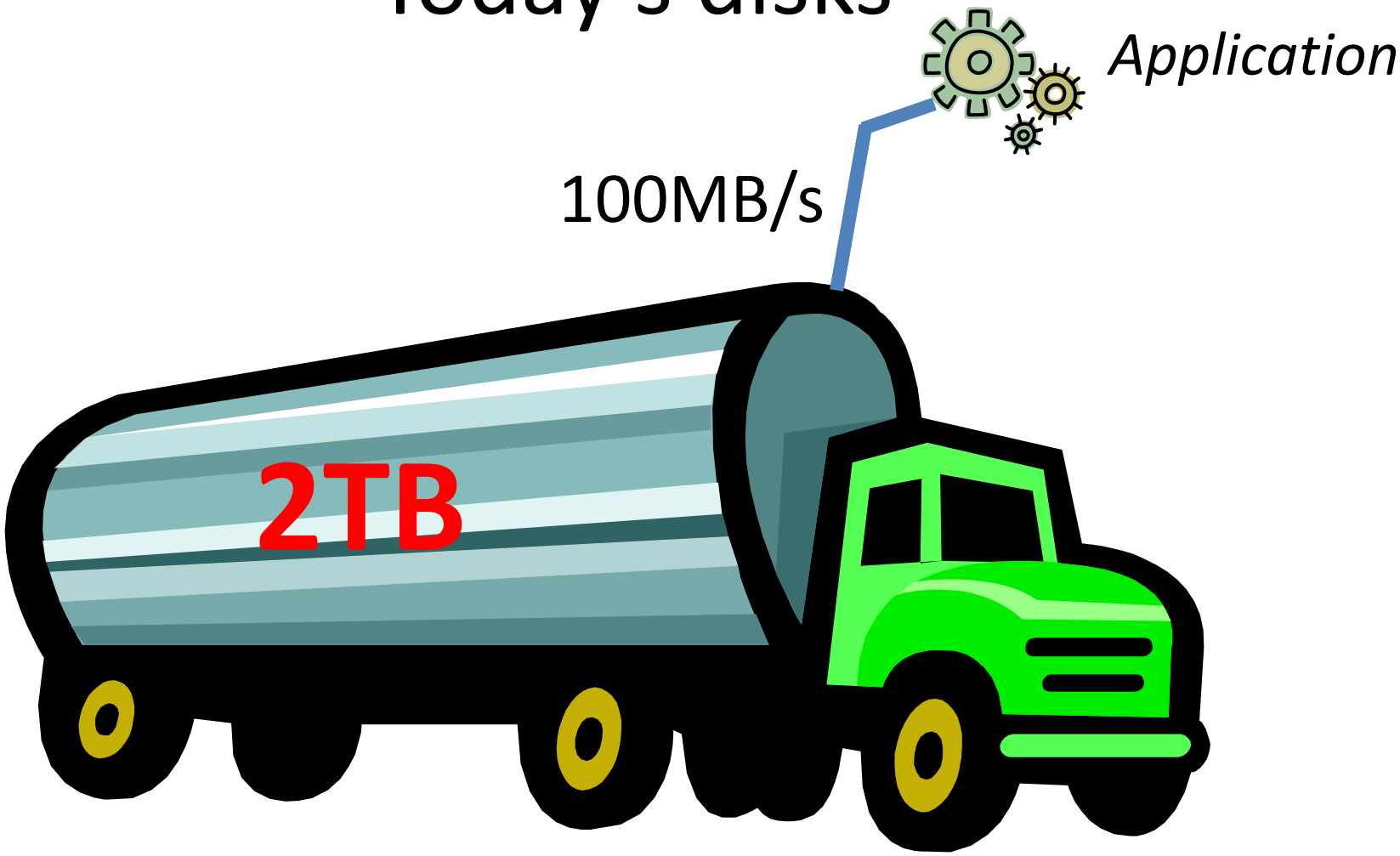


DISTRIBUTED STORAGE

Bandwidth hierarchy

Cache | RAM | Local disks | Local rack | Remote rack | Remote datacenter

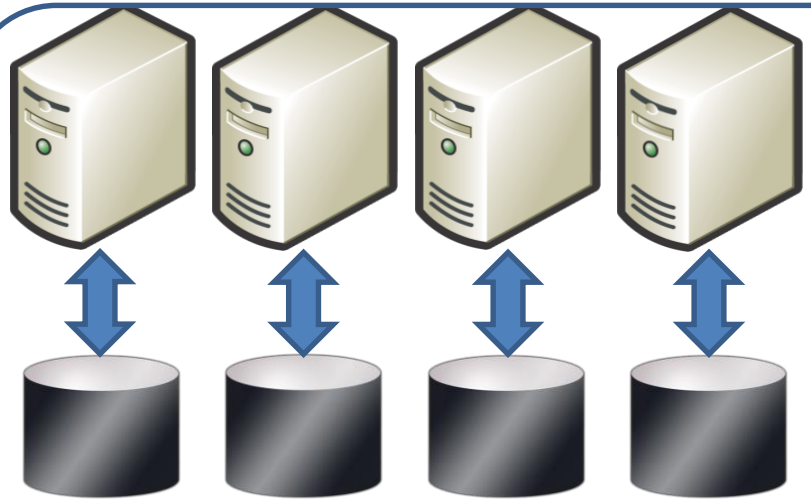
Today's disks



Storage bandwidth

- Expensive
- Fast network needed
- Limited by network b/w

SAN



JBOD

- Cheap network
- Cheap machines
- Limited by disk b/w

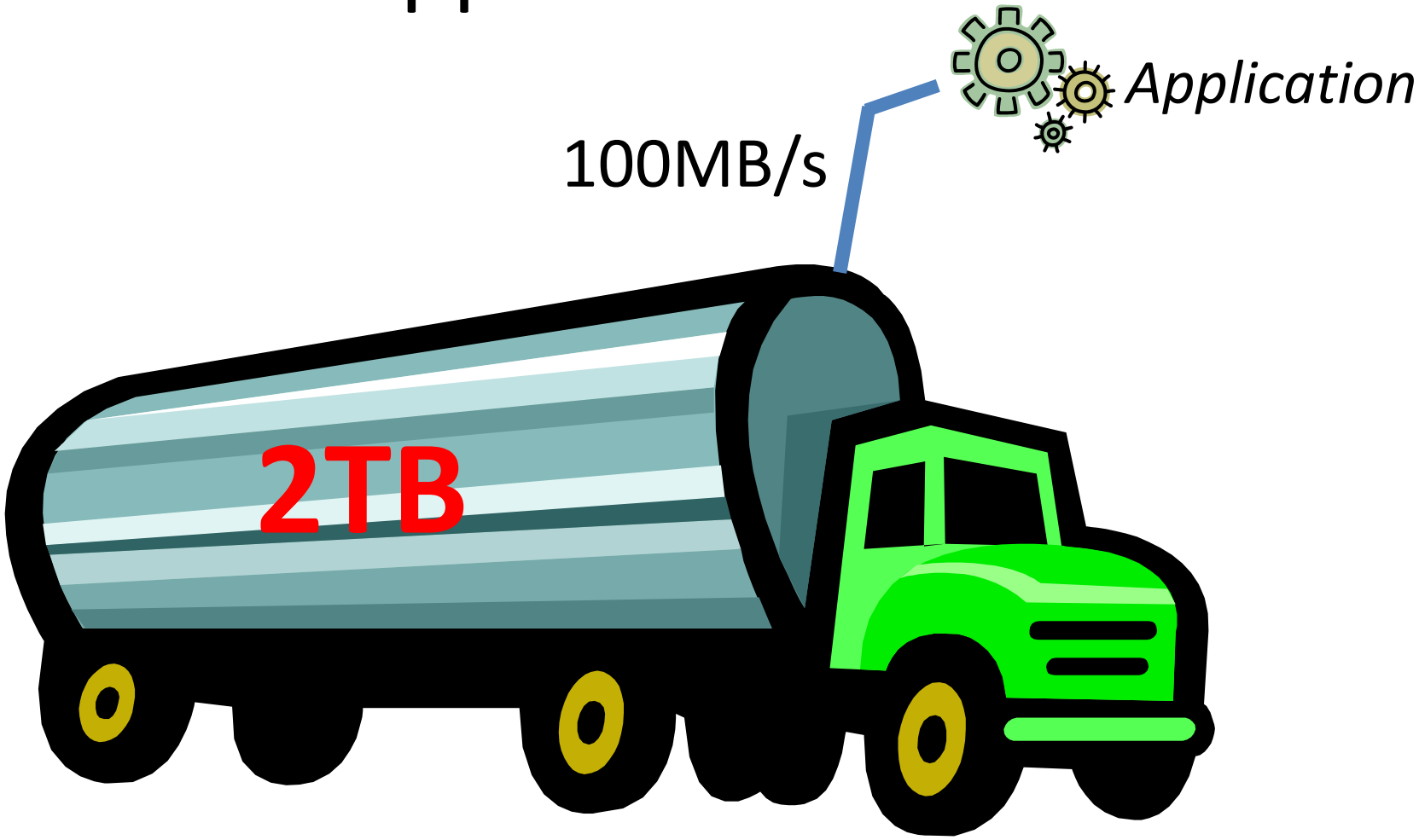
Time to read 1TB (sequential)

- 1 TB / 100MB/s = 3 hours

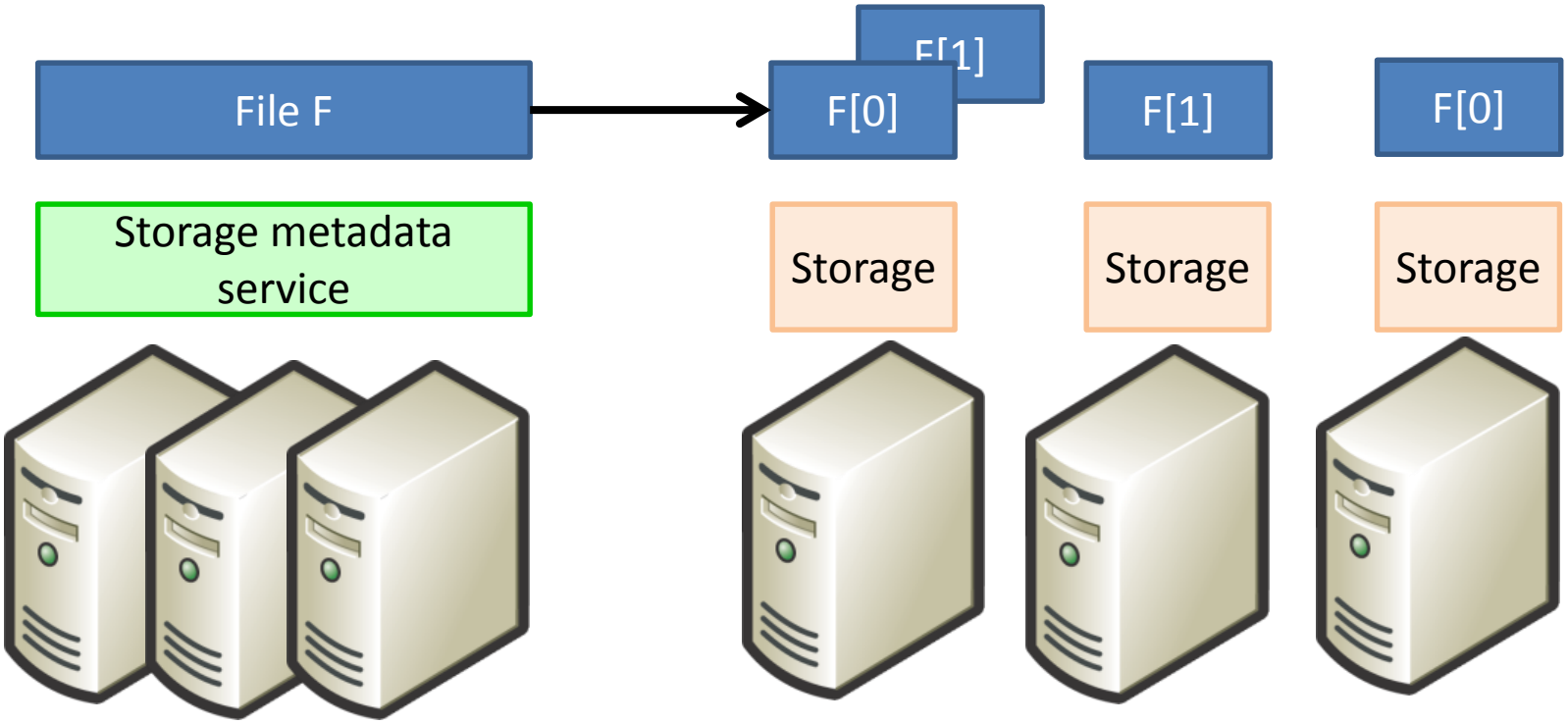
- 1 TB / 10 Gbps = 40 minutes

- 1 TB / (100 MB/s/disk x 10000 disks) = 1s
- (1000 machines x 10 disks x 1TB/disk = 10PB)

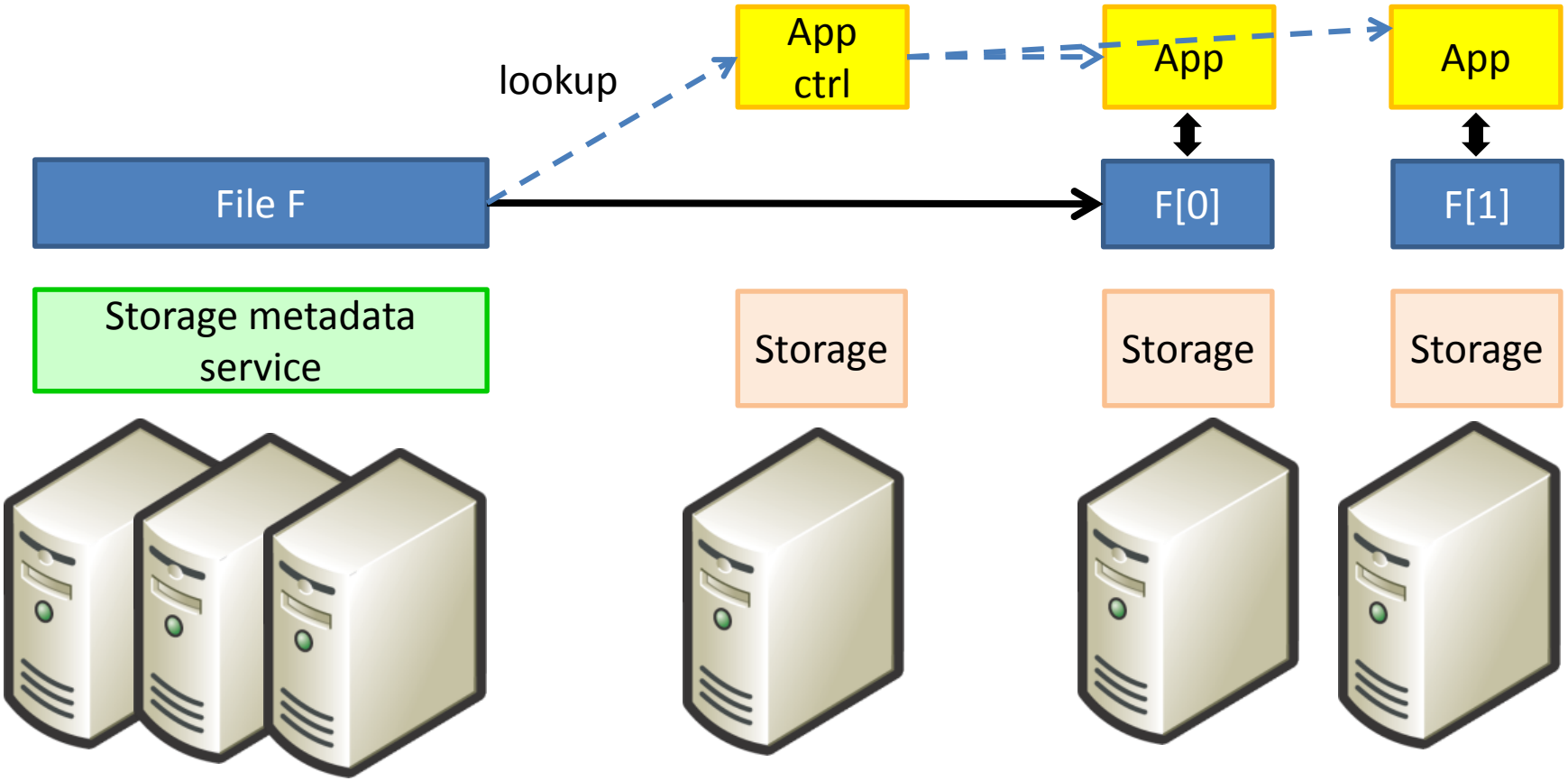
Send the application to the data!



Large-scale Distributed Storage

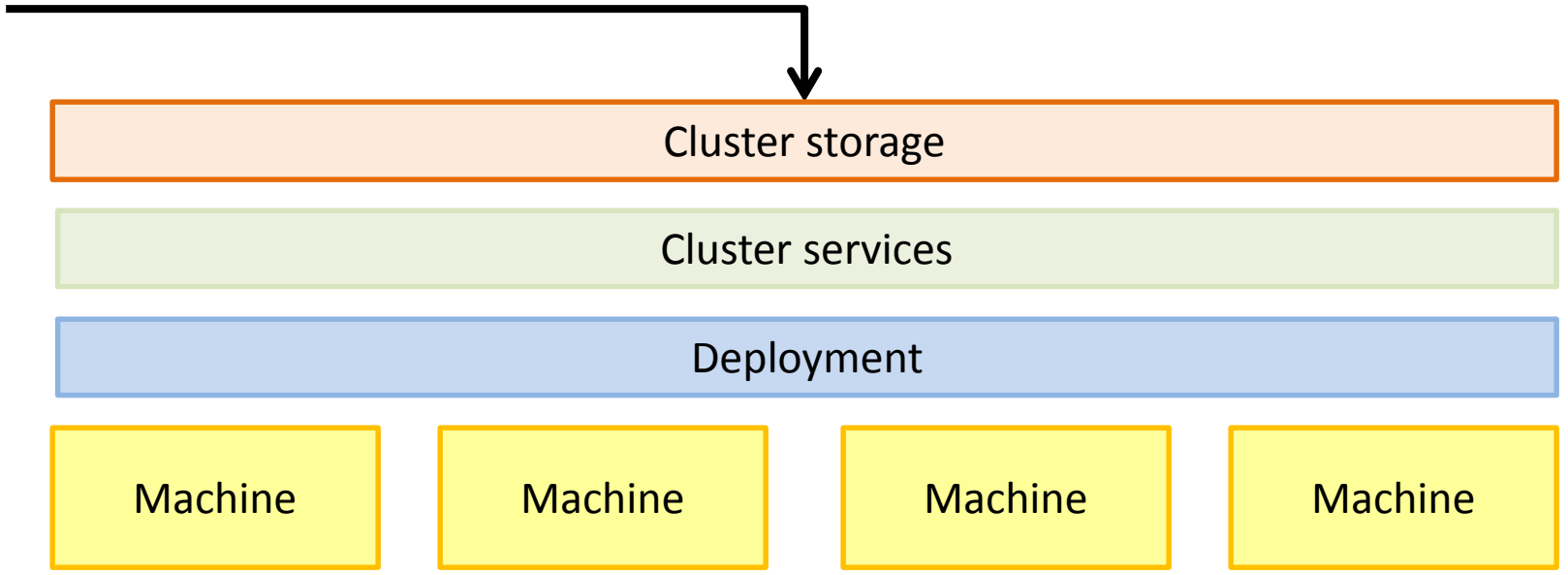


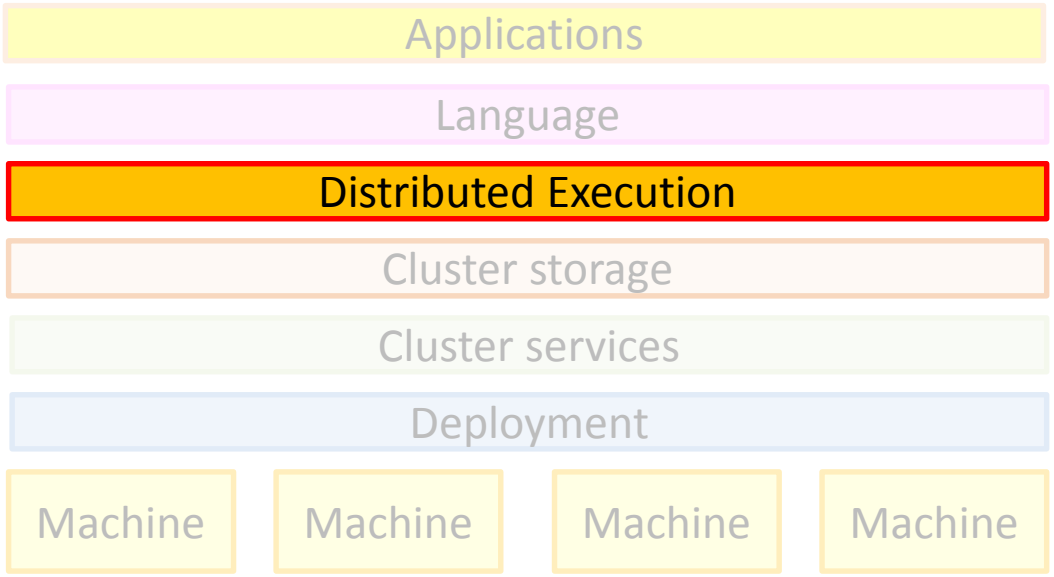
Parallel Application I/O



Cluster Storage Abstraction

Set of reliable machines with a global filesystem





DISTRIBUTED EXECUTION: DRYAD

Dryad painting by Evelyn de Morgan

Dryad = Execution Layer

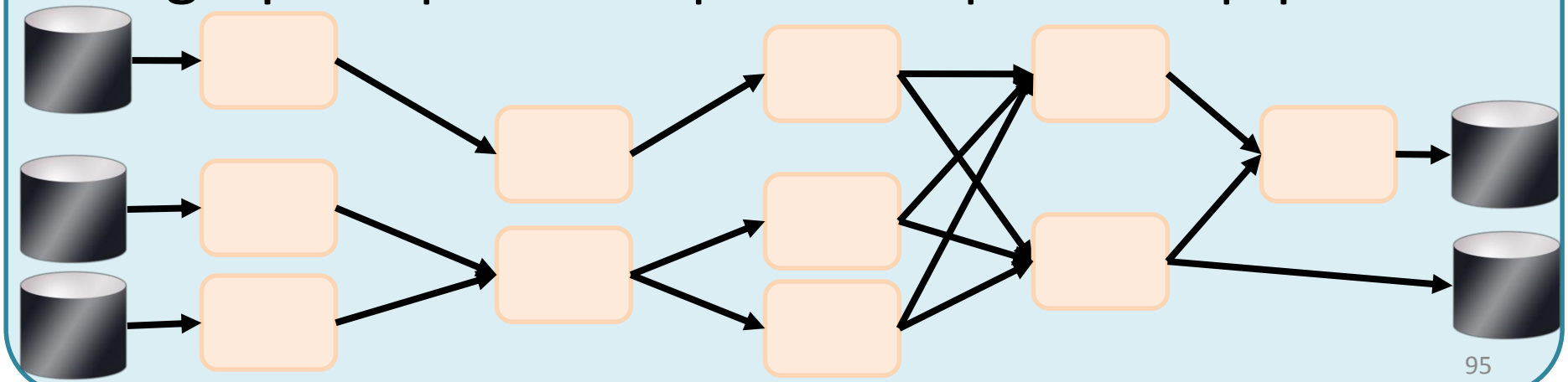
2-D Piping

- Unix Pipes: 1-D

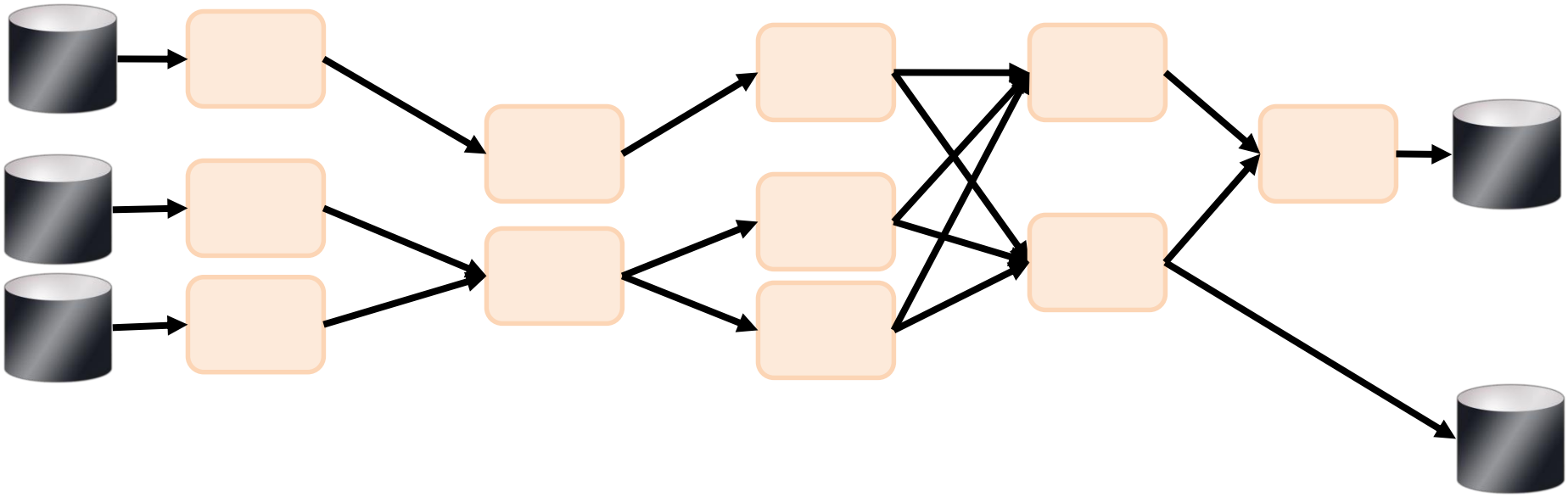
grep | sed | sort | awk | perl

- Dryad: 2-D

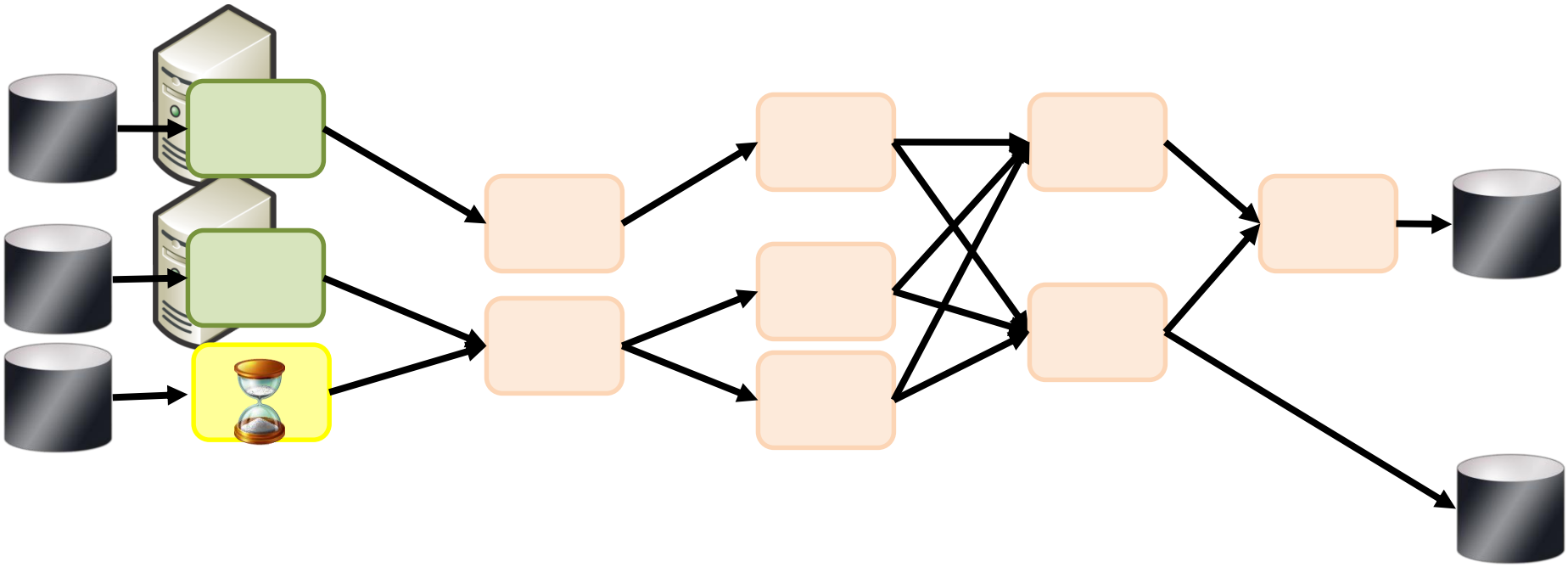
grep^{1000} | sed^{500} | sort^{1000} | awk^{500} | perl^{50}



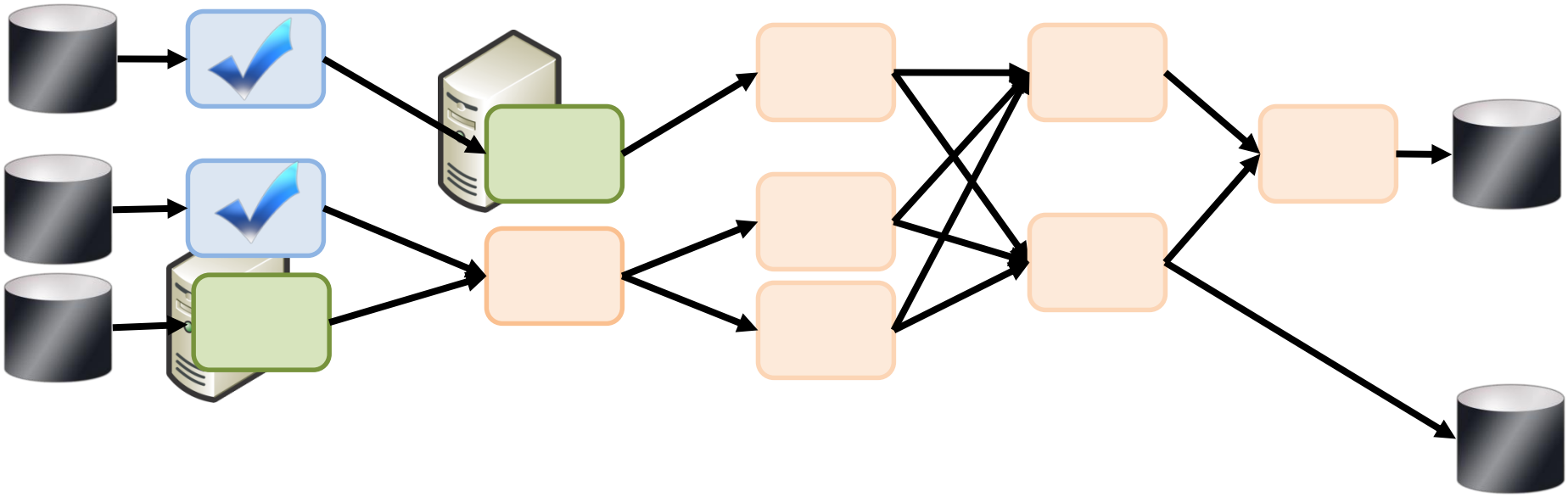
Virtualized 2-D Pipelines



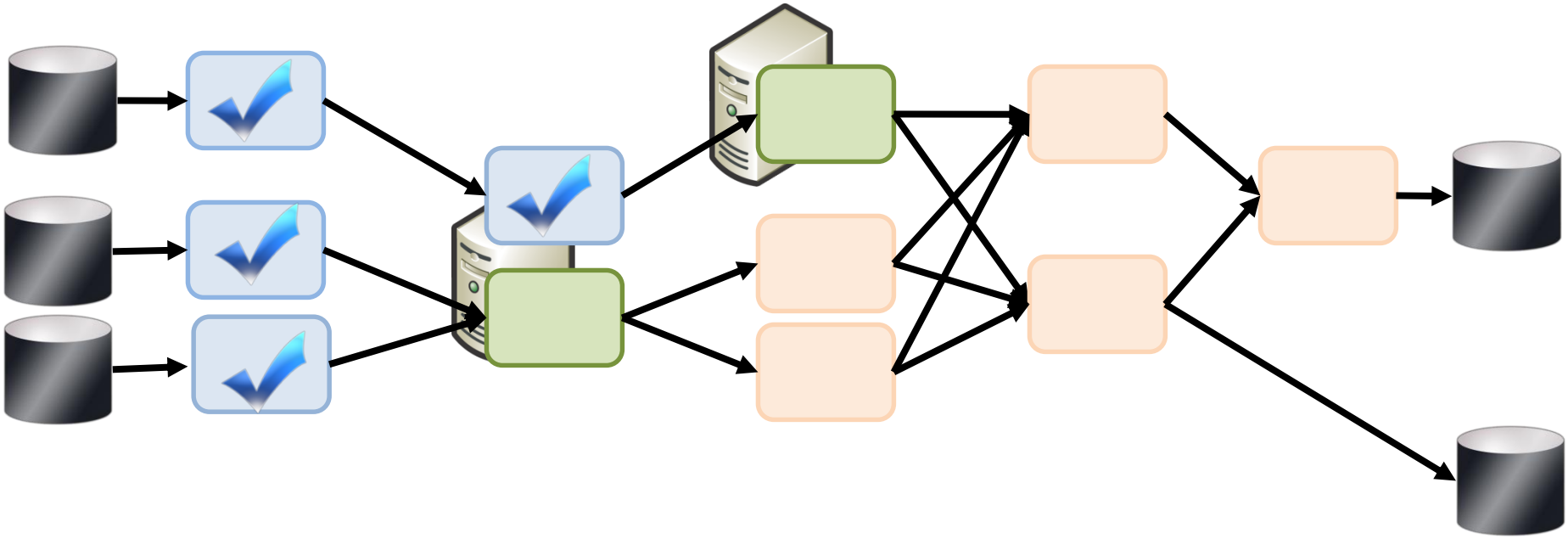
Virtualized 2-D Pipelines



Virtualized 2-D Pipelines

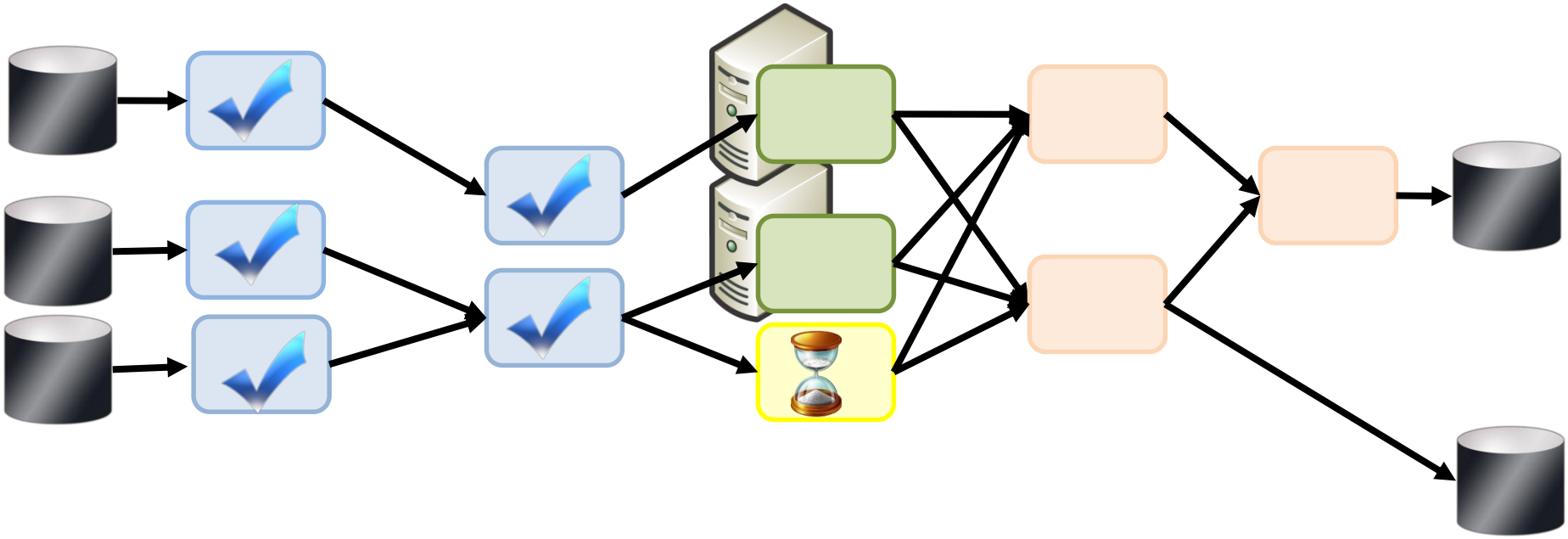


Virtualized 2-D Pipelines

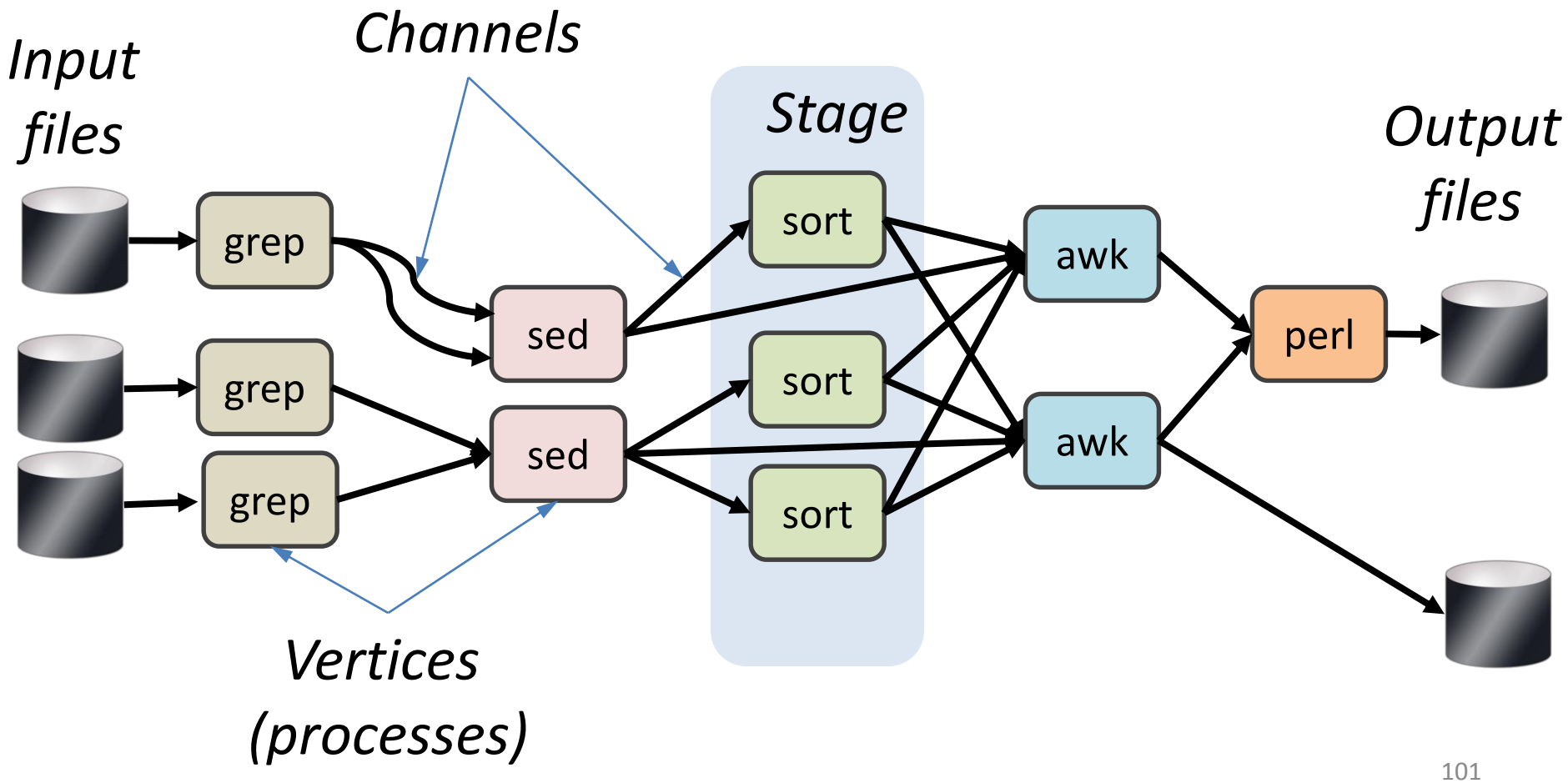


Virtualized 2-D Pipelines

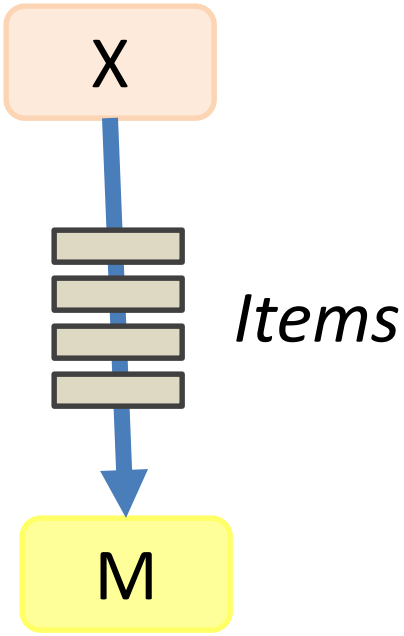
- 2D DAG
- multi-machine
- virtualized



Dryad Job Structure



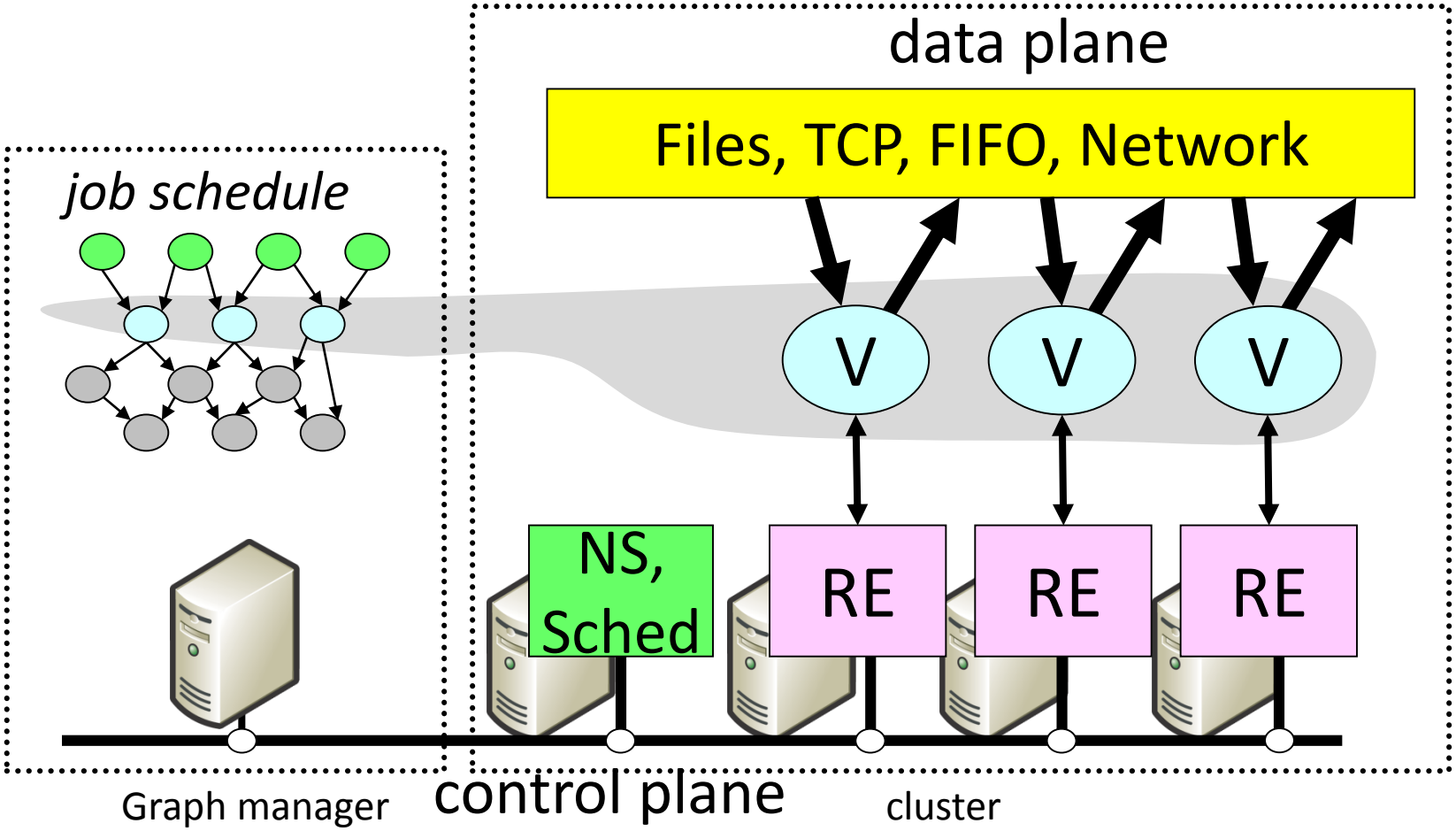
Channels



Finite streams of items

- files
- TCP pipes
- memory FIFOs

Dryad System Architecture



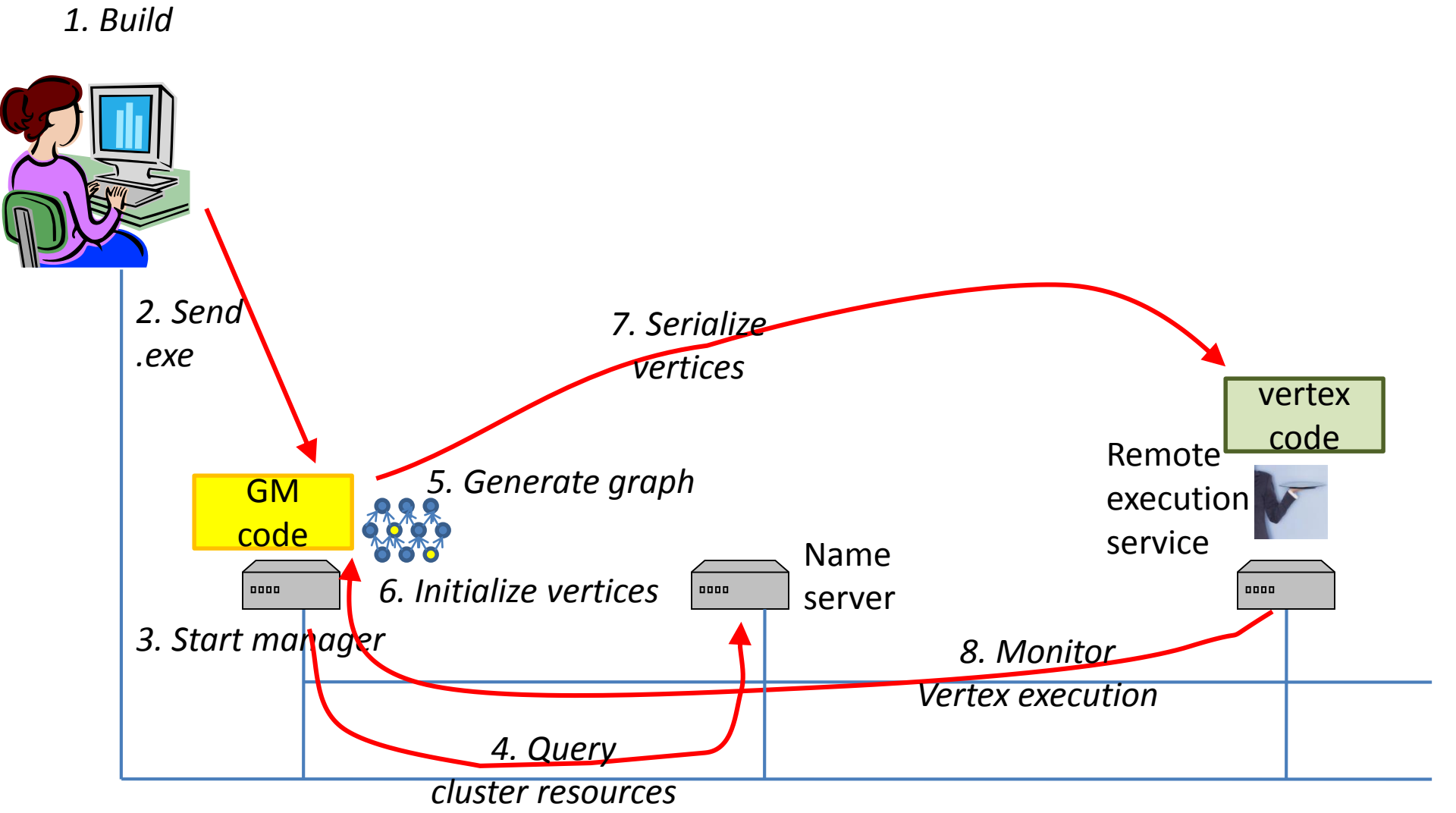
Separate Data and Control Plane

- Different kinds of traffic
  - Data = bulk, pipelined
  - Control = interactive
- Different reliability needs

Centralized control

- Manager state is not replicated
- Entire manager state is held in RAM
- Simple implementation
- Vertices use leases:
  no runaway computations on manager crash
- Manager crash causes complete job crash

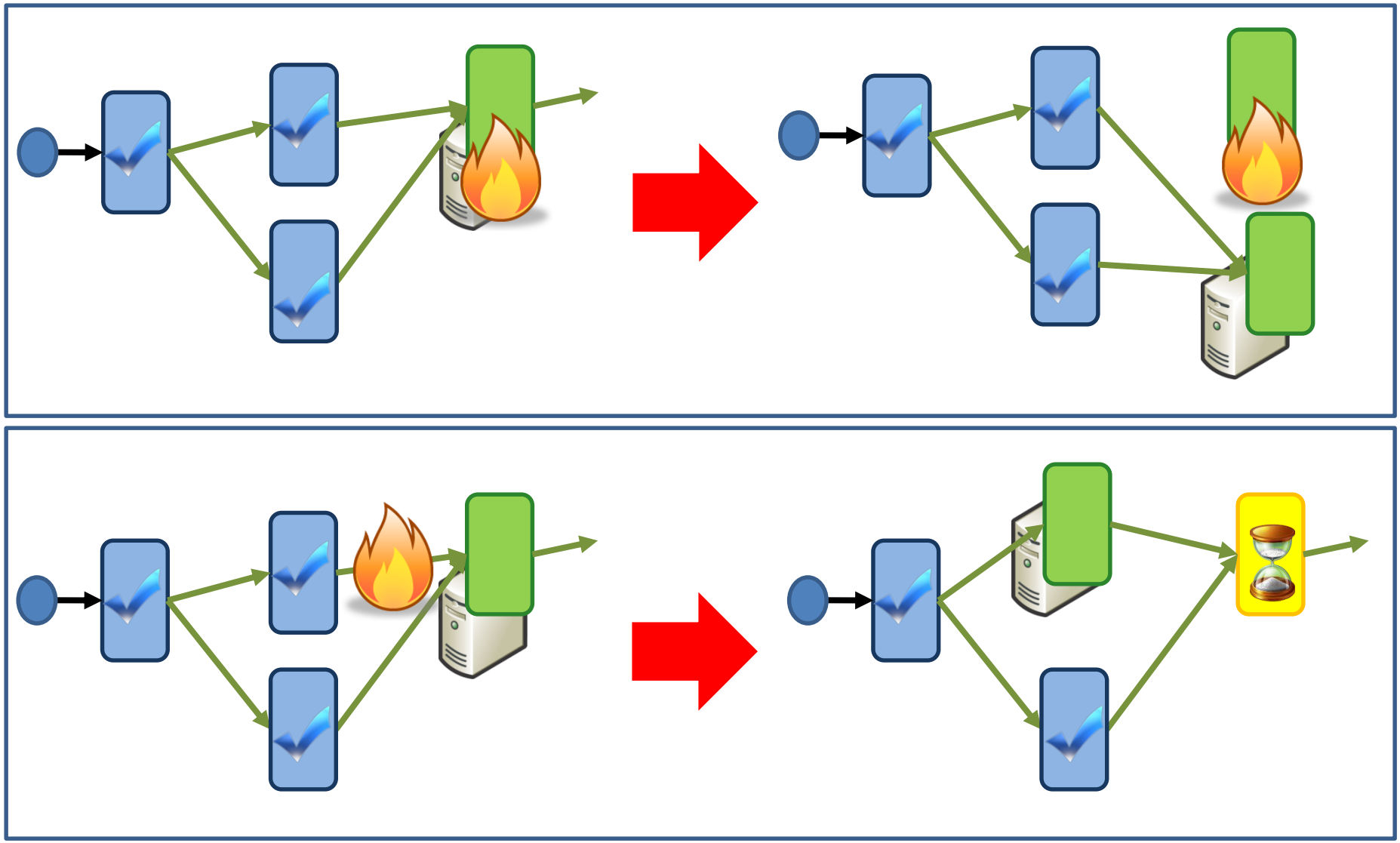
Staging


1. Build
2. Send .exe
7. Serialize vertices
vertex code
Remote execution service
GM code
5. Generate graph
Name server
6. Initialize vertices
3. Start manager
8. Monitor Vertex execution
4. Query cluster resources

Scaling Factors

- Understand how fast things scale
  - # machines << # vertices << # channels
  - # control bytes << # data bytes
- Understand the algorithm cost
  - O(# machines^2) acceptable, but O(# edges^2) not
- Every order-of-magnitude increase will reveal new bugs

Fault Tolerance



Danger of Fault Tolerance

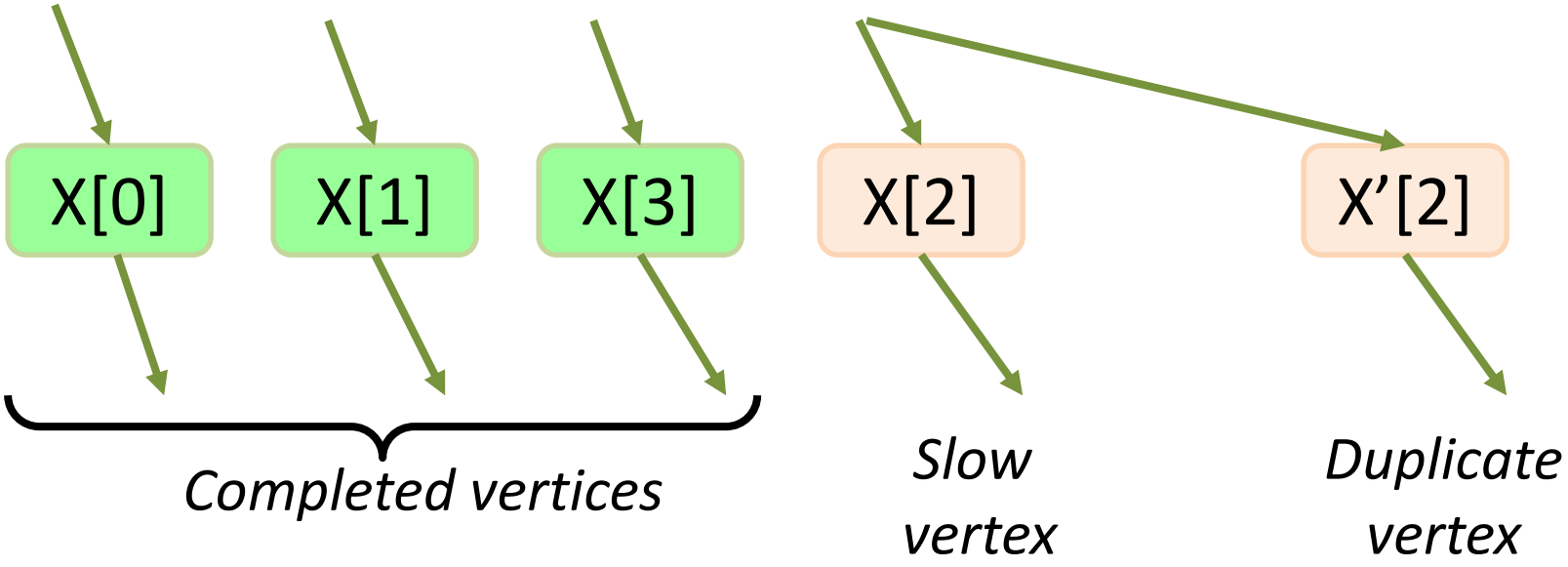
- Fault tolerance can mask defects in other software layers
- Log fault repairs
- Review the logs periodically

Failures

- Fail-stop (crash) failures are easiest to handle
- Many other kinds of failures possible
  - Very slow progress
  - Byzantine (malicious) failures
  - Network partitions

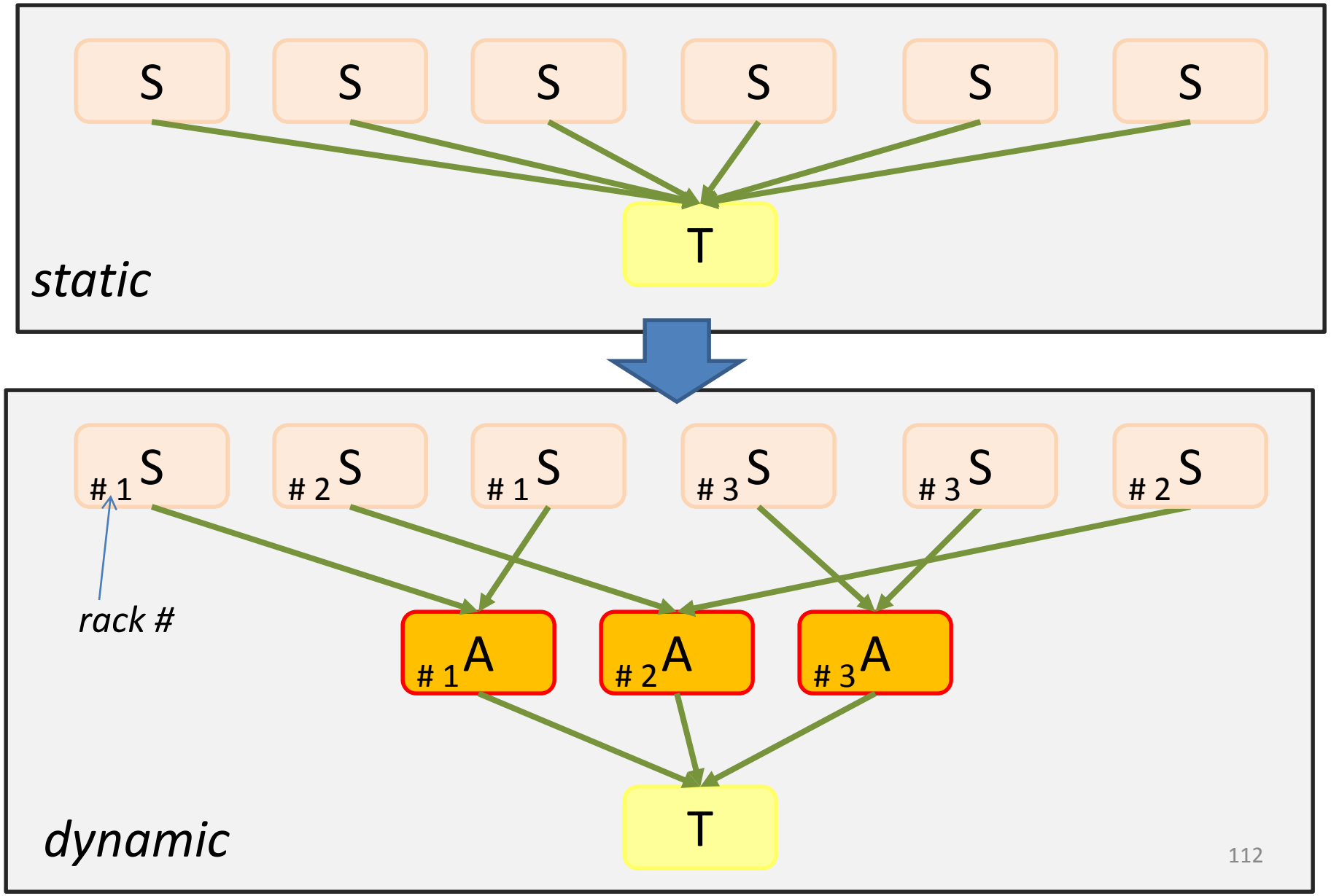
- Understand the failure model for your system
  - probability of each kind of failure
  - validate the failure model (measurements)

Dynamic Graph Rewriting



Duplication Policy = f(running times, data volumes)

Dynamic Aggregation



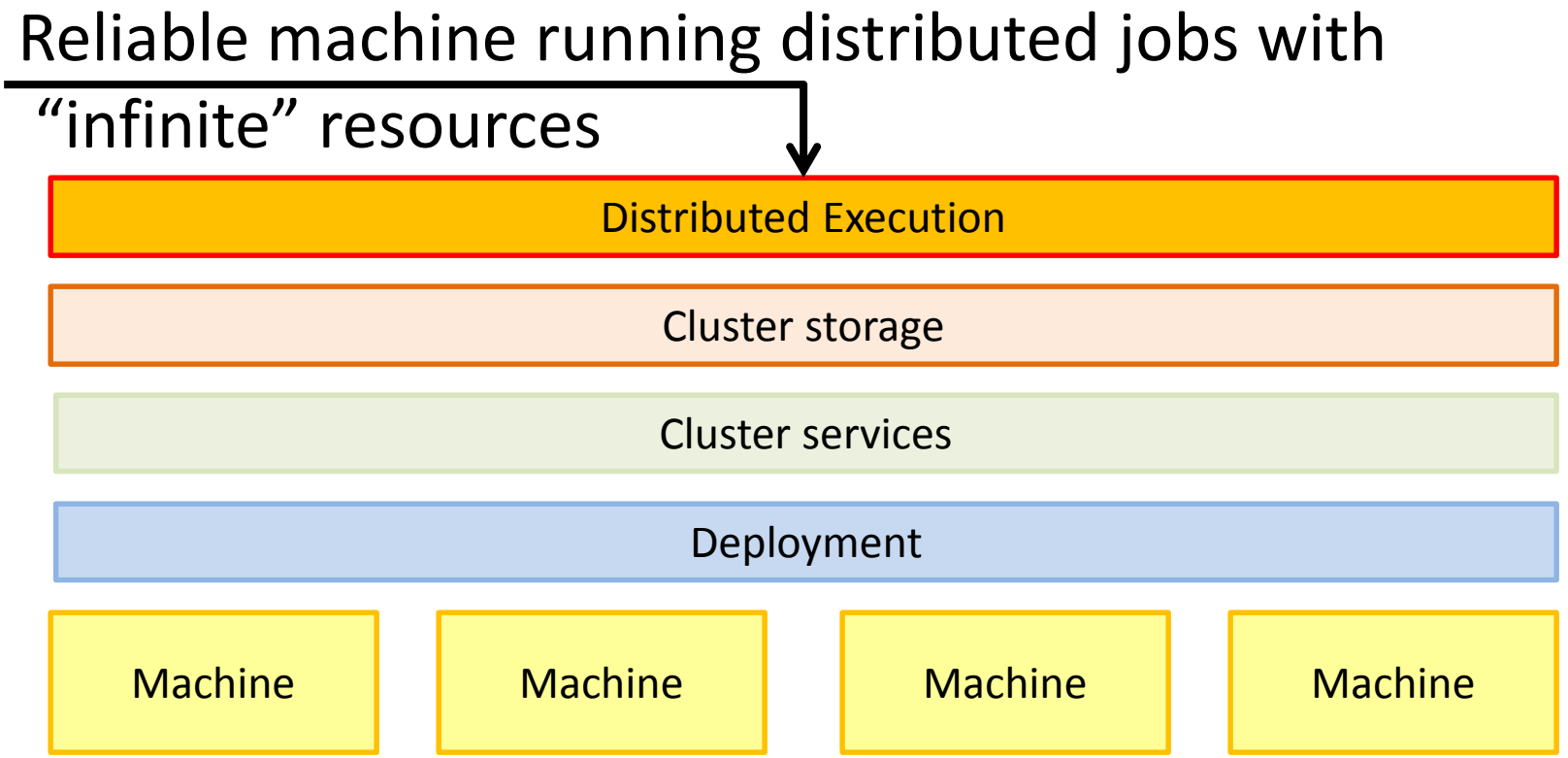
Separate policy and mechanism

- Implement a powerful and generic mechanism
- Leave policy to the application layer
- Trade-off in policy language:
  power vs. simplicity

Policy vs. Mechanism

- Application-level
- Most complex in C++ code
- Invoked with upcalls
- Need good default implementations
- DryadLINQ provides a comprehensive set
- Built-in
  - Scheduling
  - Graph rewriting
  - Fault tolerance
  - Statistics and reporting

Dryad Abstraction



Thinking in Parallel

Computing

HUMAN COMPUTERS AT NACA DRYDEN (NASA) 1930s

Definition of computer (n)

bing.com · Bing Dictionary

com·put·er [kəm pyo͞otər]

1. electronic data processor: an electronic device that accepts, processes, stores, and outputs data at high speeds according to programmed instructions
2. somebody who computes: somebody who calculates numbers or amounts using a machine

Synonyms: processor, CPU, mainframe, supercomputer, workstation, PC, laptop, notebook, palmtop

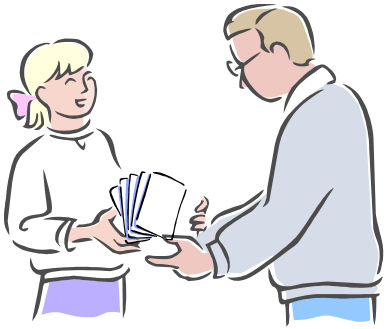
Image from: http://www.dayvectors.net/g2012m02.html

Logistics

= input data

+

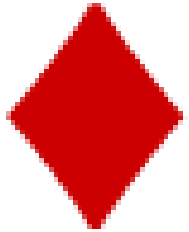
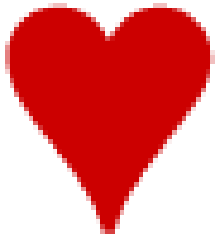
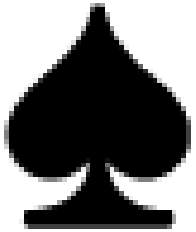
= output data



= communication is expensive

Playing Cards

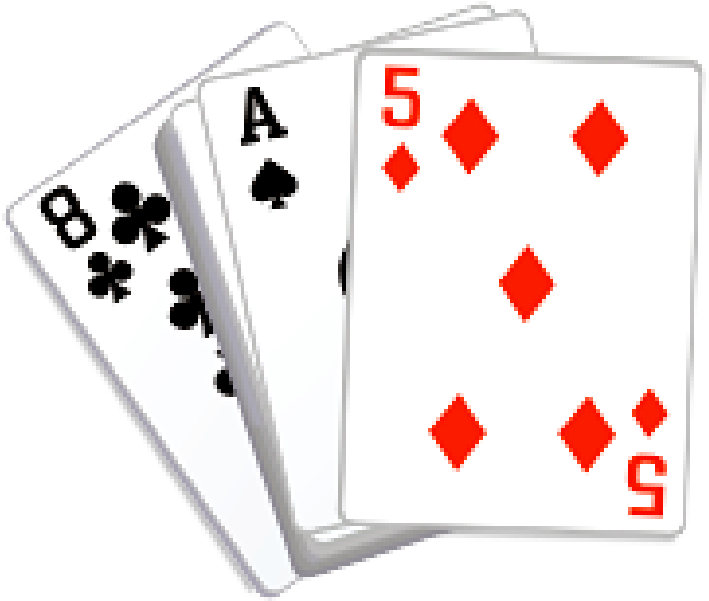
suits

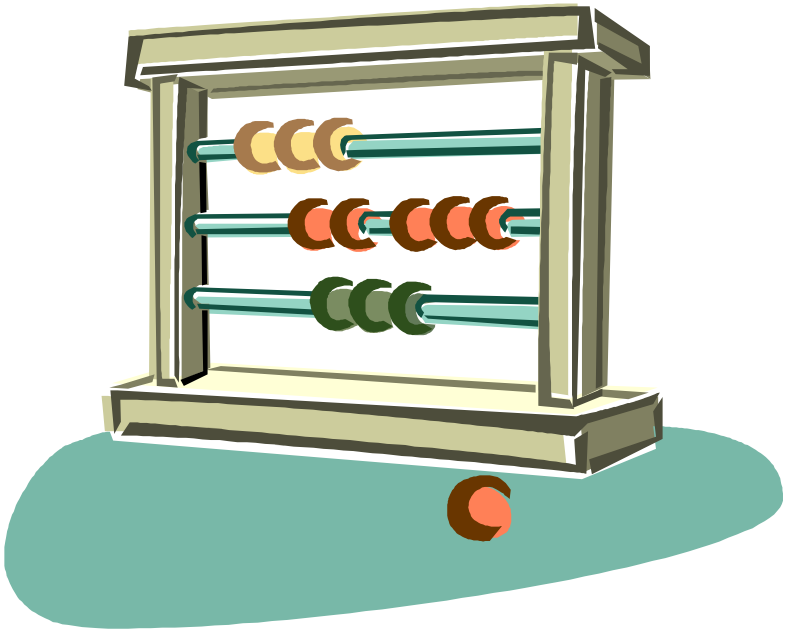






Clubs Diamonds Hearts Spades

2,3,4,5,6,7,8,9,10,J,Q,K,A our order

Count the number of cards



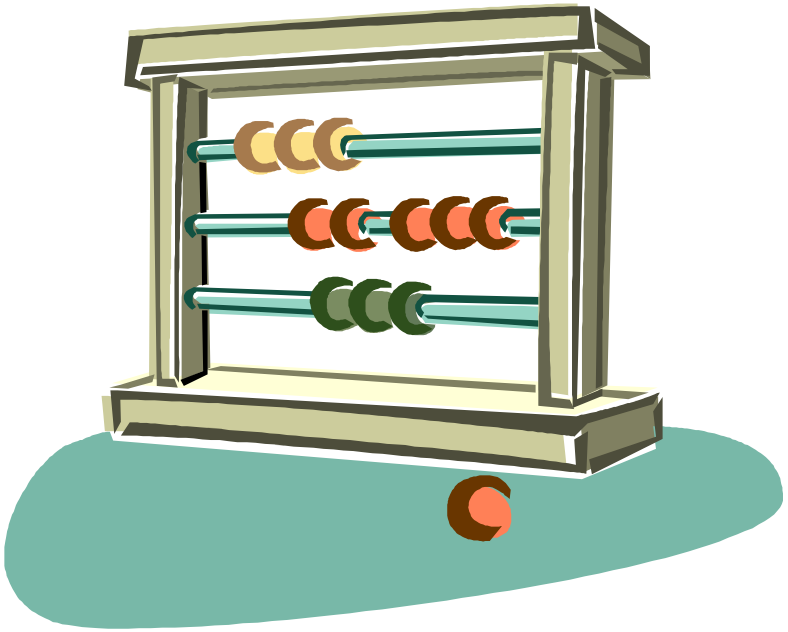


Counting, or aggregation

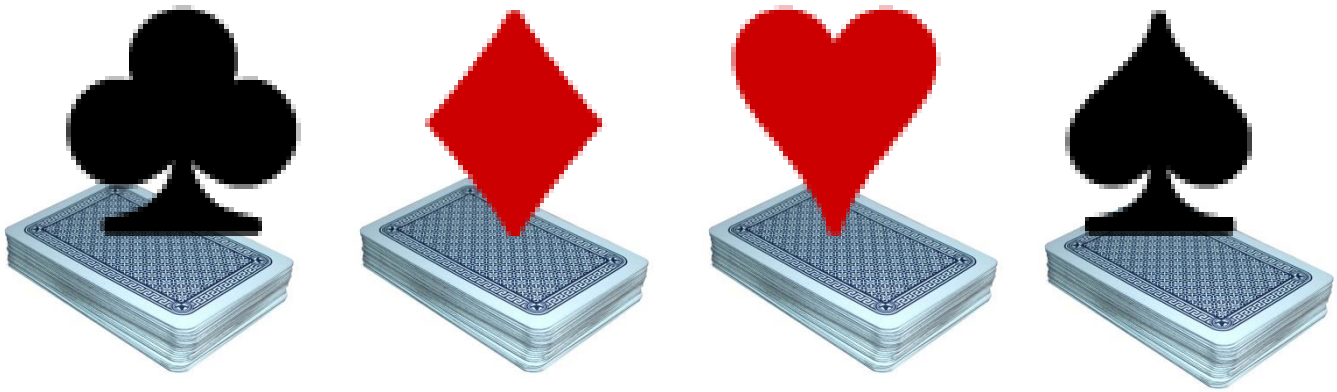
Keep only the even cards

Filter

Count the Number of Figures



Group cards by suit

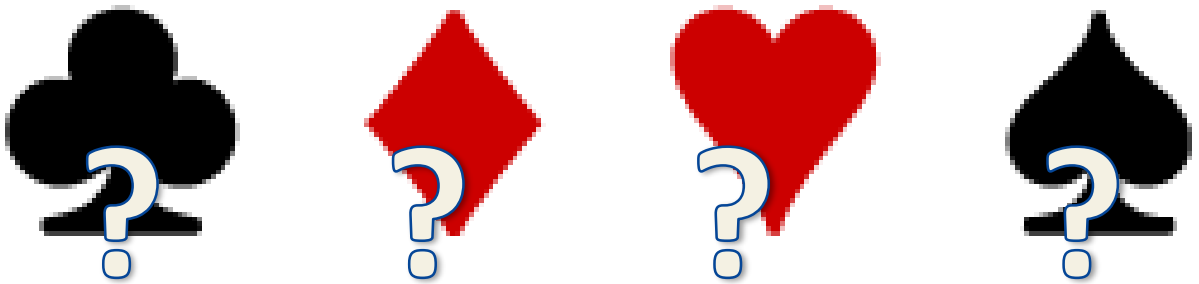


Which cards are missing?

2,3,4,5,6,7,8,9,10,J,Q,K,A

GroupBy-Aggregate = Histogram

Number of cards of each suit

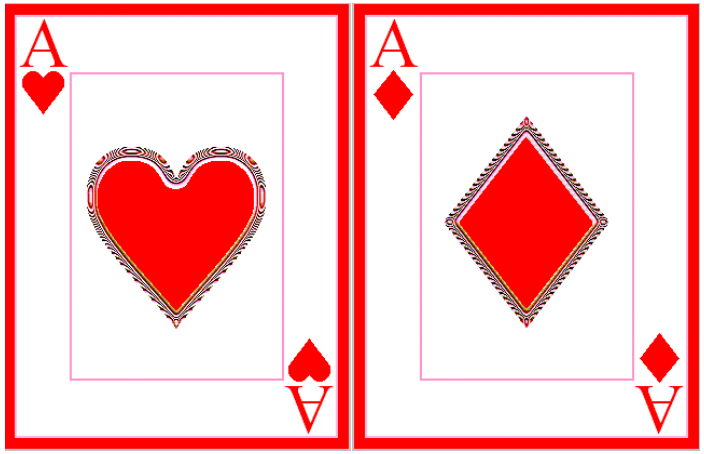


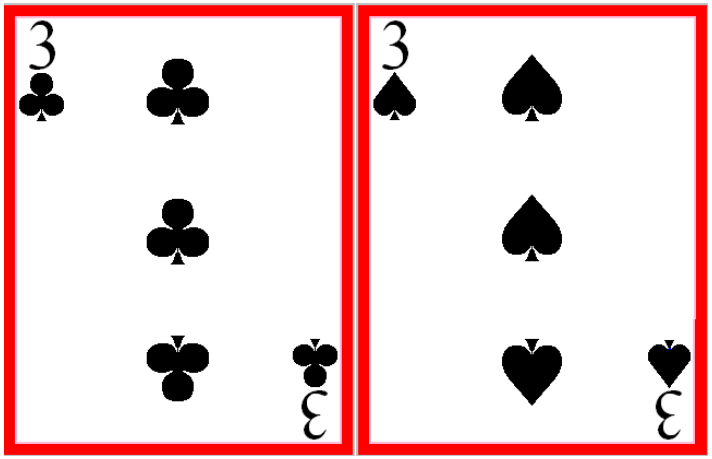
Sort the cards

2,3,4,5,6,7,8,9,10,J,Q,K,A

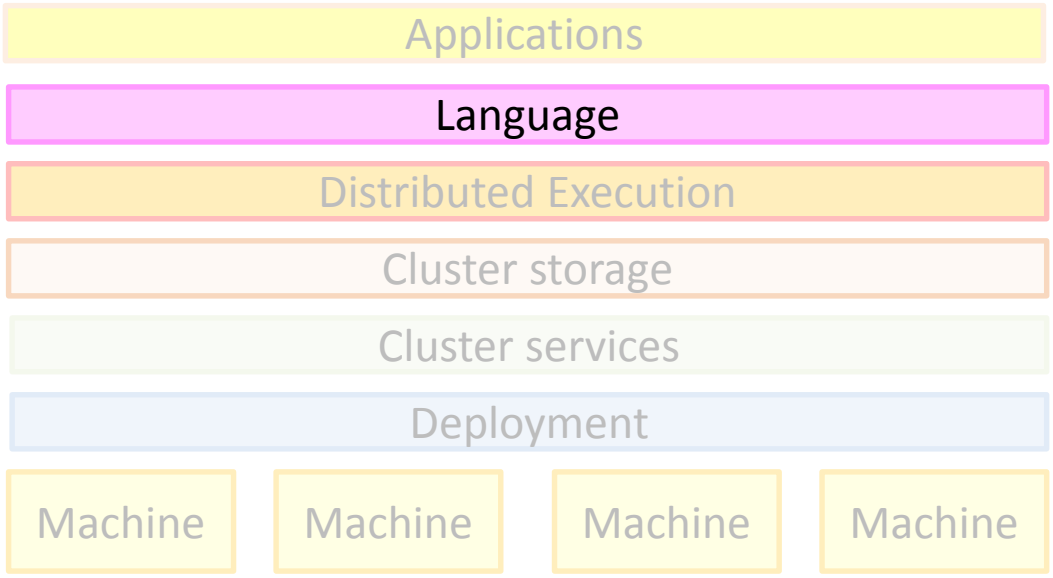
lexicographic order

Cards with same color & number



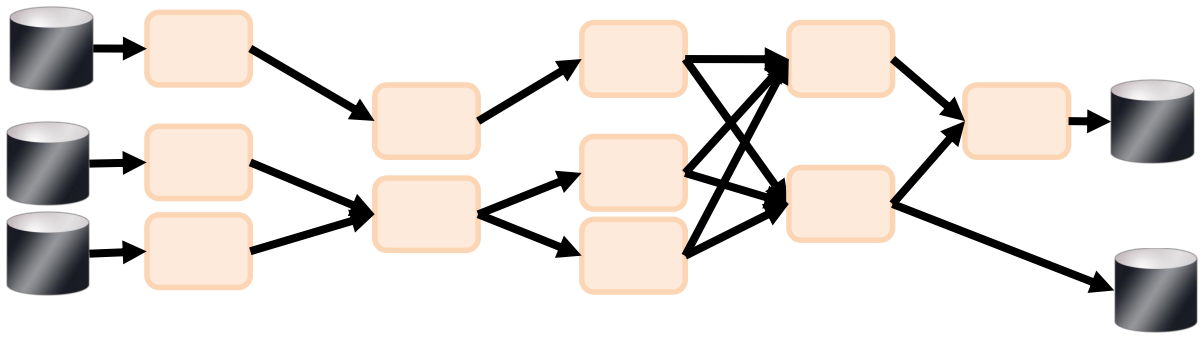


Join

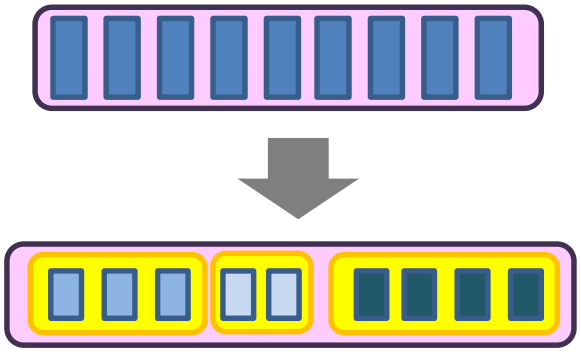

Applications
Language
Distributed Execution
Cluster storage
Cluster services
Deployment
Machine
Machine
Machine
Machine

DRYADLINQ

DryadLINQ = Dryad + LINQ

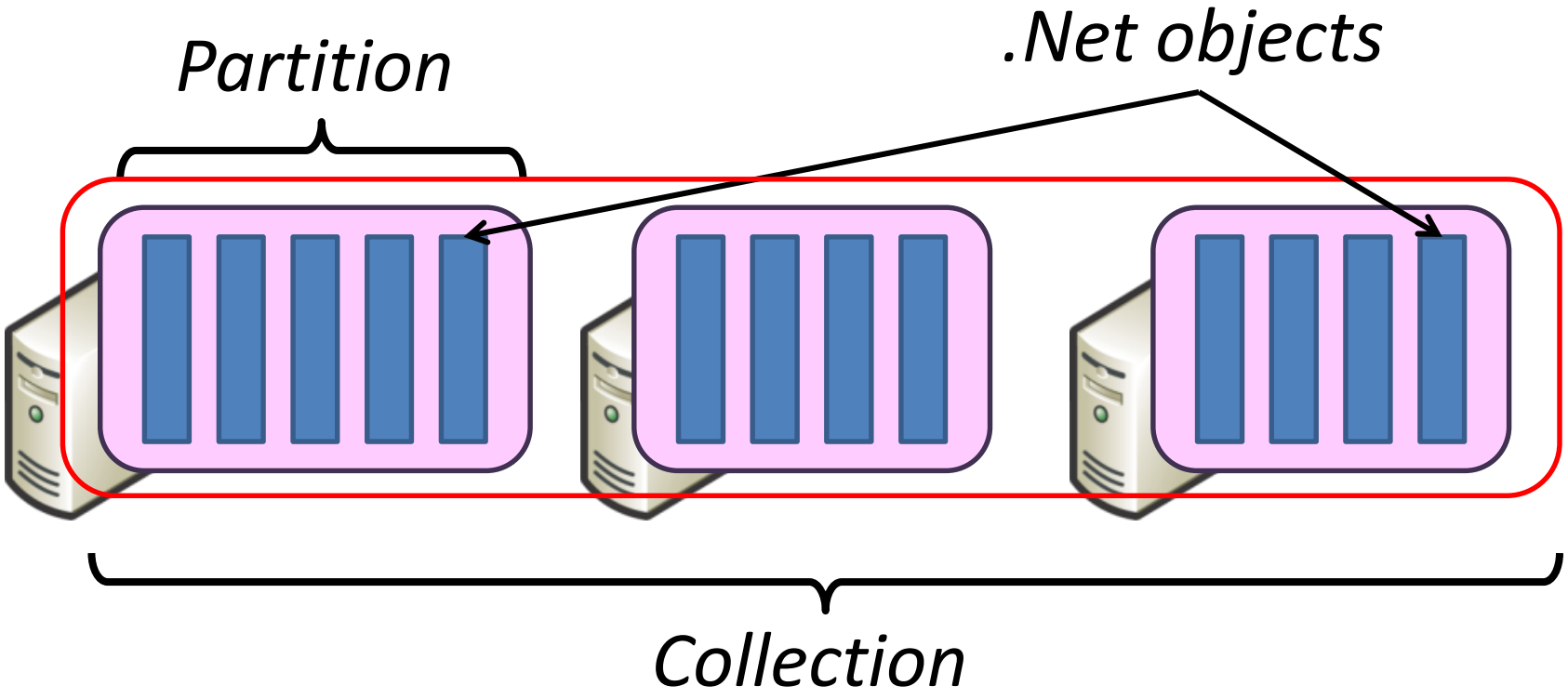


Distributed computations

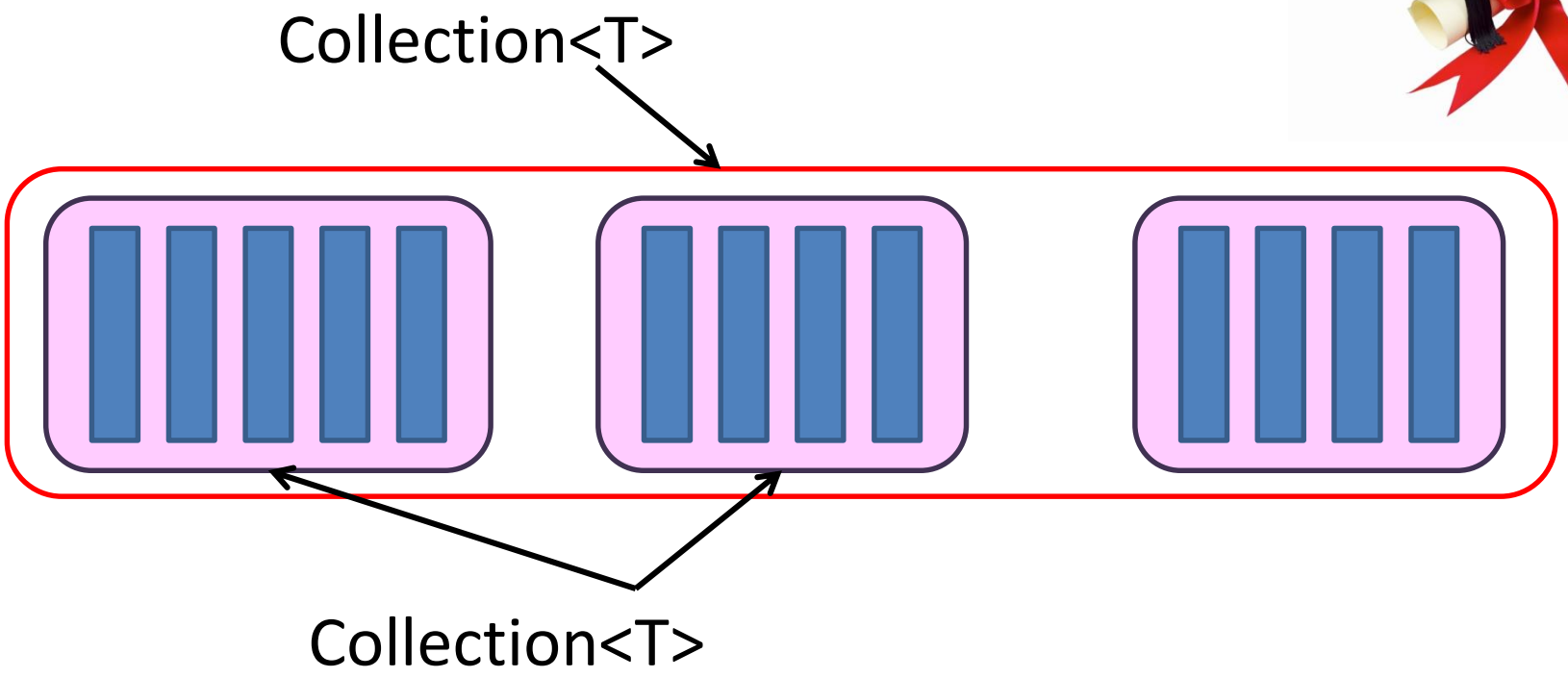


Computations on collections

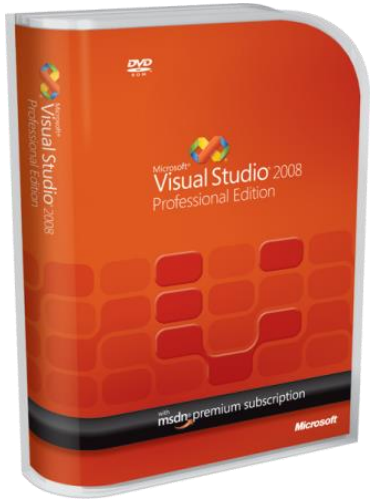
Distributed Collections



Collection = Collection of Collections

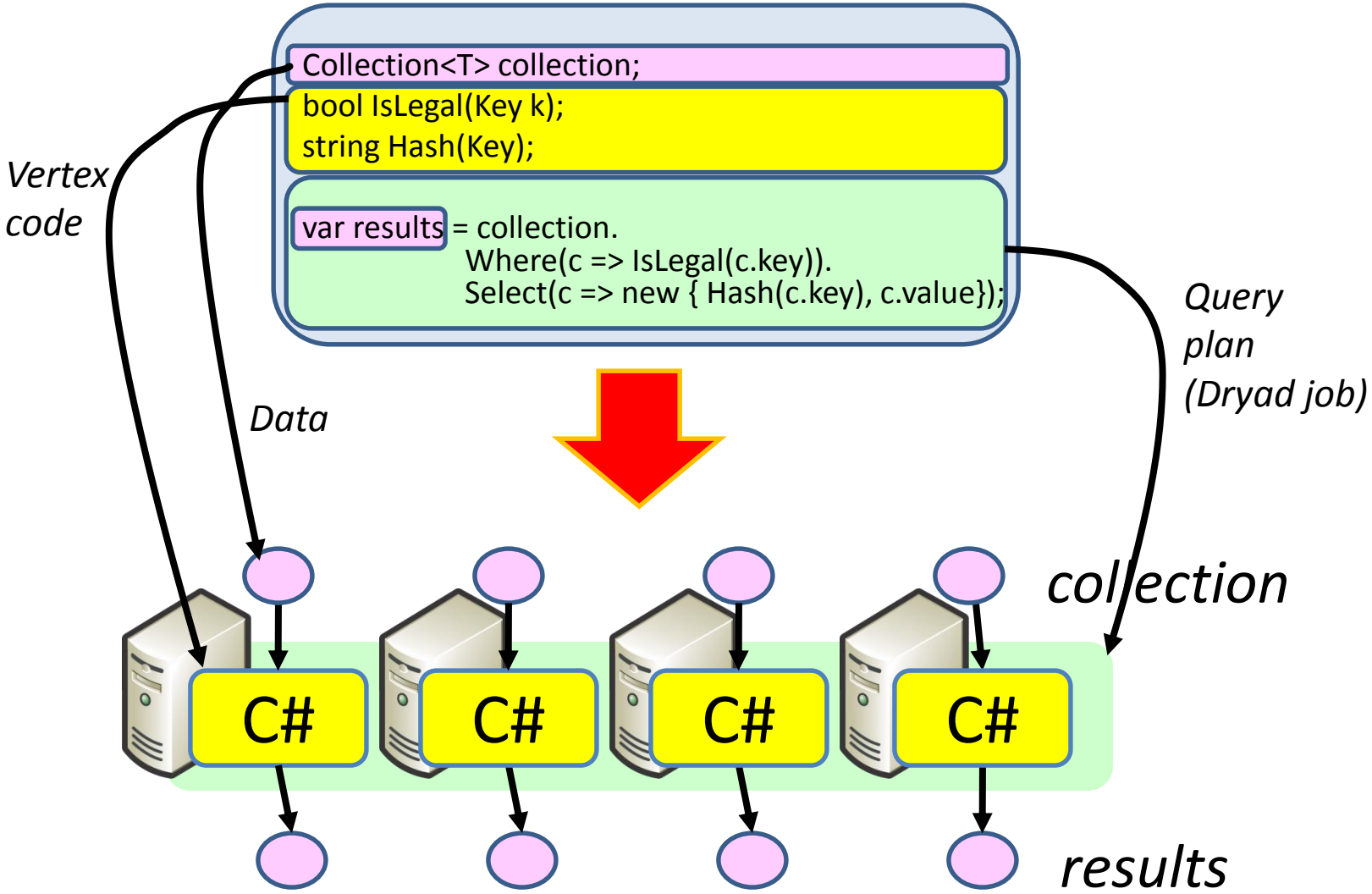


LINQ => DryadLINQ



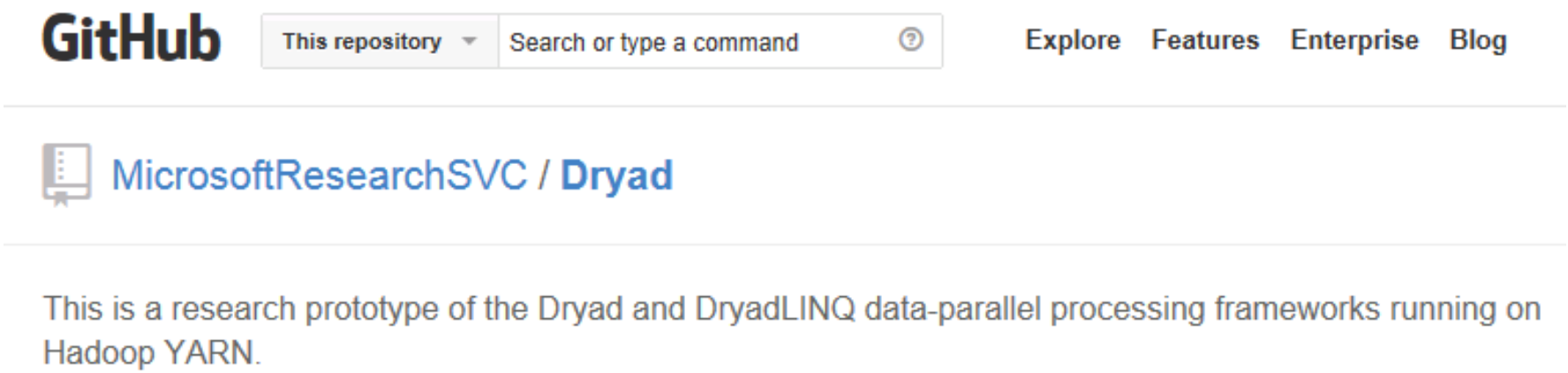
Dryad

DryadLINQ = LINQ + Dryad

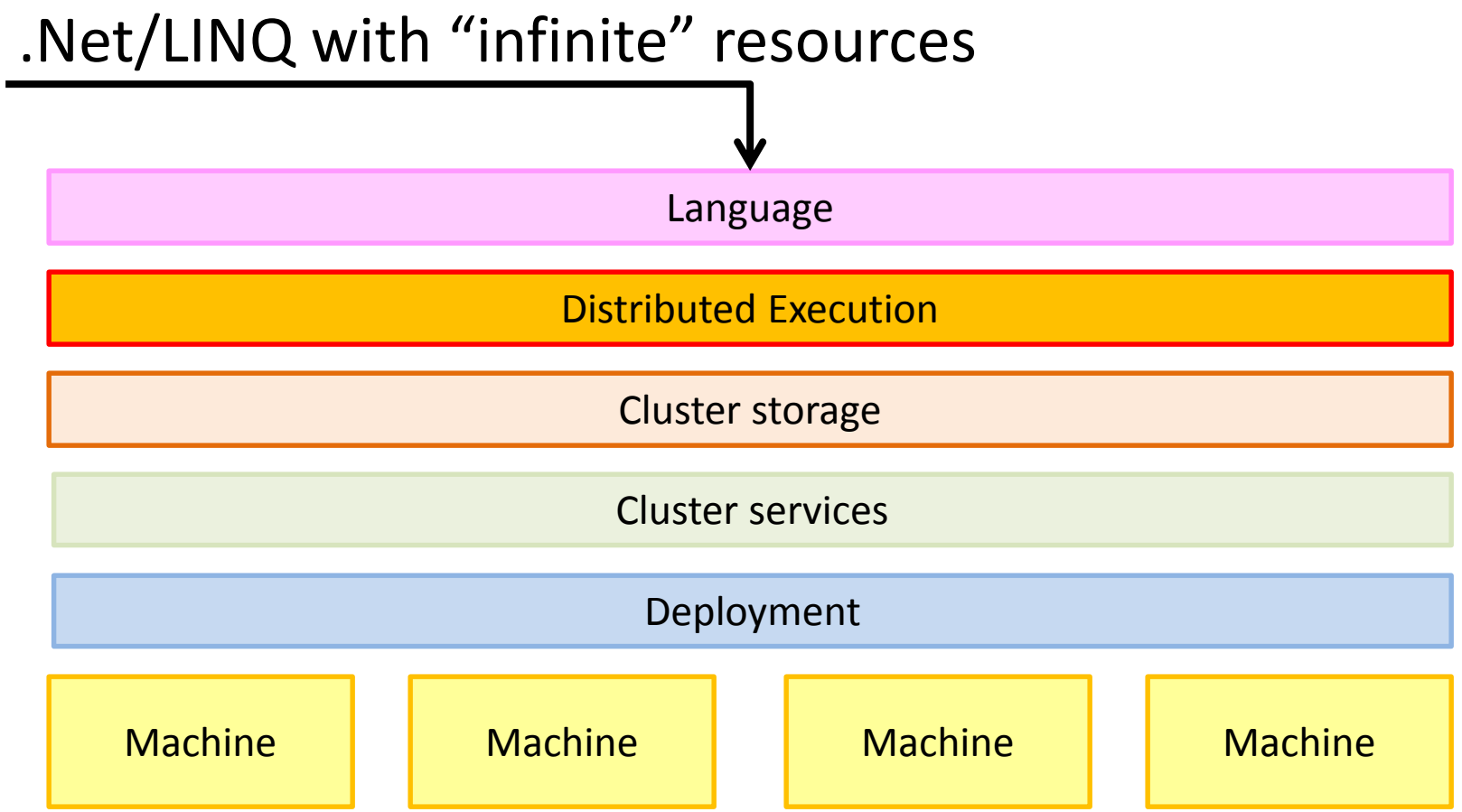


DryadLINQ source code

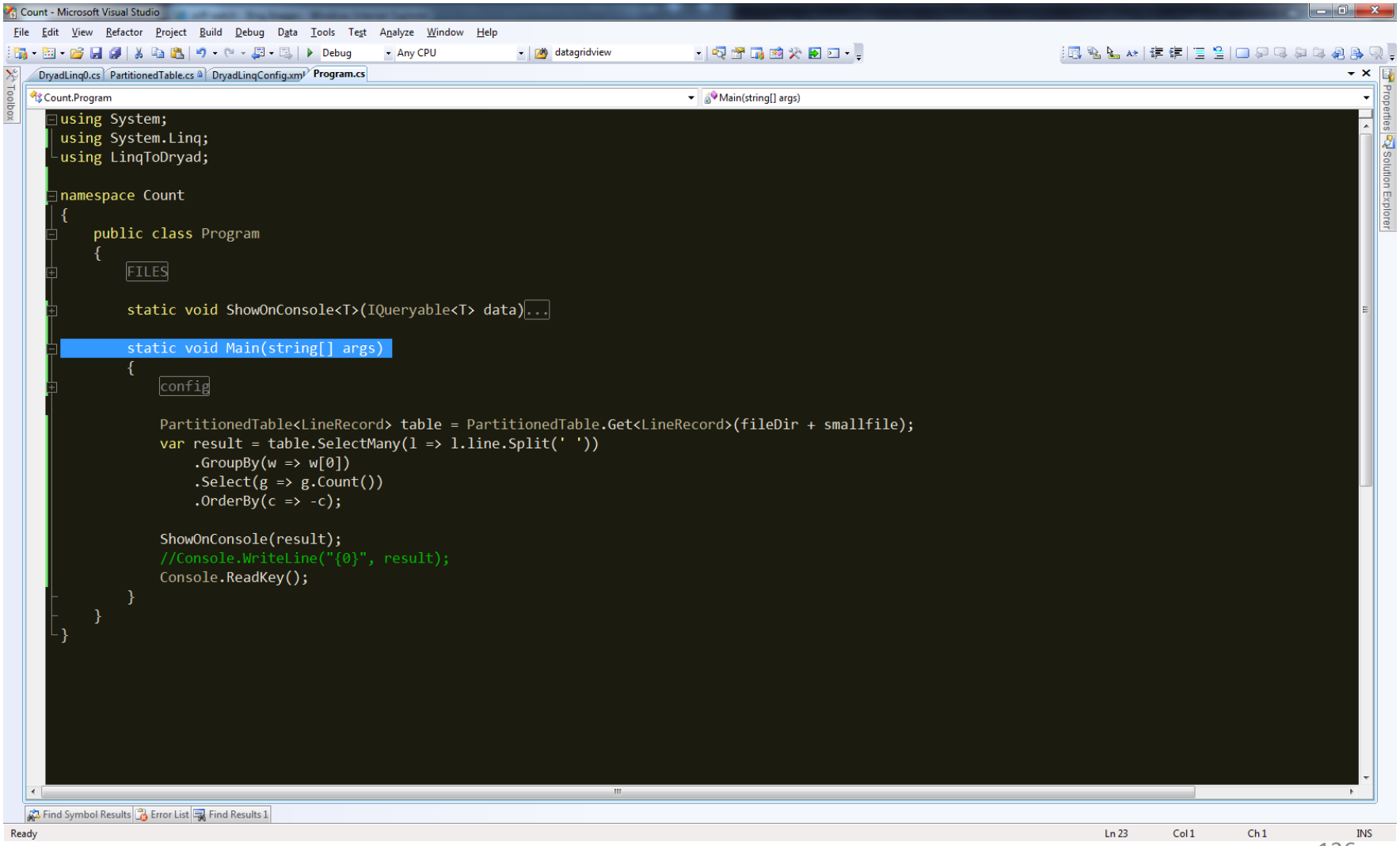
- https://github.com/MicrosoftResearchSVC/Dryad
- Apache license
- Runs on Hadoop YARN
- Research prototype code quality



DryadLINQ Abstraction

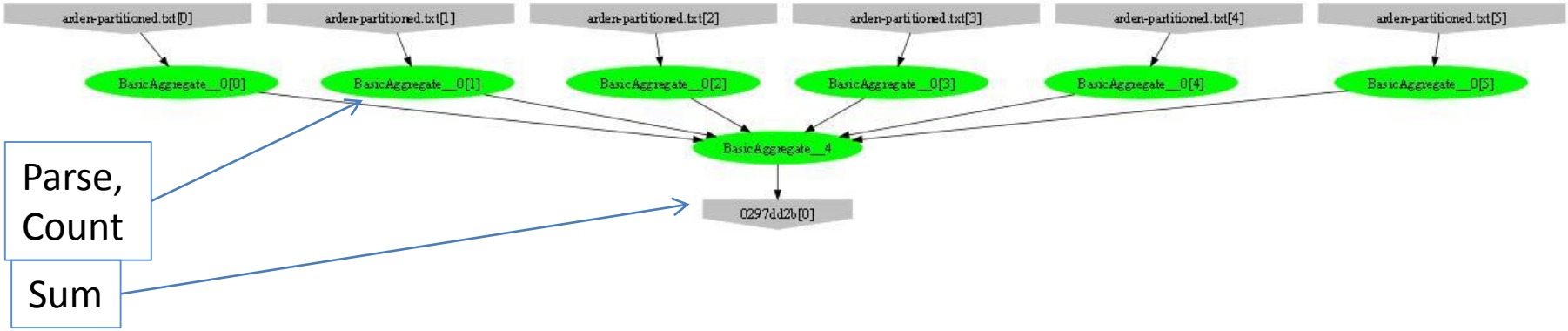


Demo


Count - Microsoft Visual Studio
File Edit View Refactor Project Build Debug Data Tools Test Analyze Window Help
Debug
Any CPU
datagridview
DryadLinq0.cs
PartitionedTable.cs
DryadLinqConfig.xml
Program.cs
Count.Program
Main(string[] args)
using System;
using System.Linq;
using LinqToDryad;
namespace Count
{
public class Program
{
FILES
static void ShowOnConsole<T>(IQueryable<T> data)...
static void Main(string[] args)
{
config
PartitionedTable<LineRecord> table = PartitionedTable.Get<LineRecord>(fileDir + smallfile);
var result = table.SelectMany(l => l.line.Split(' '))
.GroupBy(w => w[0])
.Select(g => g.Count())
.OrderBy(c => -c);
ShowOnConsole(result);
//Console.WriteLine("{0}", result);
Console.ReadKey();
}
}
}
Find Symbol Results
Error List
Find Results 1
Ready
Ln 23
Col 1
Ch 1
INS

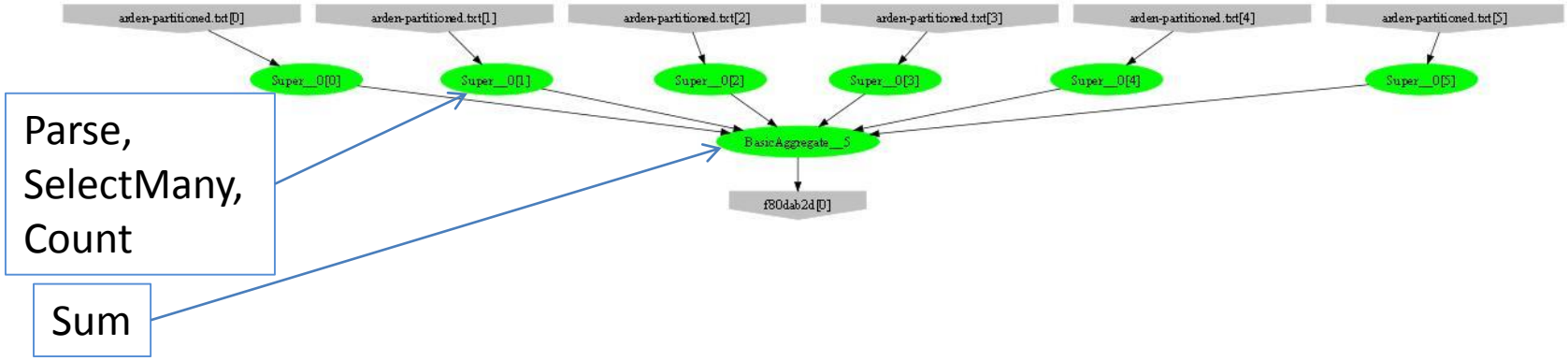
Example: counting lines

```
var table = PartitionedTable.Get<LineRecord>(file);
int count = table.Count();
```



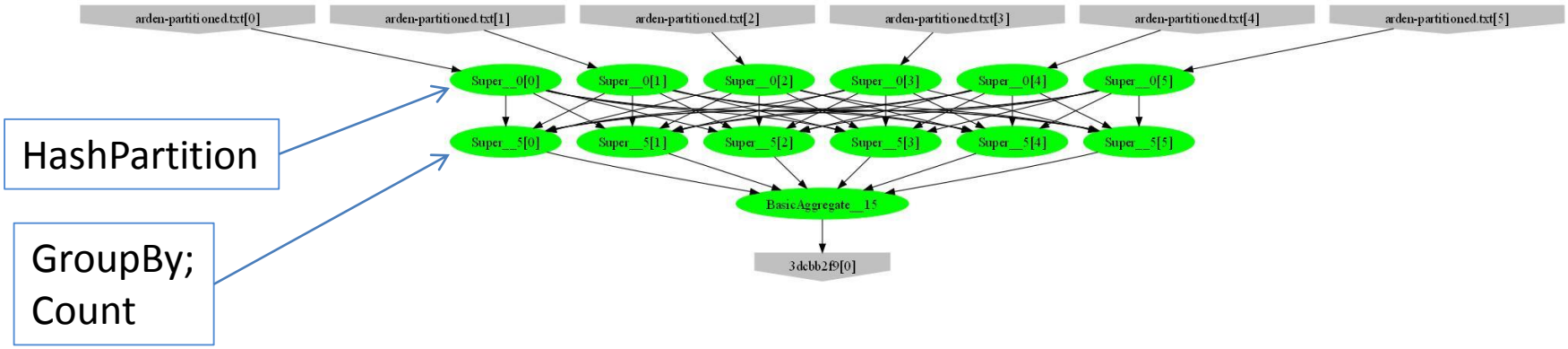
Example: counting words

```
var table = PartitionedTable.Get<LineRecord>(file);
int count = table
        .SelectMany(l => l.line.Split(' '))
        .Count();
```



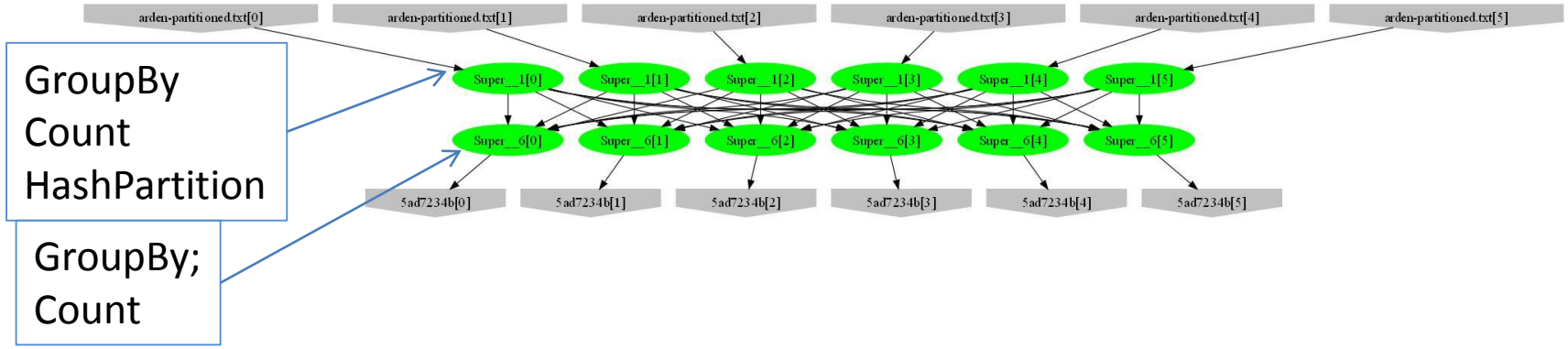
Example: counting unique words

```
var table = PartitionedTable.Get<LineRecord>(file);
int count = table
        .SelectMany(l => l.line.Split(' '))
        .GroupBy(w => w)
        .Count();
```



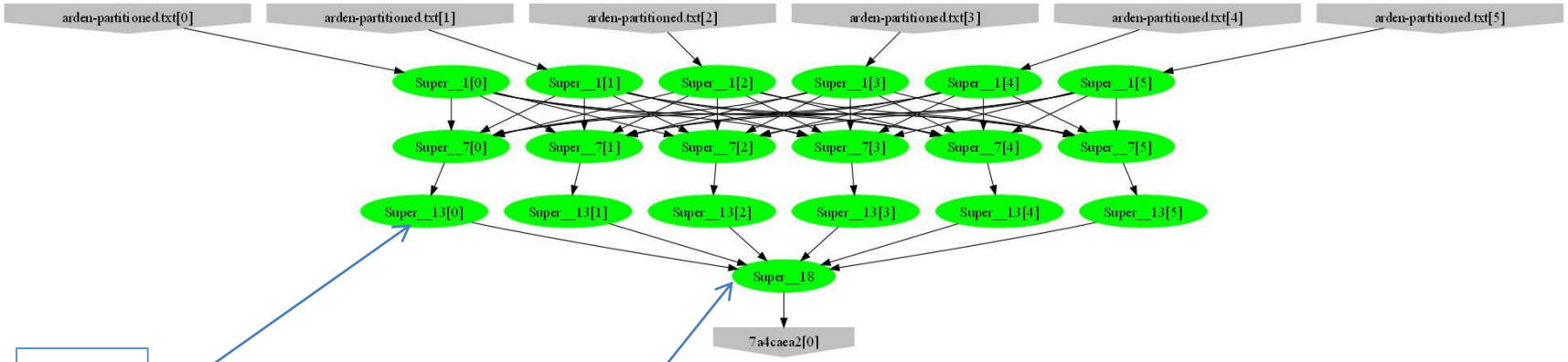
Example: word histogram

```
var table = PartitionedTable.Get<LineRecord>(file);
var result = table.SelectMany(l => l.line.Split(' '))
                  .GroupBy(w => w)
                  .Select(g => new { word = g.Key, count = g.Count() });
```



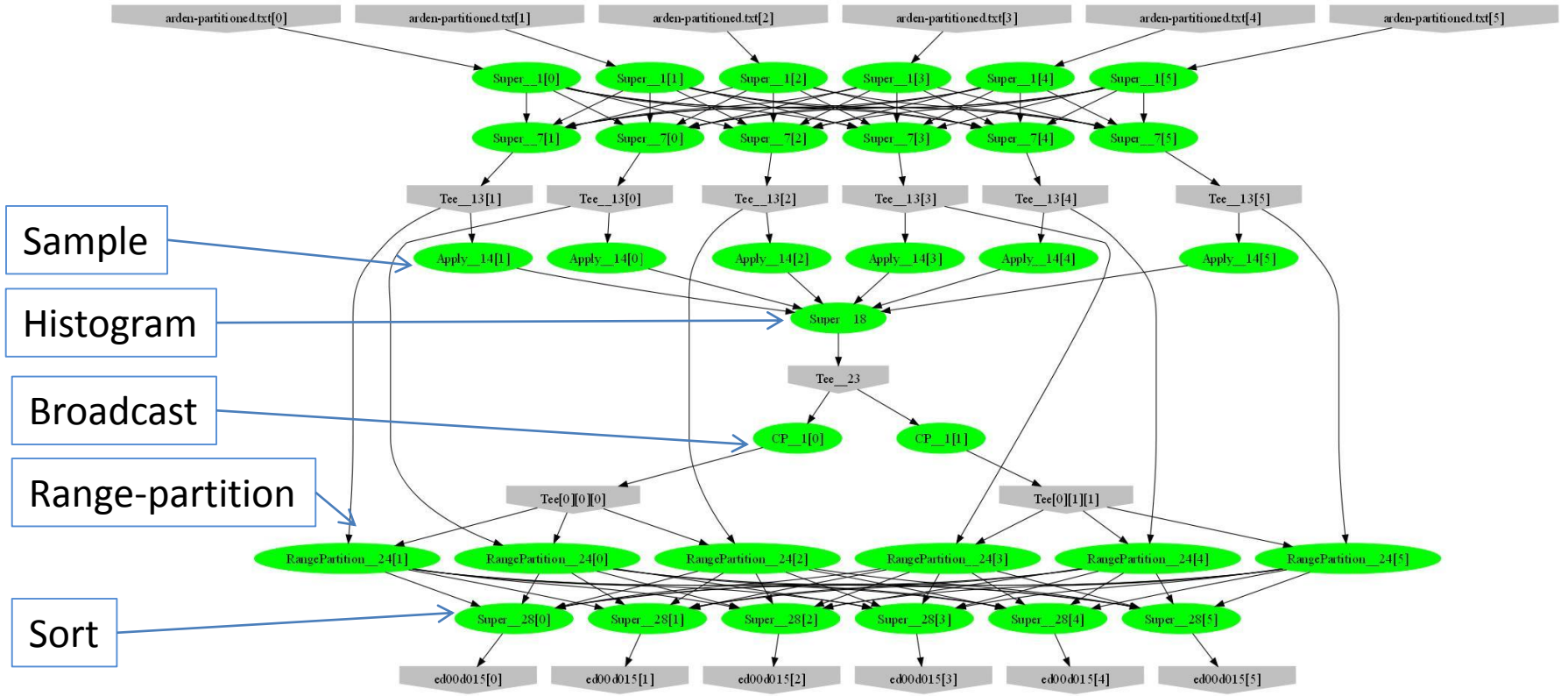
Example: high-frequency words

```
var table = PartitionedTable.Get<LineRecord>(file);
var result = table.SelectMany(l => l.line.Split(' '))
        .GroupBy(w => w)
        .Select(g => new { word = g.Key, count = g.Count() })
        .OrderByDescending(t => t.count)
        .Take(100);
```



Example: words by frequency

```
var table = PartitionedTable.Get<LineRecord>(file);
var result = table.SelectMany(l => l.line.Split(' '))
        .GroupBy(w => w)
        .Select(g => new { word = g.Key, count = g.Count() })
        .OrderByDescending(t => t.count);
```

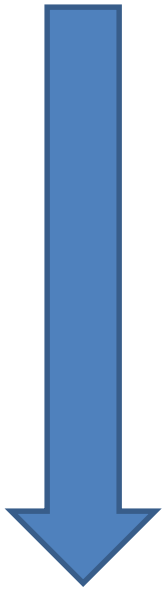


Example: Map-Reduce

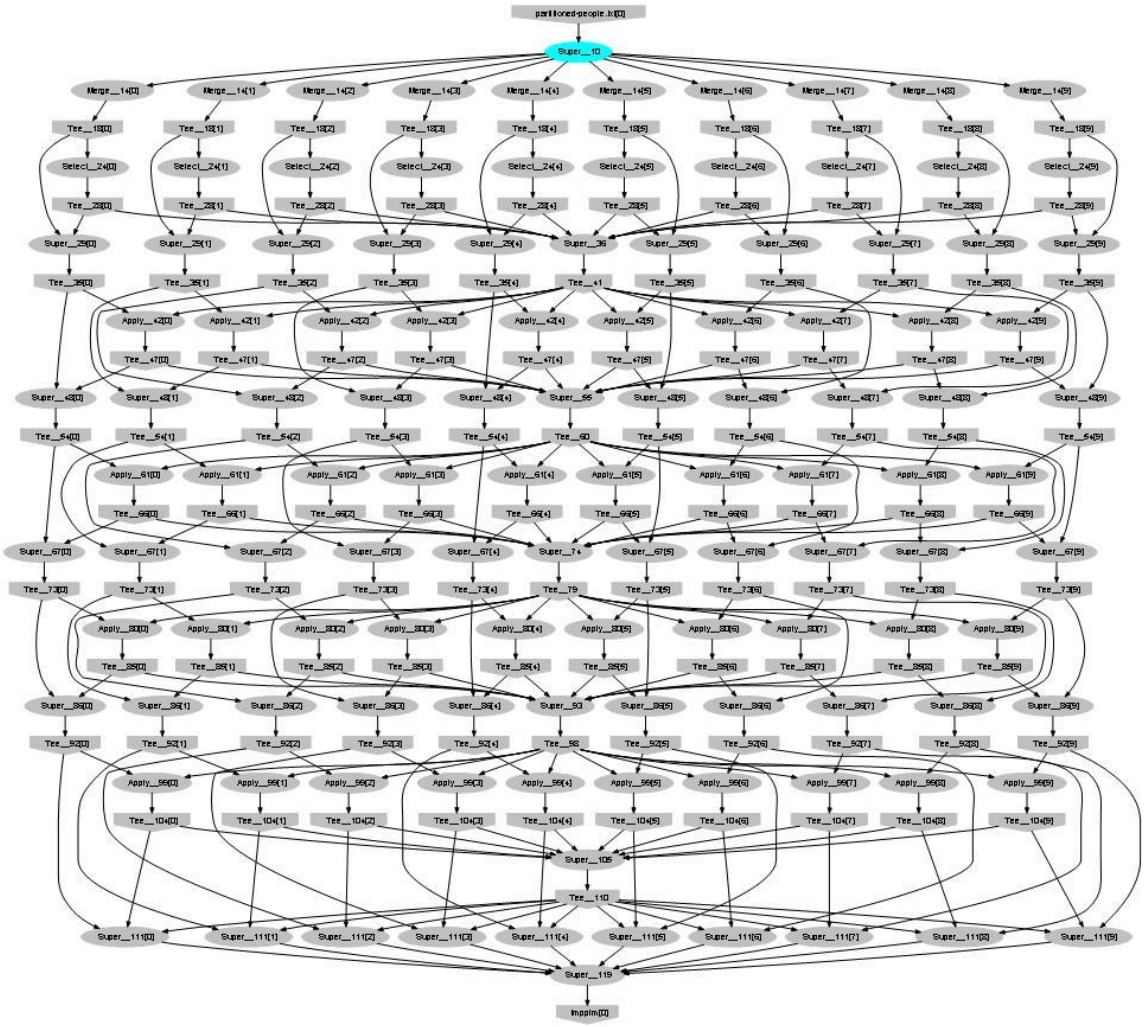
```
public static IQueryable<S>
MapReduce<T,M,K,S>(
        IQueryable<T> input,
        Func<T, IEnumerable<M>> mapper,
        Func<M,K> keySelector,
        Func<IGrouping<K,M>,S> reducer)
{
    var map = input.SelectMany(mapper);
    var group = map.GroupBy(keySelector);
    var result = group.Select(reducer);
    return result;
}
```

Probabilistic Index Maps

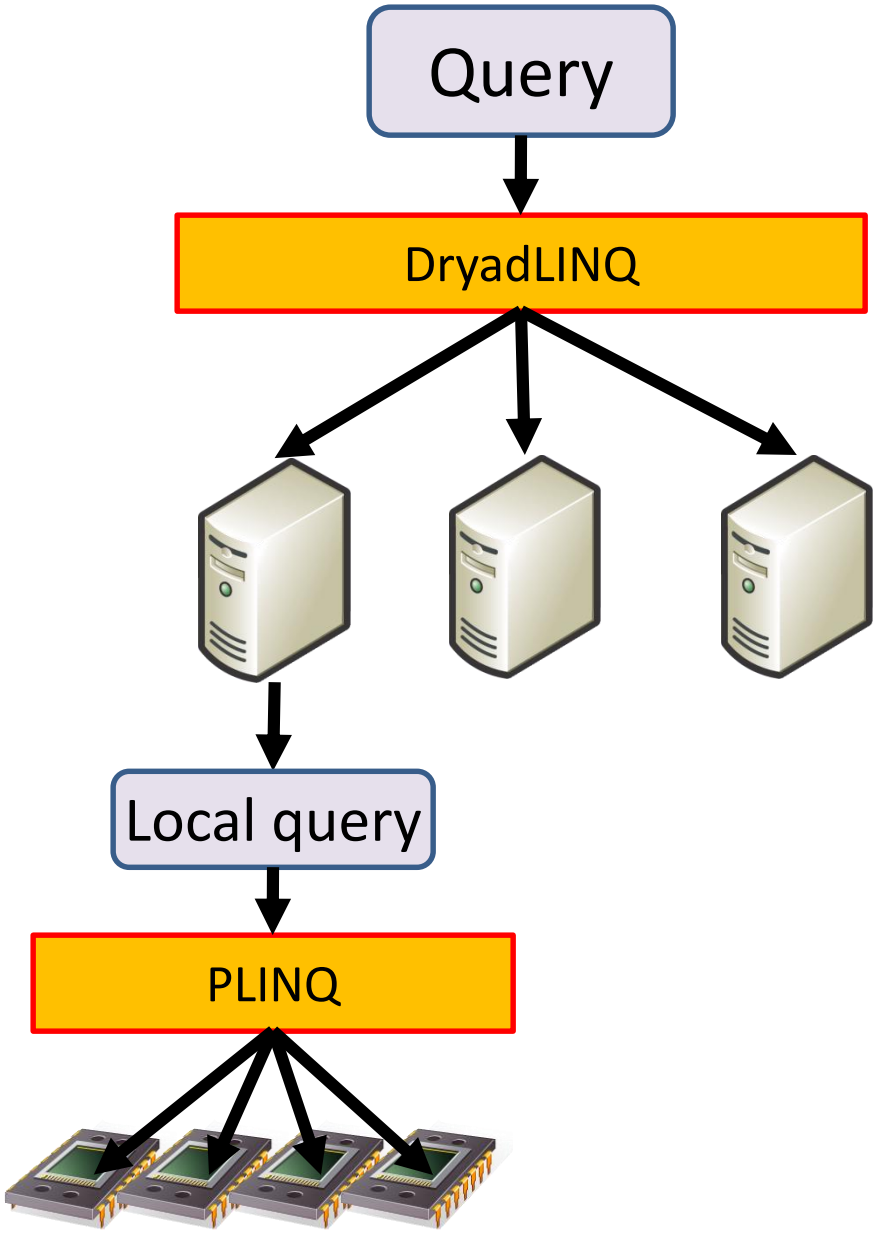
Images

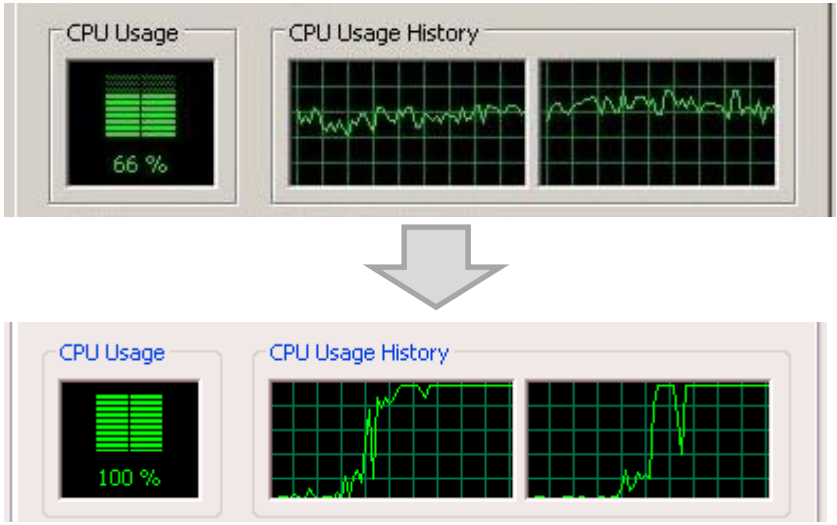


features

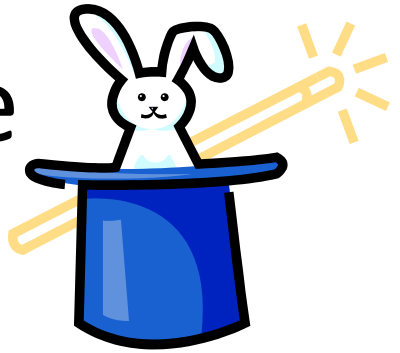


Parallelizing on Cores

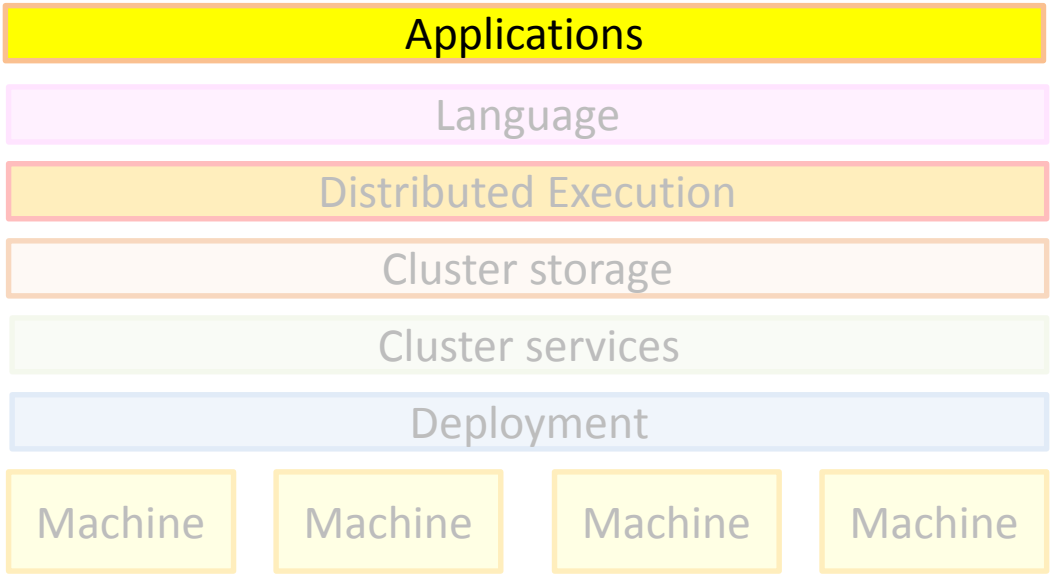




More Tricks of the trade

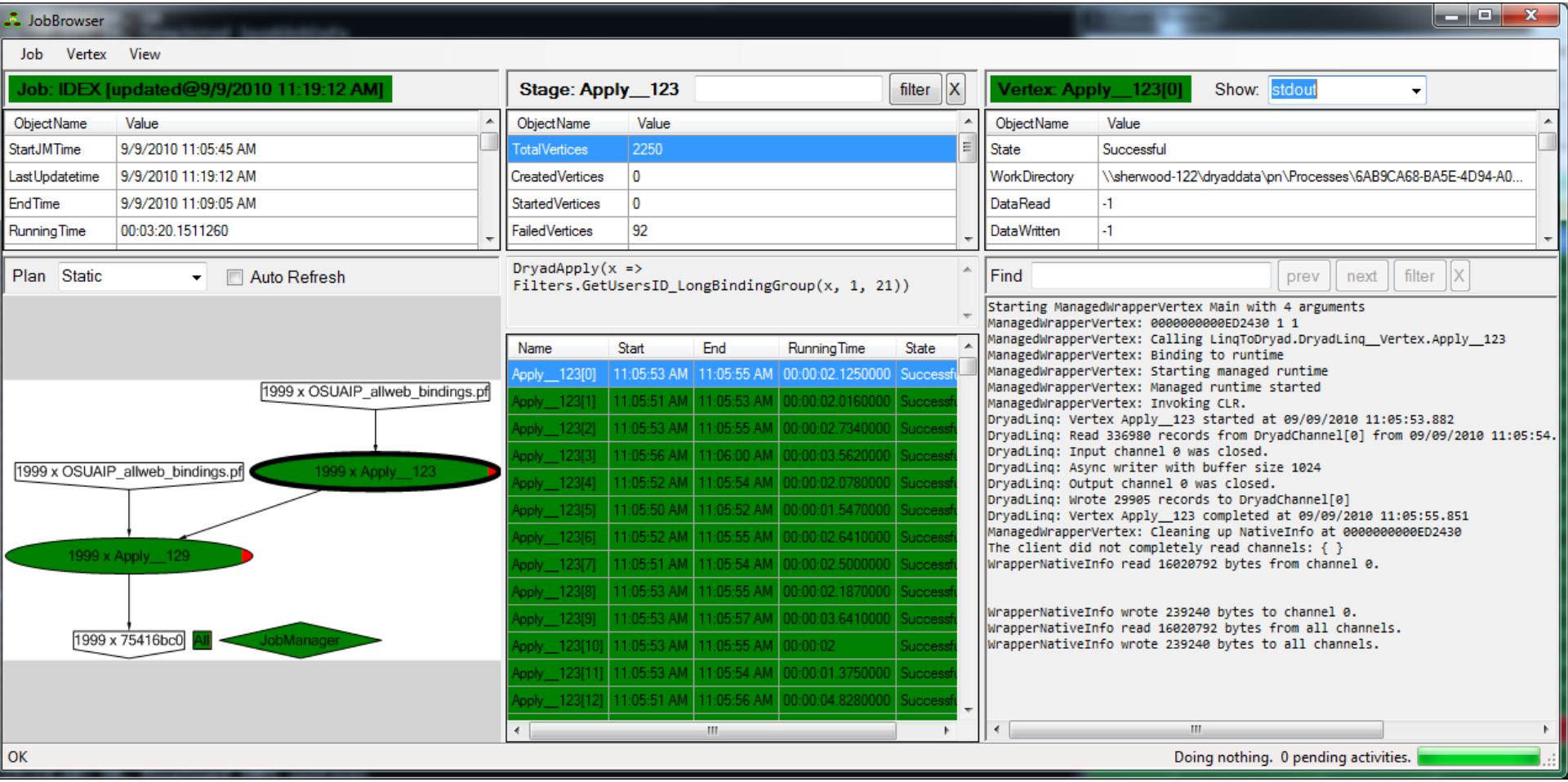


- Asynchronous operations hide latency
- Management using distributed state machines
- Logging state transitions for debugging
- Compression trades-off bandwidth for CPU

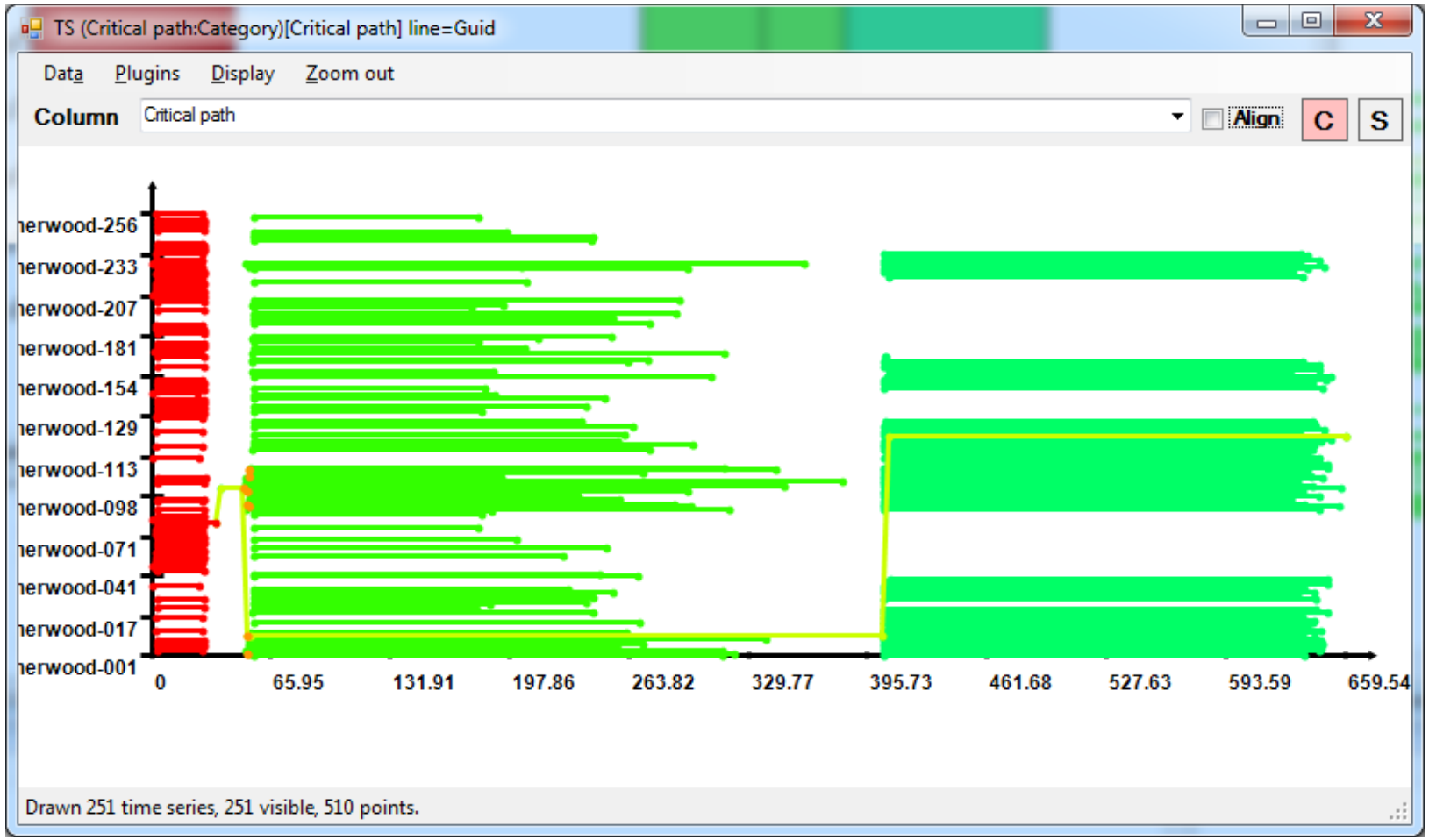


BUILDING ON DRYADLINQ

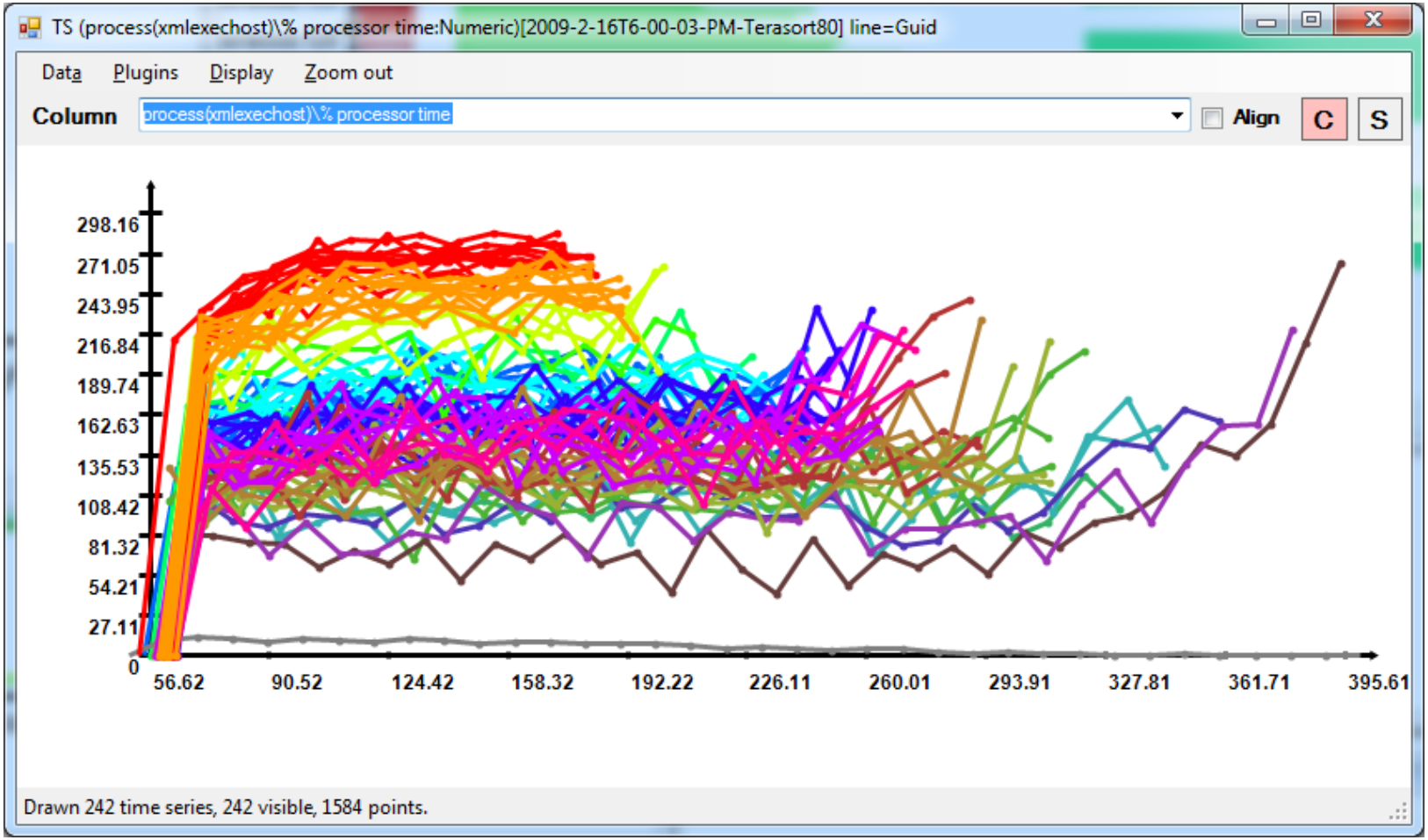
Job Visualization



Job Schedule



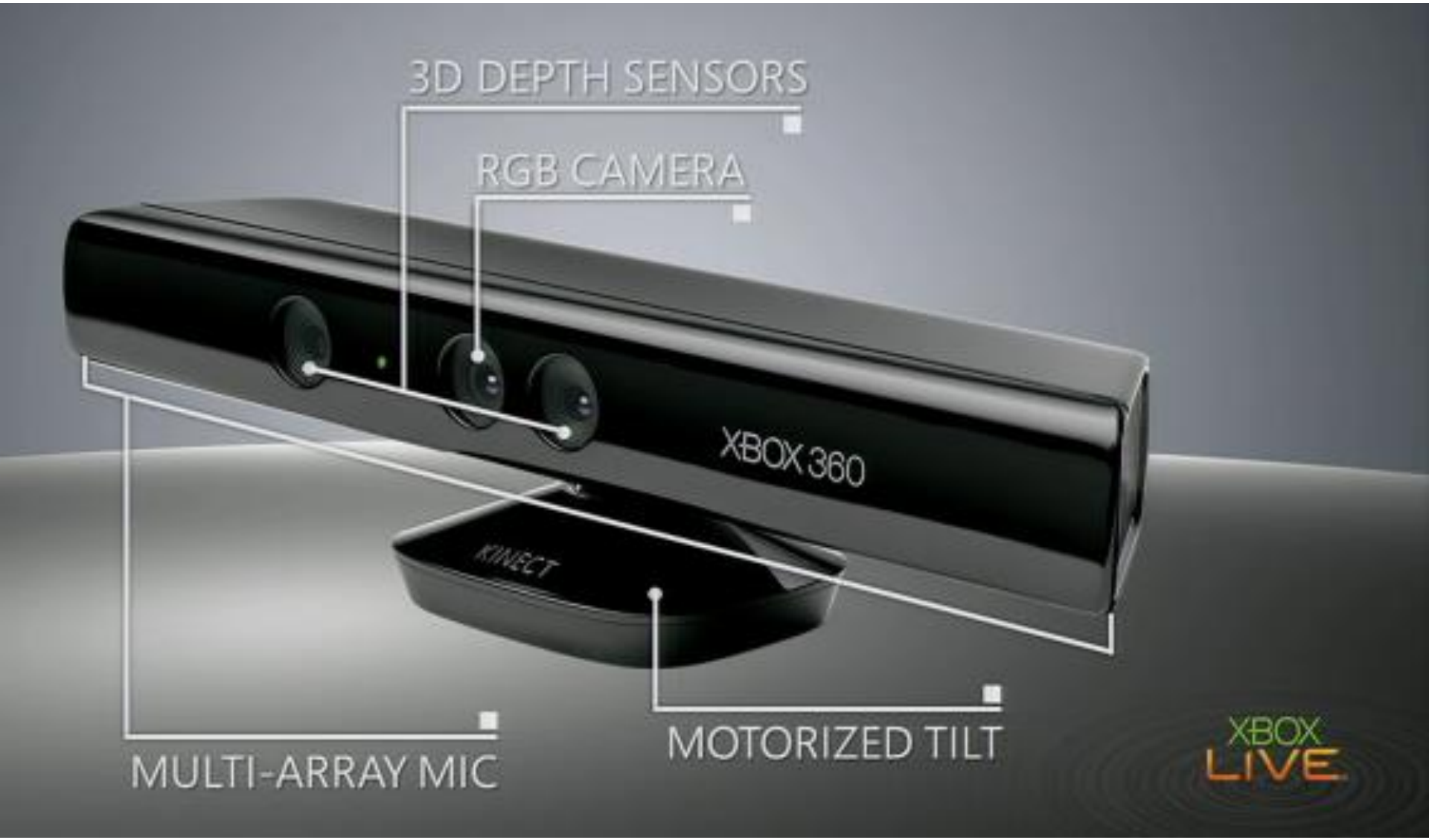
CPU Utilization



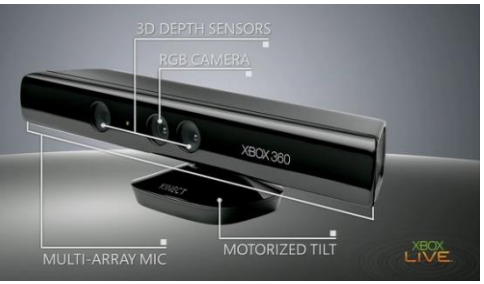
So, What Good is it For?

KINECT™

Input Device



Data Streams

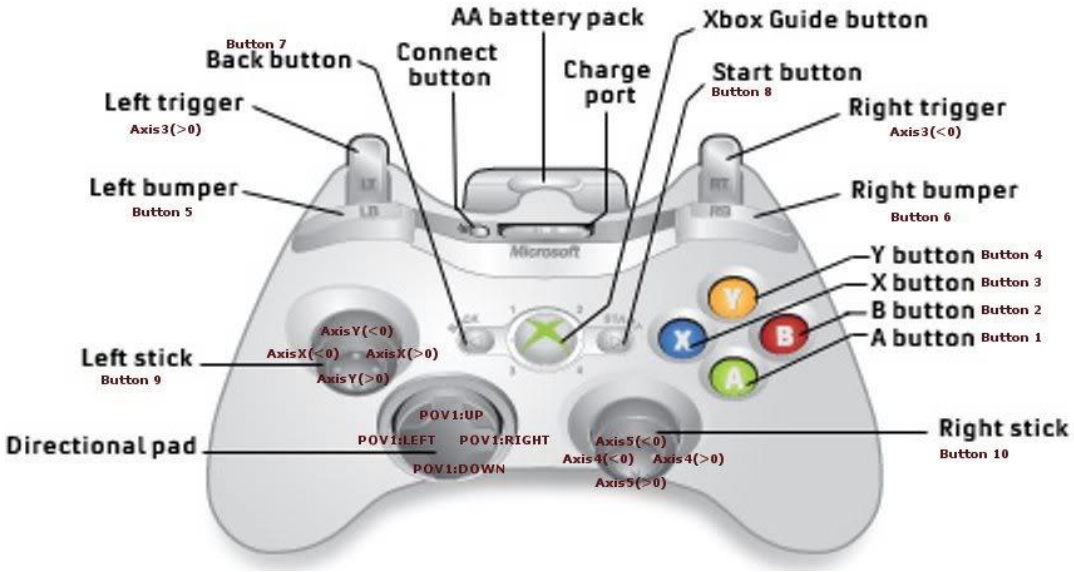


Audio

Video

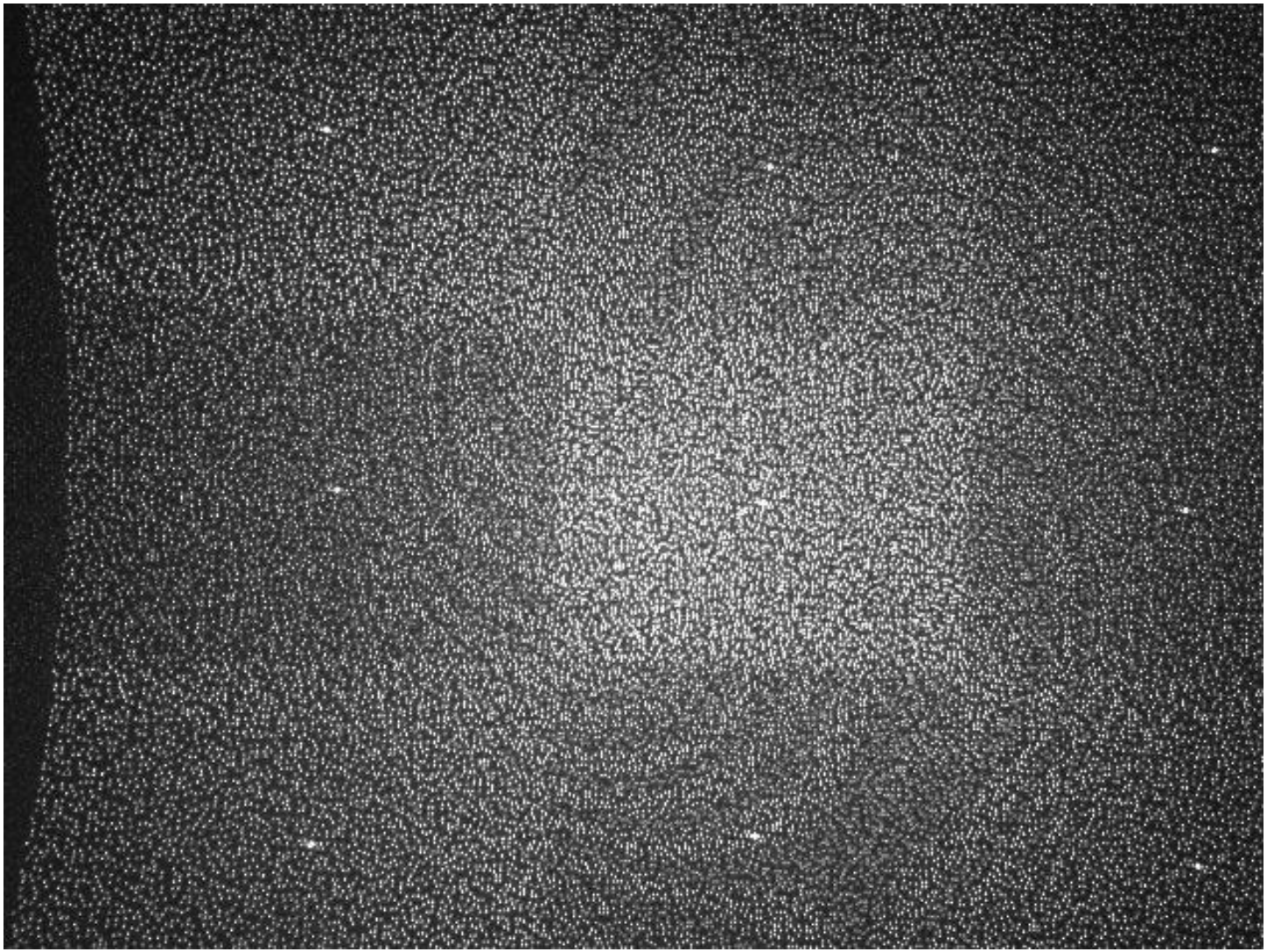
Depth

the Controller”



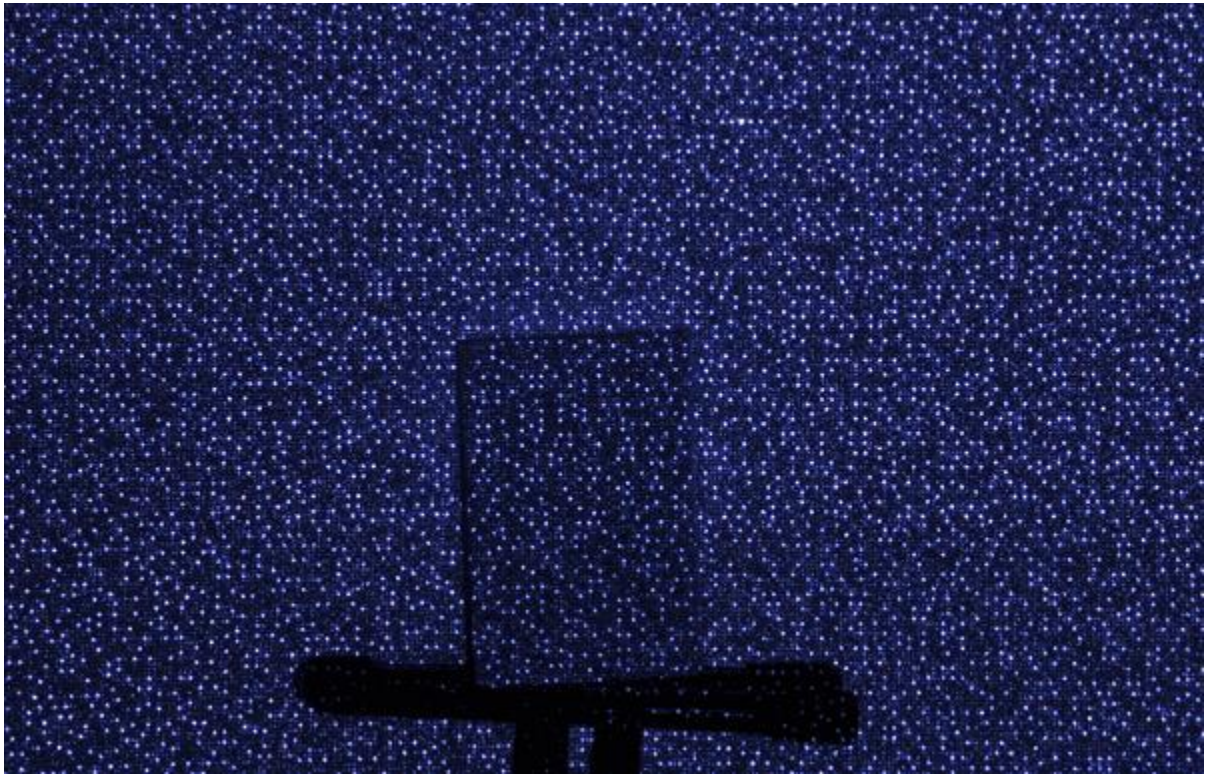
source: forums.steampowered.com

Projected IR pattern



Source: www.ros.org

Depth computation



Source: http://nuit-blanche.blogspot.com/2010/11/unsing-kinect-for-compressive-sensing.html

The Body Tracking Problem

XBox 360 Hardware

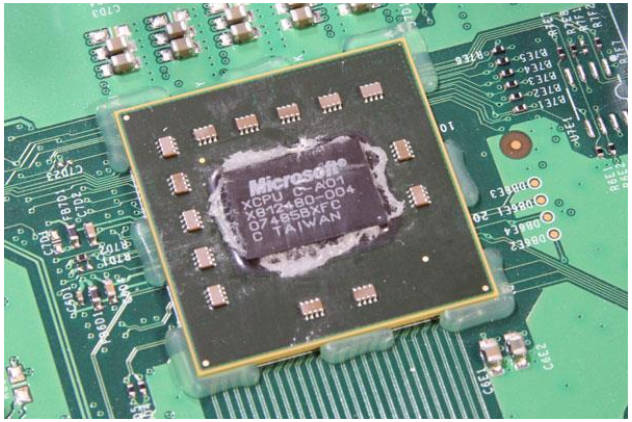
- Triple Core PowerPC 970, 3.2GHz
- Hyperthreaded, 2 threads/core

- 500 MHz ATI graphics card
- DirectX 9.5

- 512 MB RAM

- 2005 performance envelope

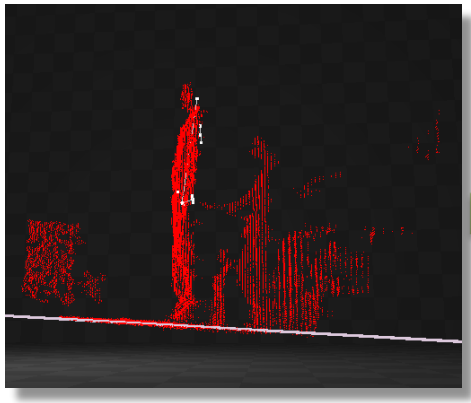
- Must handle
  - real-time vision AND
  - a modern game



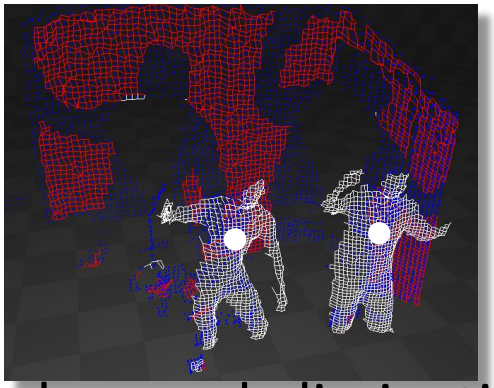
Source: http://www.pcper.com/article.php?aid=940&type=expert

Tracking Pipeline

Sensor

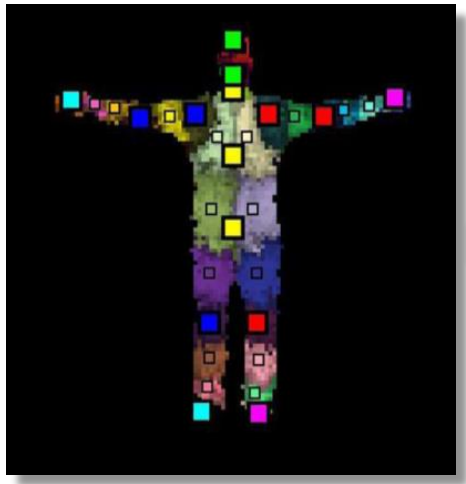


Depth map

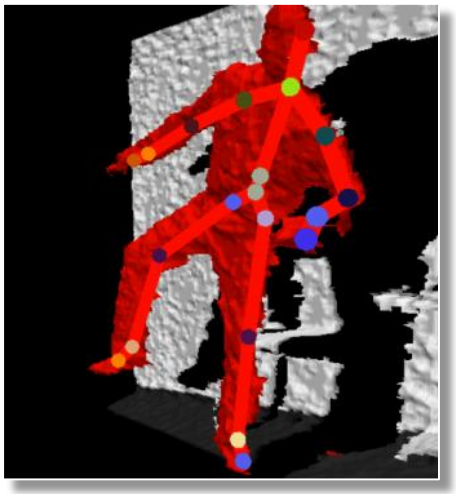


Background elimination
Player segmentation

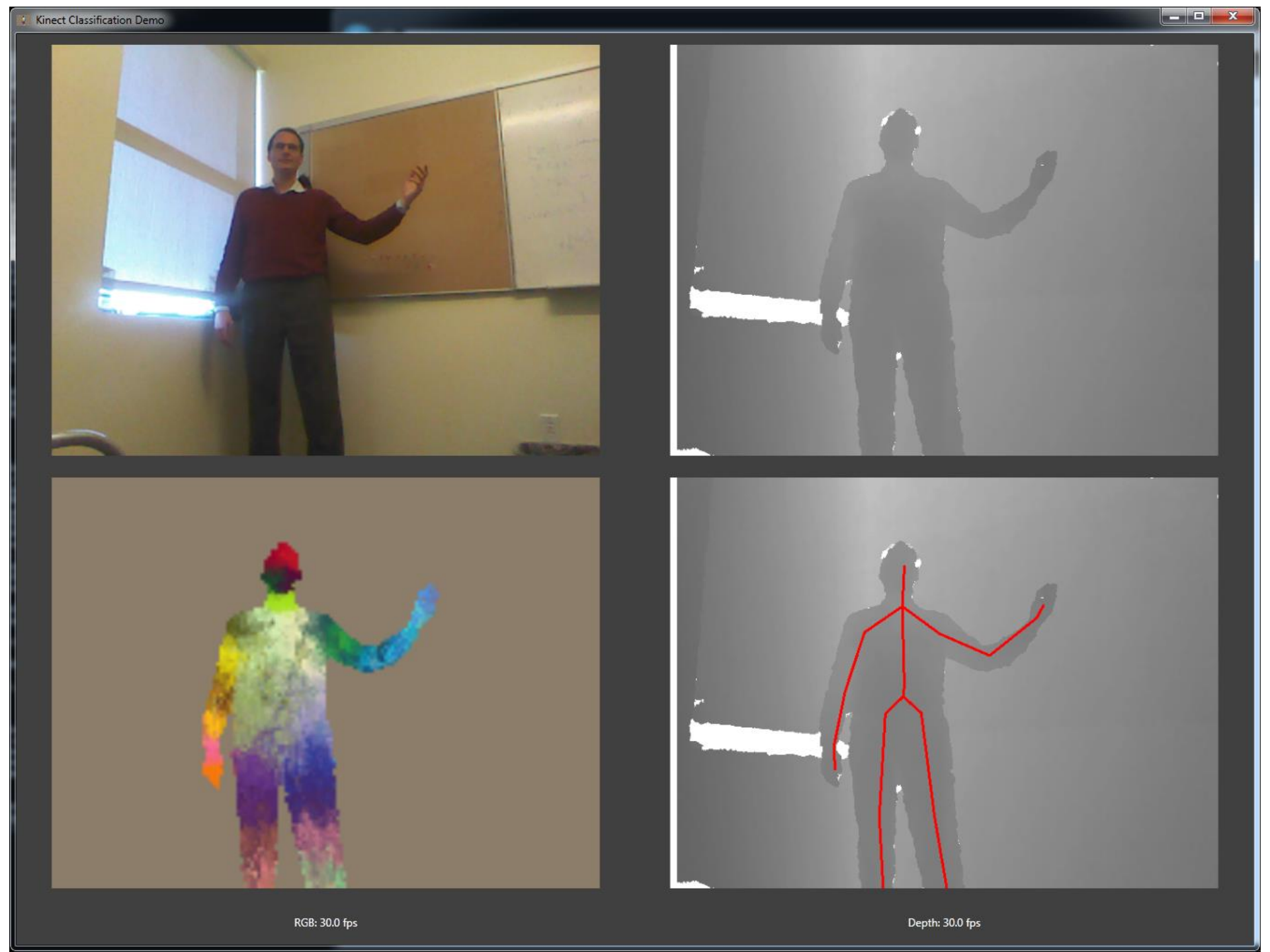
Body Part Classifier



Body Part Identification



Skeleton


Kinect Classification Demo
RGB: 30.0 fps
Depth: 30.0 fps

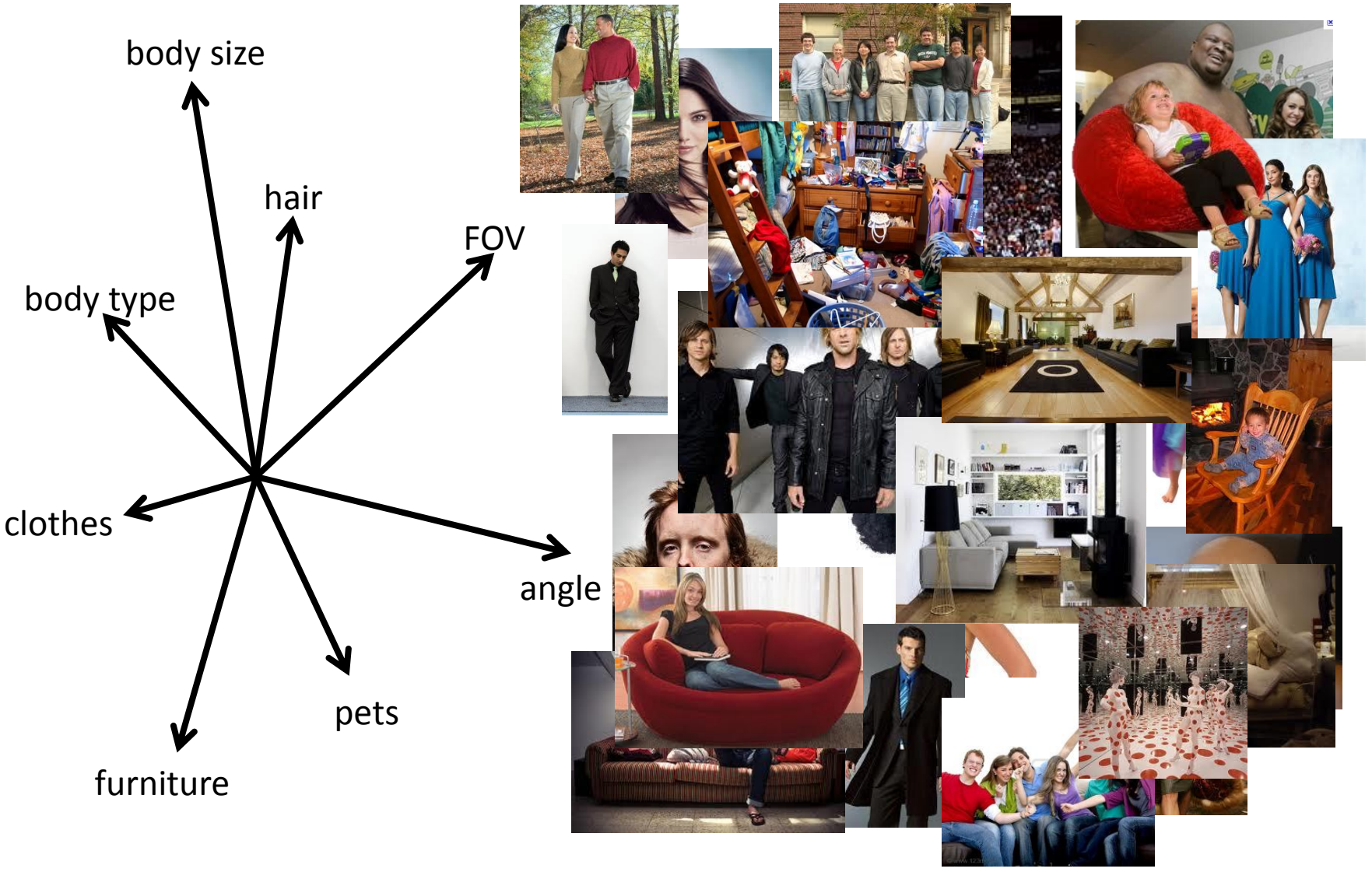
From Depth Map to Body Parts

Depth map

Xbox GPU

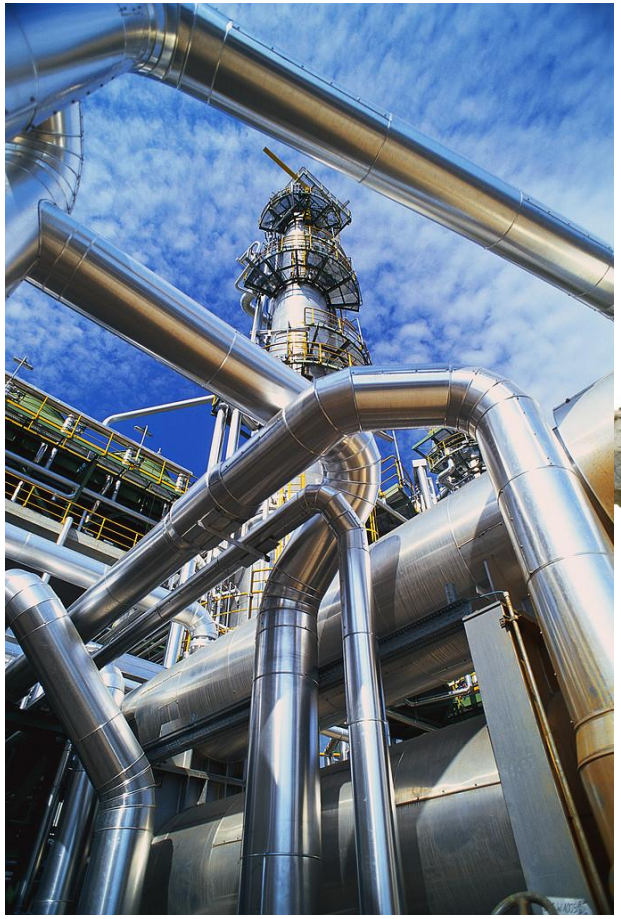
Body parts

What is the Shape of a Human?



How do *You* Recognize a Human?

Learn from Examples



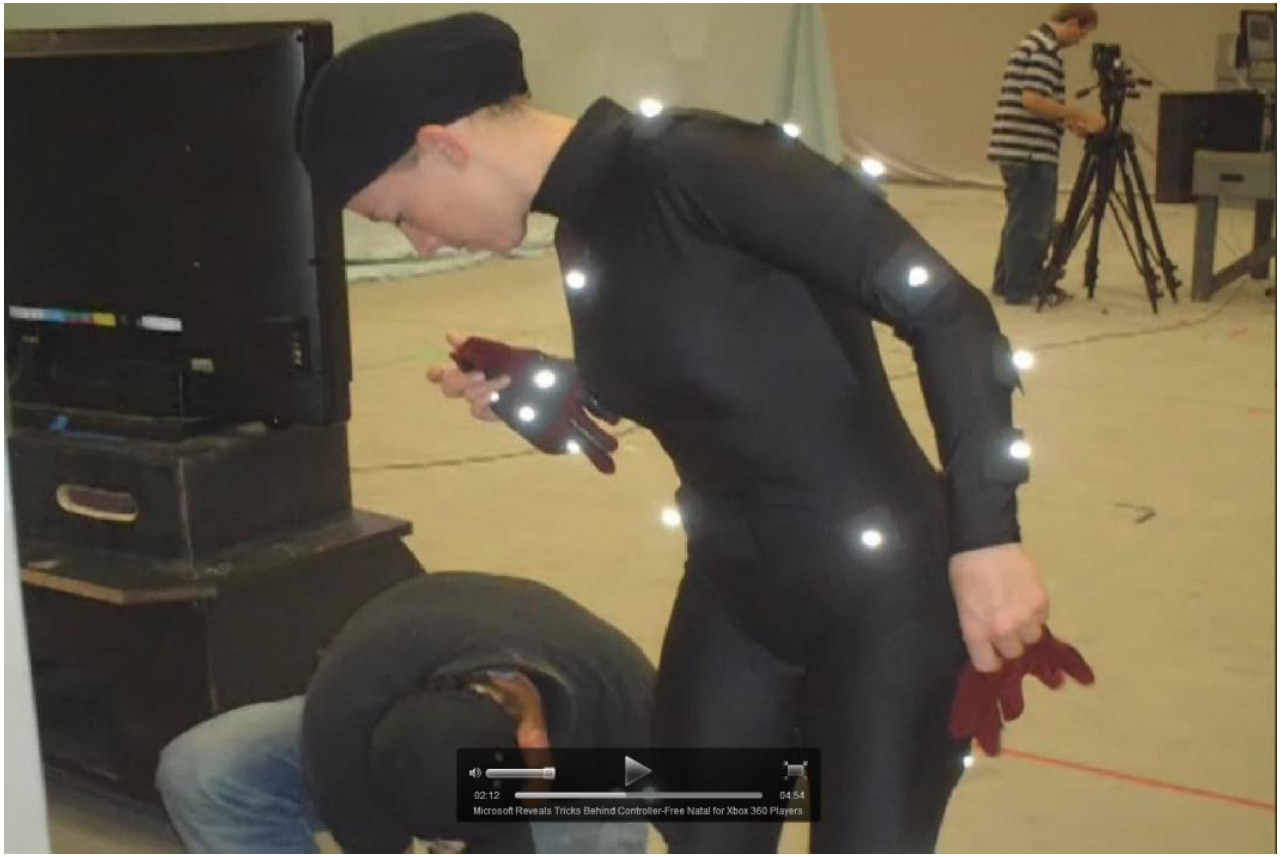
Classifier

Machine learning

Examples

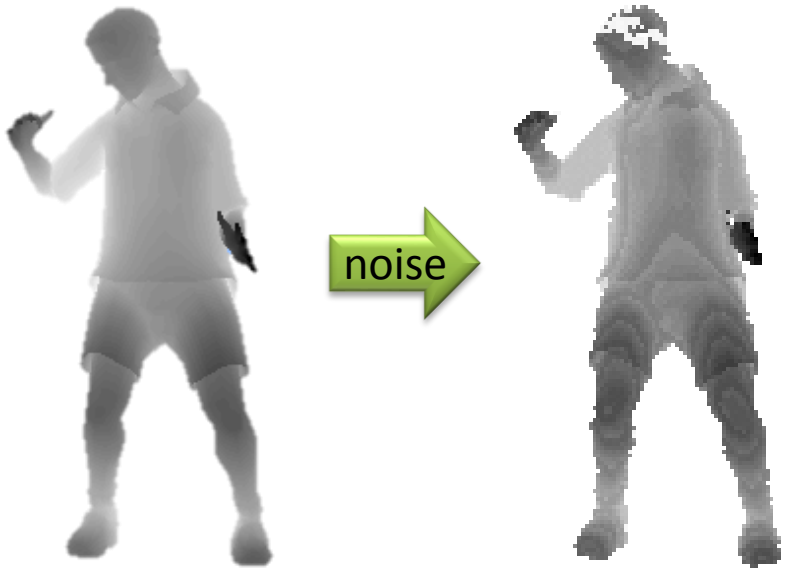
source: www.fanpop.com

Motion Capture (Mocap)

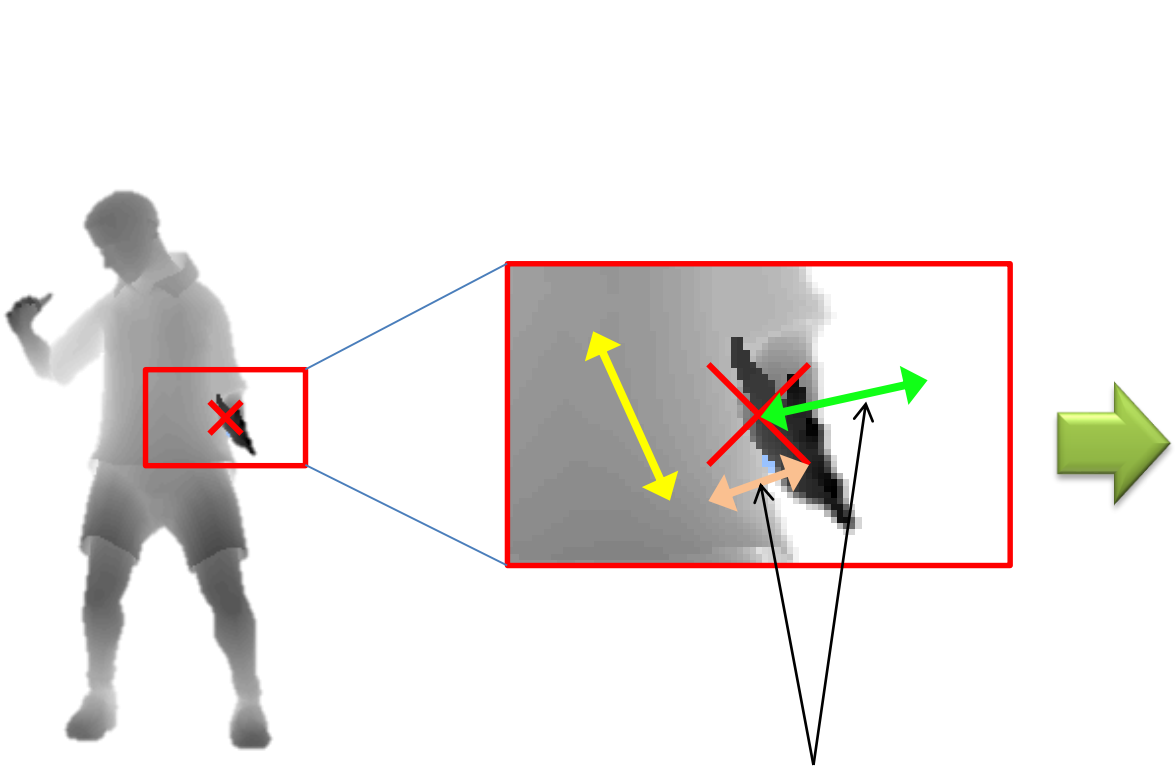


Rendered Avatar Models

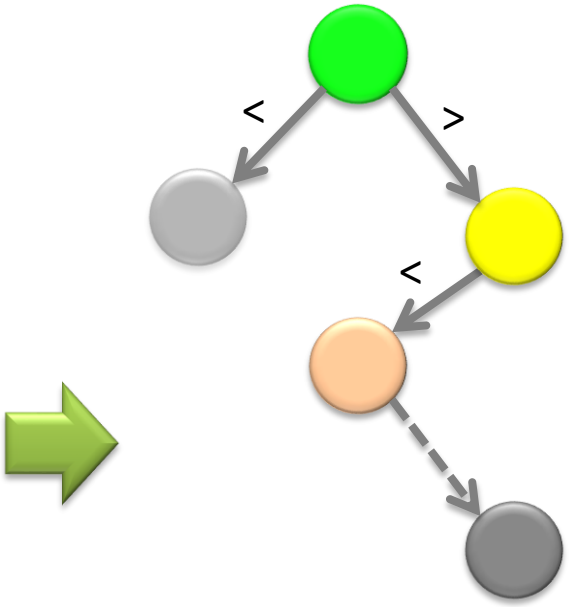
Ground Truth Data

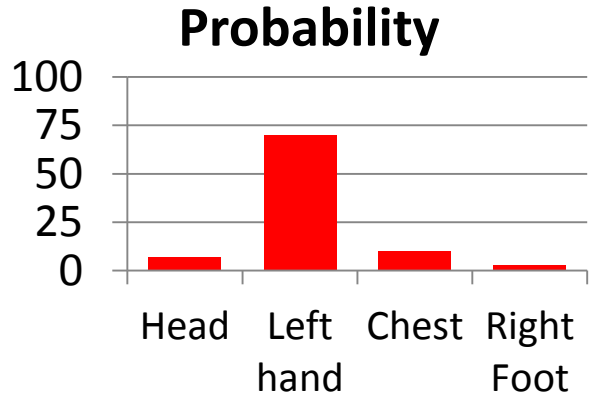


Decision Trees

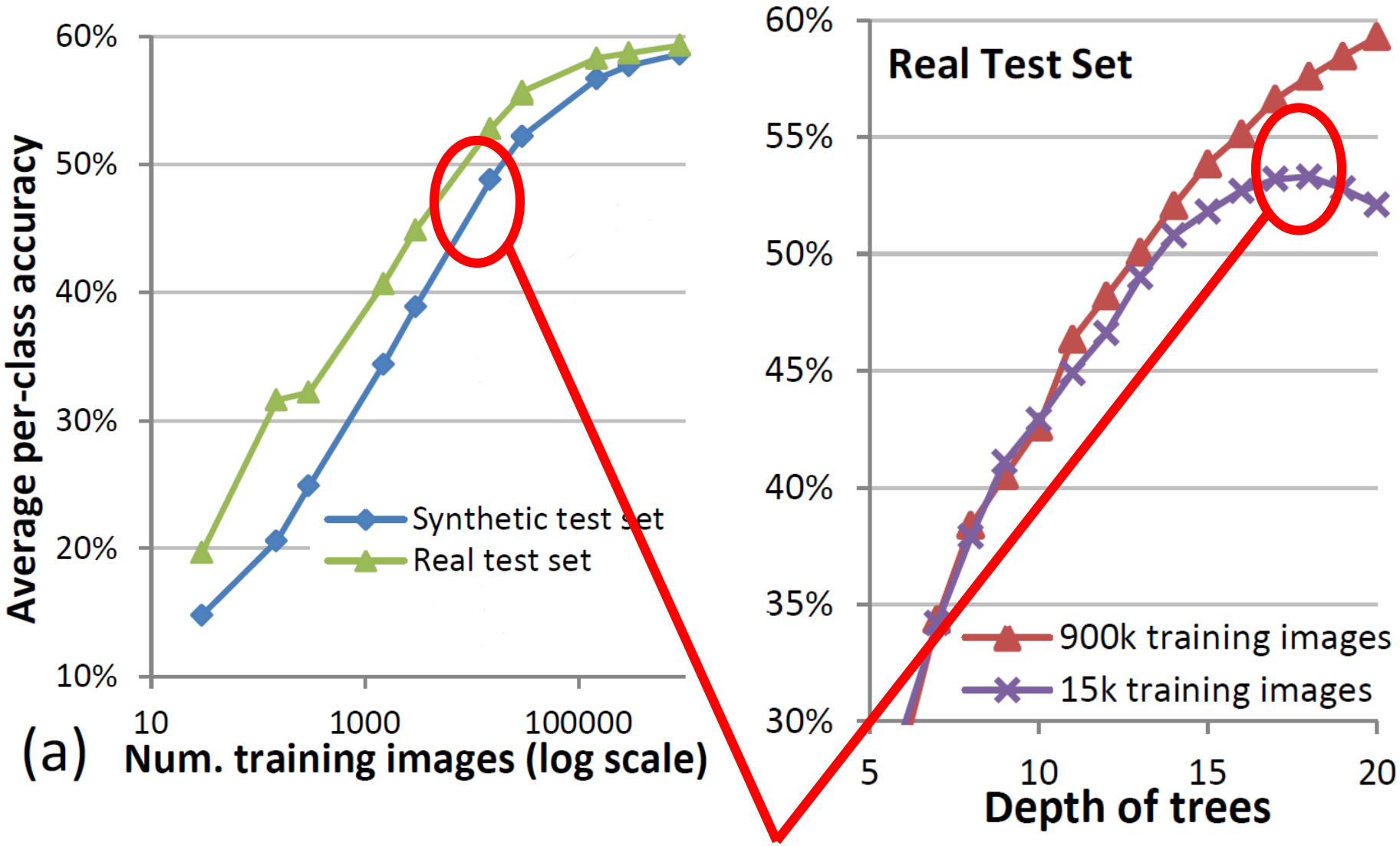


Features to learn



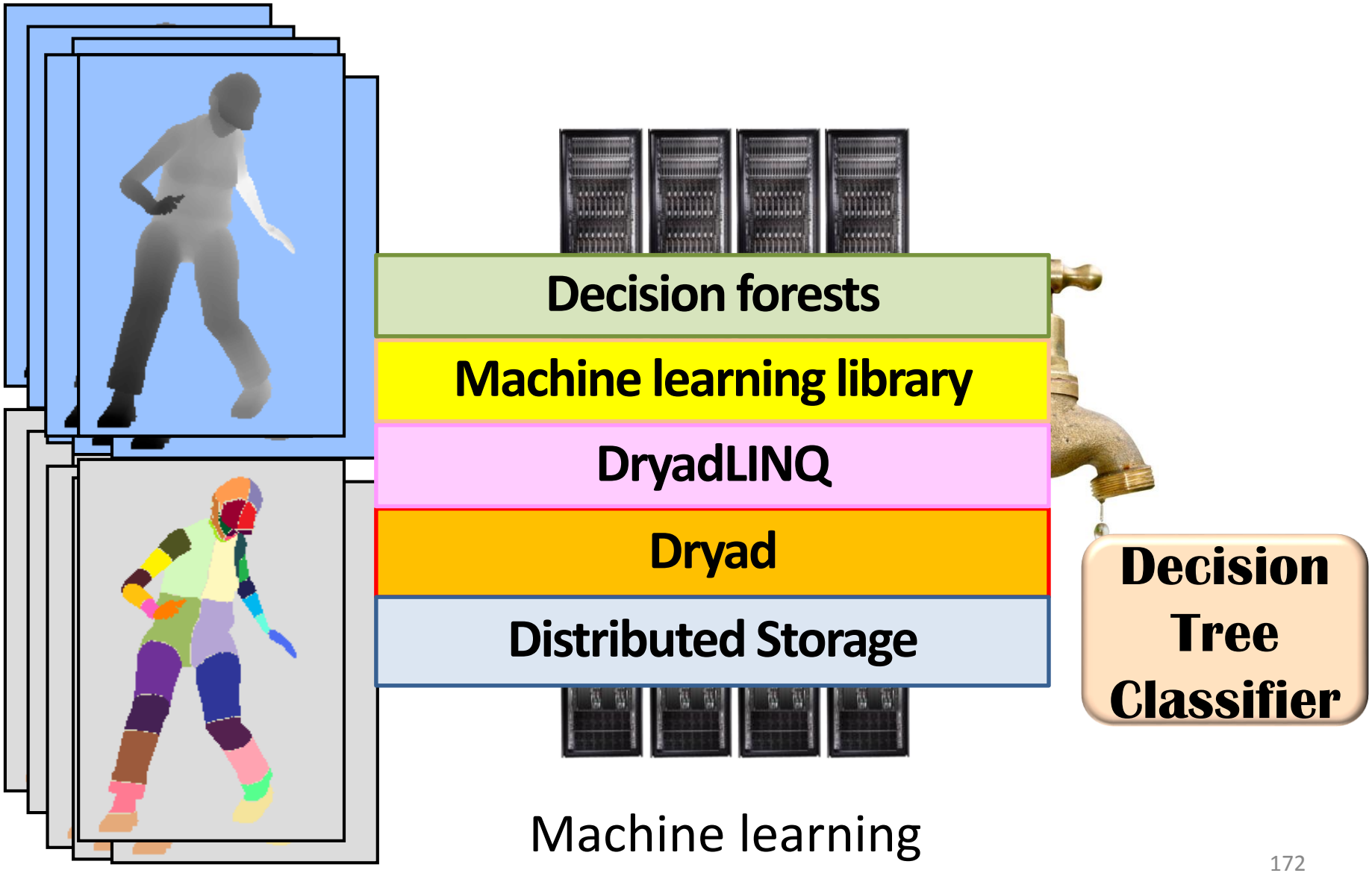


Accuracy



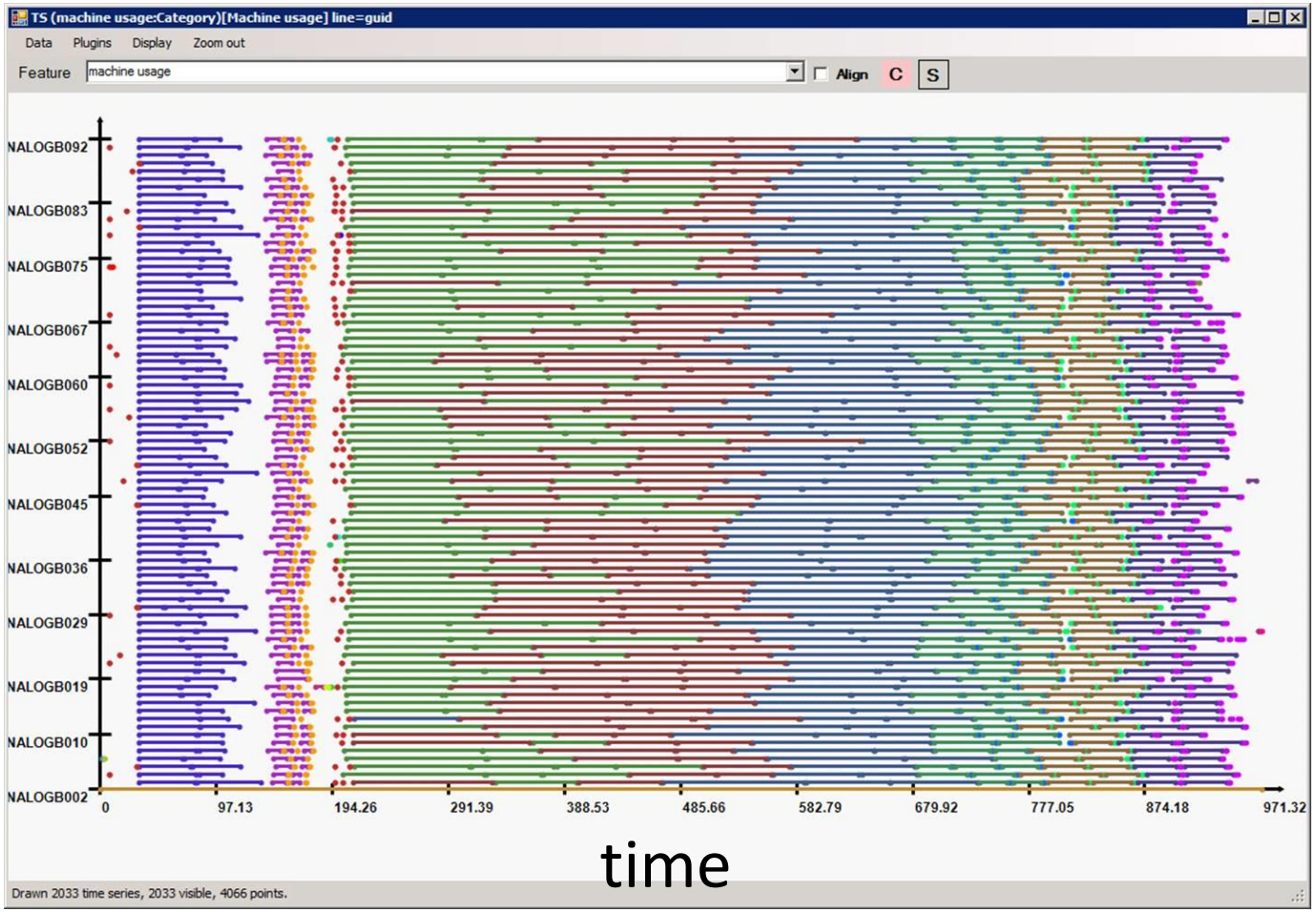
24 hours/8 core machine

Learn from Many Examples



Machine learning

Highly efficient parallellization



THE END

The ‘60s

PDP/8

BASIC

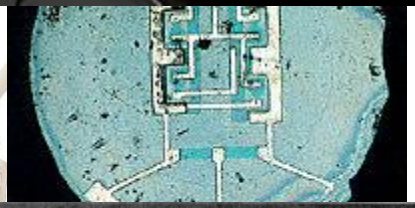
A Manual for BASIC, the elementary
algebraic language designed for use
with the Dartmouth Time Sharing System.

John G. Kemeny
Thomas E. Kurtz

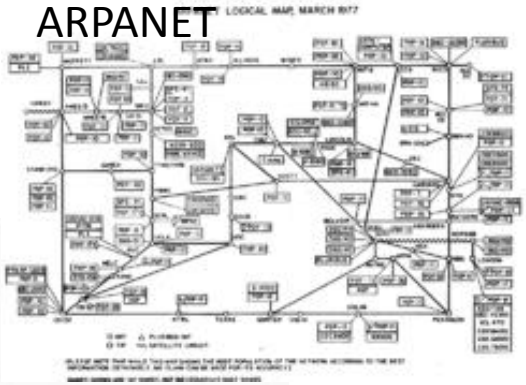
This third edition prepared
the assistance of William
Gail Hannagen, Prof. Willi
Slesnick.

1 January 1966

Spacewars

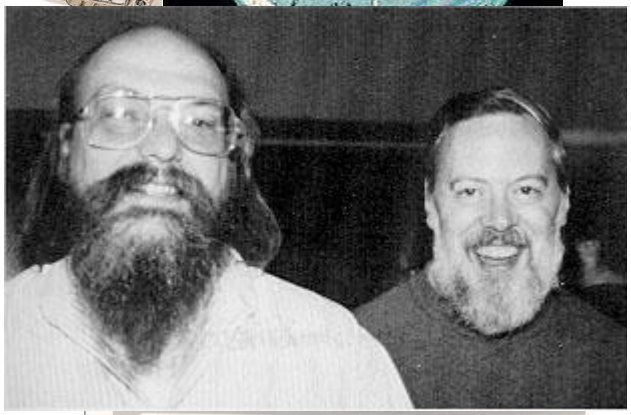


ARPANET



Multics
Time-sharing

A	1	0	0	0	0	0	1
B	1	0	0	0	0	1	0
C	1	0	0	0	0	1	1
D	1	0	0	0	1	0	0
E	1	0	0	0	1	0	1
F	1	0	0	0	1	1	0
G	1	0	0	0	1	1	1
H	1	0	0	1	0	0	0
I	1	0	0	1	0	0	1
J	1	0	0	1	0	1	0
K	1	0	0	1	0	1	1
L	1	0	0	1	1	0	0
M	1	0	0	1	1	0	1
N	1	0	0	1	1	1	0
O	1	0	0	1	1	1	1
P	1	0	1	0	0	0	0
Q	1	0	1	0	0	0	1
R	1	0	1	0	0	1	0
S	1	0	1	0	0	1	1
T	1	0	1	0	1	0	0
U	1	0	1	0	1	0	1
V	1	0	1	0	1	1	0
W	1	0	1	0	1	1	1
X	1	0	1	1	0	0	0
Y	1	0	1	1	0	0	1
Z	1	0	1	1	0	1	0



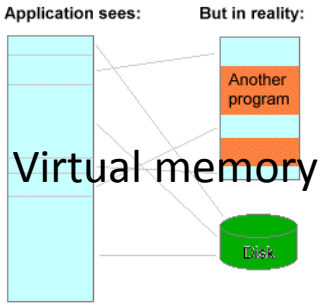
Artificial Intelligence Group

J. McCarthy
R. Brayton
D. Edwards
P. Fox
L. Hodes
D. Luckham
K. Maling
D. Park
A. Runyan

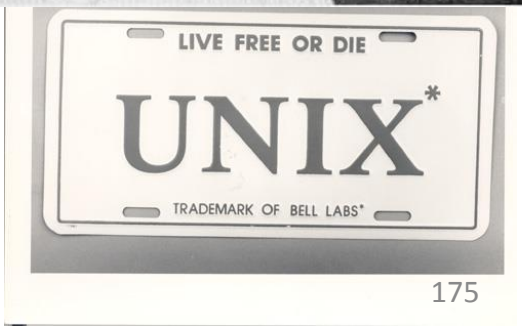
COMPUTATION CENTER
RESEARCH LABORATORY OF ELECTRONICS
Massachusetts Institute of Technology
Cambridge, Massachusetts

```
(defun factorial (n)
  (if (<= n 1) 1
      (* n (factorial (- n 1)))))
```

OS/360

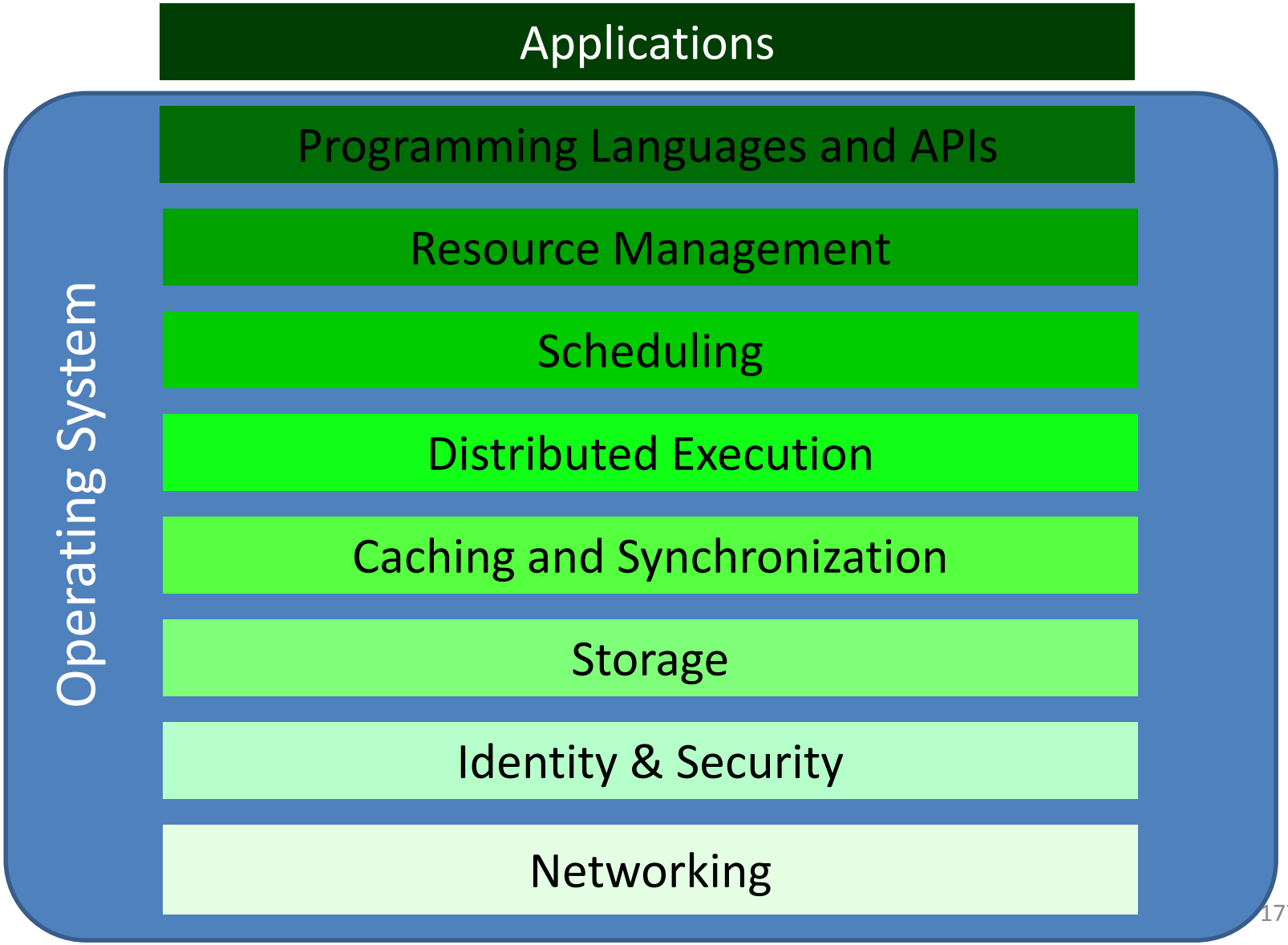


Virtual memory



What about the 2010's?

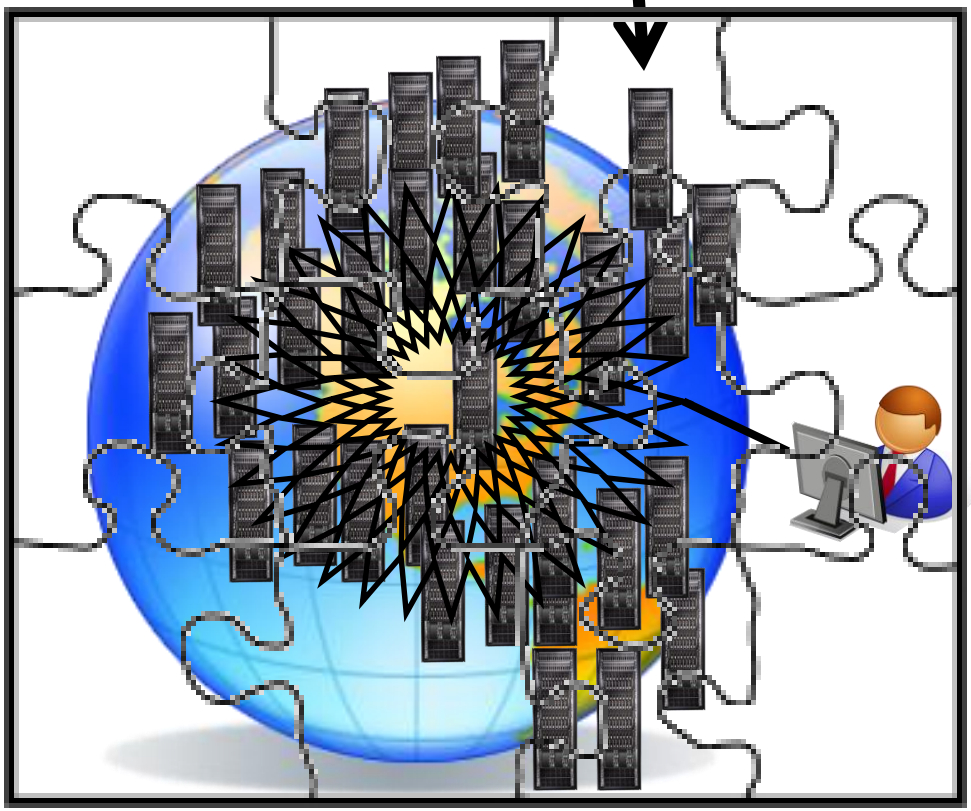
Layers


Applications
Operating System
Programming Languages and APIs
Resource Management
Scheduling
Distributed Execution
Caching and Synchronization
Storage
Identity & Security
Networking

Pieces of the Global Computer

And many, many more…

This lecture

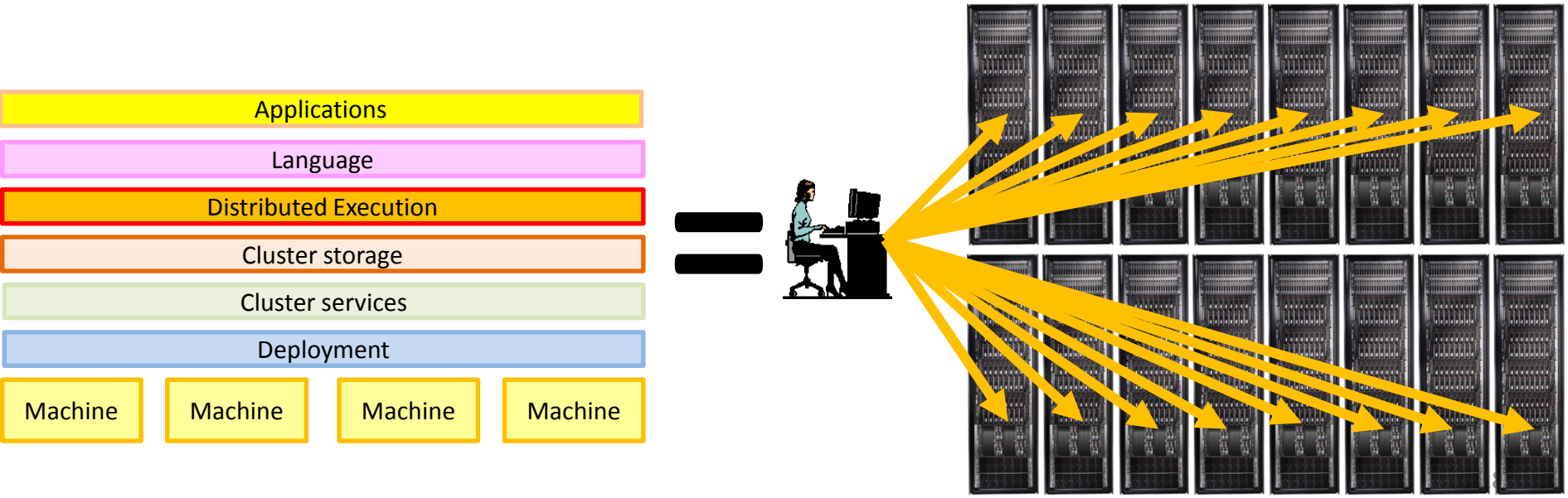


The cloud

- “The cloud” is evolving rapidly
- New frontiers are being conquered
- The face of computing will change forever
- There is still a lot to be done

You might do it!

Conclusion


Applications
Language
Distributed Execution
Cluster storage
Cluster services
Deployment
Machine
Machine
Machine
Machine

Bibliography (1)

Dryad: Distributed Data-Parallel Programs from Sequential Building Blocks
Michael Isard, Mihai Budiu, Yuan Yu, Andrew Birrell, and Dennis Fetterly
European Conference on Computer Systems (EuroSys), Lisbon, Portugal, March 21-23, 2007

DryadLINQ: A System for General-Purpose Distributed Data-Parallel Computing Using a High-Level Language
Yuan Yu, Michael Isard, Dennis Fetterly, Mihai Budiu, Úlfar Erlingsson, Pradeep Kumar Gunda, and Jon Currey
Symposium on Operating System Design and Implementation (OSDI), San Diego, CA, December 8-10, 2008

Hunting for problems with Artemis
Gabriela F. Creţu-Ciocârlie, Mihai Budiu, and Moises Goldszmidt
USENIX Workshop on the Analysis of System Logs (WASL), San Diego, CA, December 7, 2008

DryadInc: Reusing work in large-scale computations
Lucian Popa, Mihai Budiu, Yuan Yu, and Michael Isard
Workshop on Hot Topics in Cloud Computing (HotCloud), San Diego, CA, June 15, 2009

Distributed Aggregation for Data-Parallel Computing: Interfaces and Implementations,
Yuan Yu, Pradeep Kumar Gunda, and Michael Isard,
ACM Symposium on Operating Systems Principles (SOSP), October 2009

Quincy: Fair Scheduling for Distributed Computing Clusters
Michael Isard, Vijayan Prabhakaran, Jon Currey, Udi Wieder, Kunal Talwar, and Andrew Goldberg
ACM Symposium on Operating Systems Principles (SOSP), October 2009

Bibliography (2)

Autopilot: Automatic Data Center Management, *Michael Isard*, in *Operating Systems Review*, vol. 41, no. 2, pp. 60-67, April 2007

Distributed Data-Parallel Computing Using a High-Level Programming Language, *Michael Isard and Yuan Yu*, in *International Conference on Management of Data (SIGMOD)*, July 2009

SCOPE: Easy and Efficient Parallel Processing of Massive Data Sets
Ronnie Chaiken, Bob Jenkins, Per-Åke Larson, Bill Ramsey, Darren Shakib, Simon Weaver, and Jingren Zhou, Very Large Databases Conference (VLDB), Auckland, New Zealand, August 23-28 2008

Incorporating Partitioning and Parallel Plans into the SCOPE Optimizer, *Jingren Zhou, Per-Åke Larson, and Ronnie Chaiken*, in Proc. of the 2010 ICDE Conference (ICDE'10).

Nectar: Automatic Management of Data and Computation in Datacenters, *Pradeep Kumar Gunda, Lenin Ravindranath, Chandramohan A. Thekkath, Yuan Yu, and Li Zhuang*, in *Proceedings of the 9th Symposium on Operating Systems Design and Implementation (OSDI)*, October 2010

Optimus: A Dynamic Rewriting Framework for Execution Plans of Data-Parallel Computations, *Qifa Ke, Michael Isard, Yuan Yu*, Proceedings of EuroSys 2013, April 2013