Condor: Supercomputing Without a Super-Budget

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Outline

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Why Condor
Computation is cheap

- Amazon.com EC2: 10 cents/hour
- Academic computing: 4 cents/hour
- Opportunistic computing: even cheaper

Condor is a cluster computing manager for HTC

HTC: High Throughput Computing

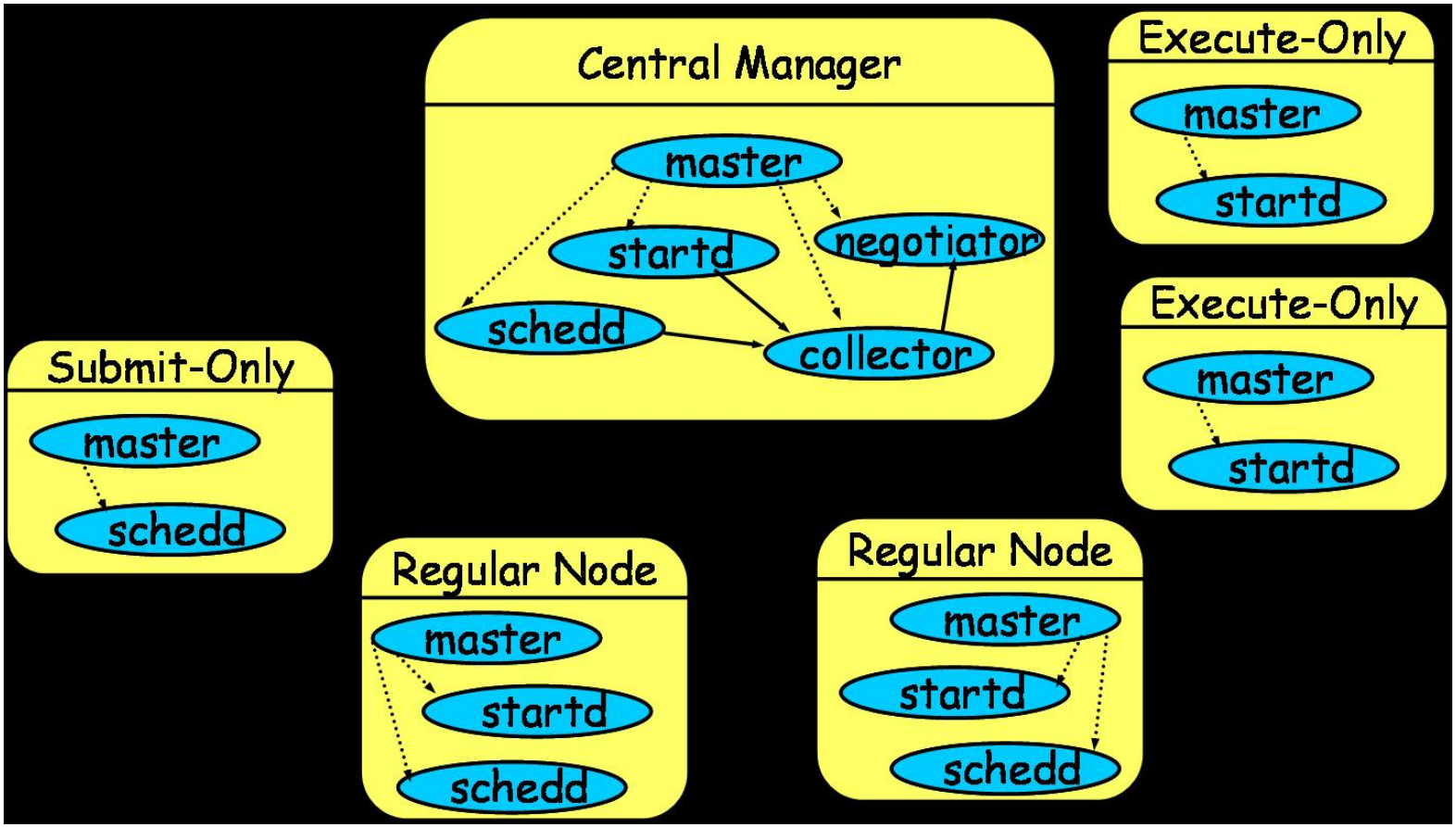
- High Throughput Computing, not
- High Performance Computing

- Dedicated Clusters
- Cycle scavanging from desktops

Installing Condor

- Call your IT department!

Typical Condor pool



Three steps to cluster computing

- Prepare your job and inputs
- Write a `submit_file`
- Run and manage your job

Step 1: Prepare your job

- Like going on vacation – pack carefully!
- Check for library and other dependencies
- Run condor_compile for checkpointed
- Gather all inputs together

Step 2: Write a submit file

Submit file describes your jobs to Condor

submit_file

```
universe   = vanilla

executable = /usr/bin/matlab
arguments  = gonkulate.m

transfer_input_files = gonkulate.m
should_transfer_files = yes
when_to_transfer_output = always

output = out
error  = err
log    = log
queue 1
```

Step 3: Submit your job(s)

Shell prompt

```
# condor_submit submit_file
Submitting job(s).....
Logging submit event(s).....
1 job(s) submitted to cluster 11.
```

Step 3a: Manage your job(s)

Shell prompt

```
condor_rm my_job_number
condor_hold my_job_number
condor_release my_job_number

condor_q
condor_q -run

condor_status
```

Outline

Long running jobs

What if you need to run a job that takes a month to run?

- And the machine crashes?
- Or loses power?
- Or gets rebooted?

Long running jobs

Solution: Checkpointing!

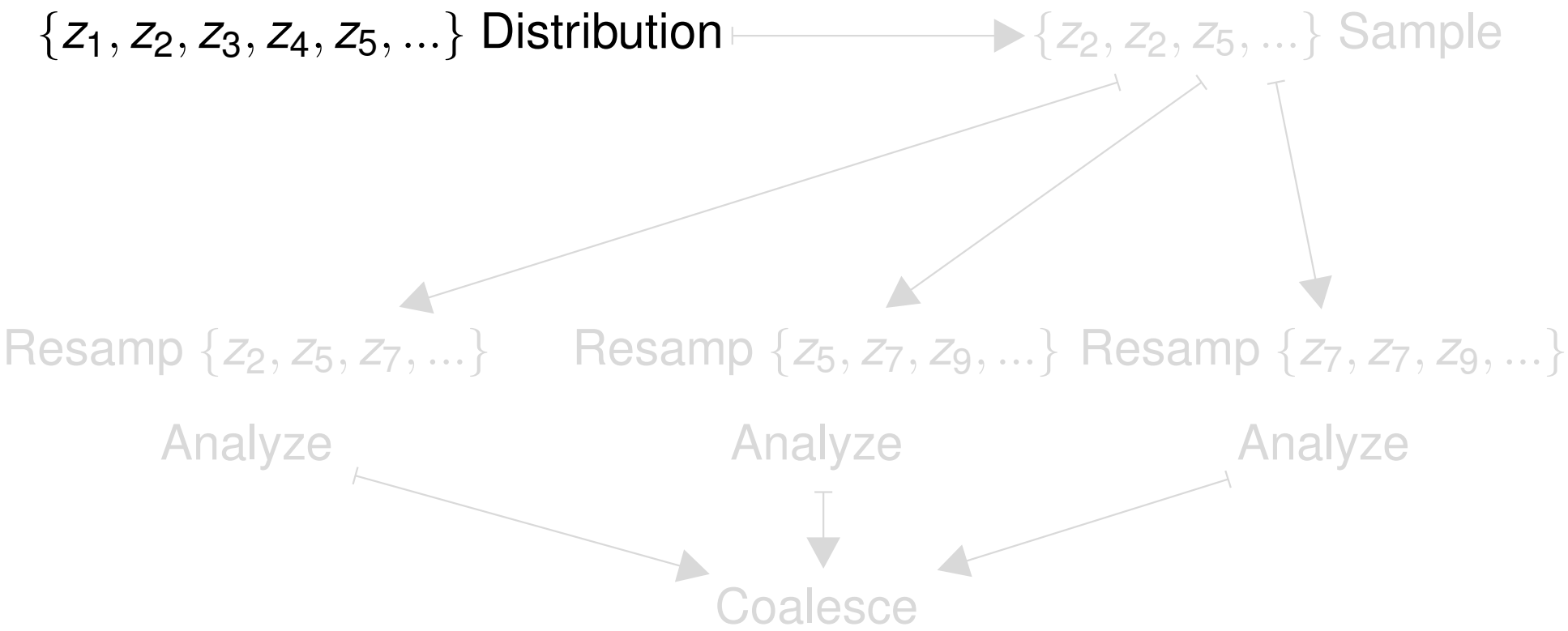
- Condor can periodically save the whole state of the job
- And restore it on a another machine, if needed

Running Standard Universe Jobs

- `condor_compile` your code
  - condor_compile gcc -o solver solver.c
  - condor_compile f77 -o executable source.f
- indicate `Standard` universe in your submit file
- Submit as normal
- If execute machine dies, Condor restarts the job elsewhere
- If submit machine dies, Condor restarts the job elsewhere

Example: Statistical Bootstrapping

A Parameter Sweep



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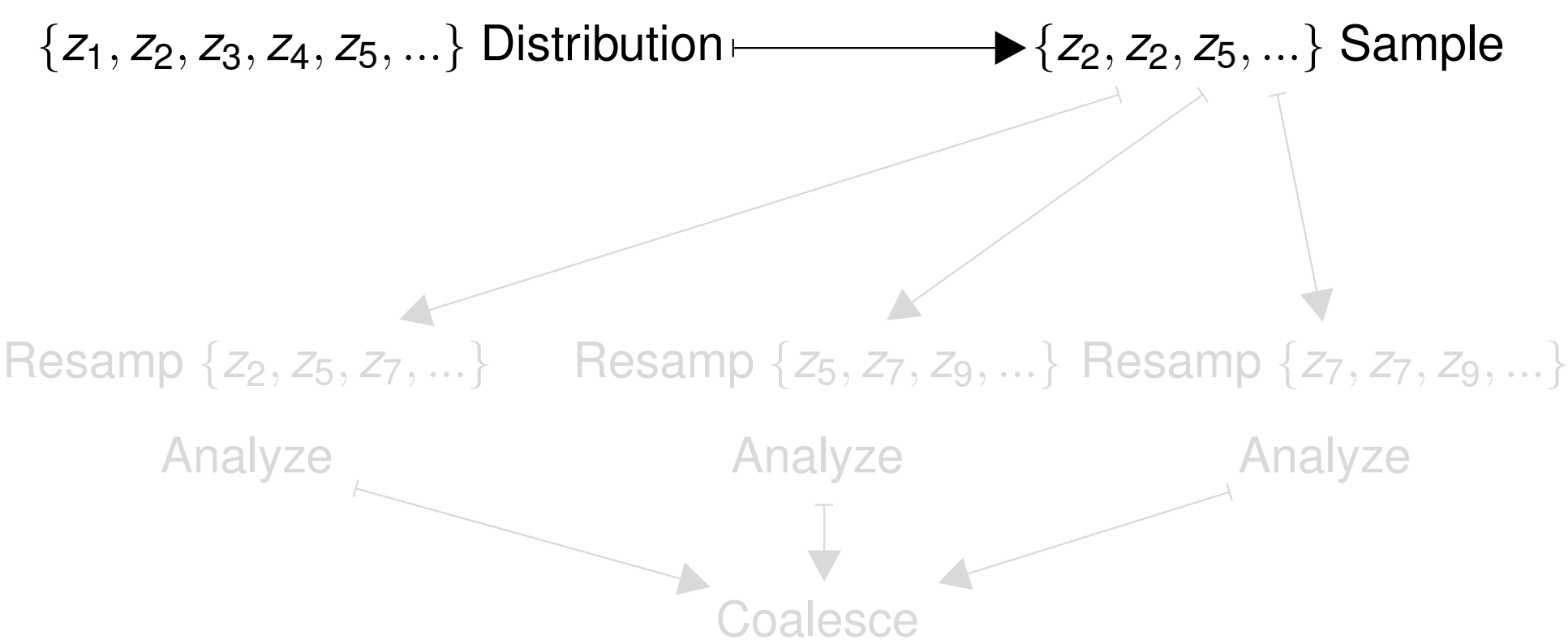

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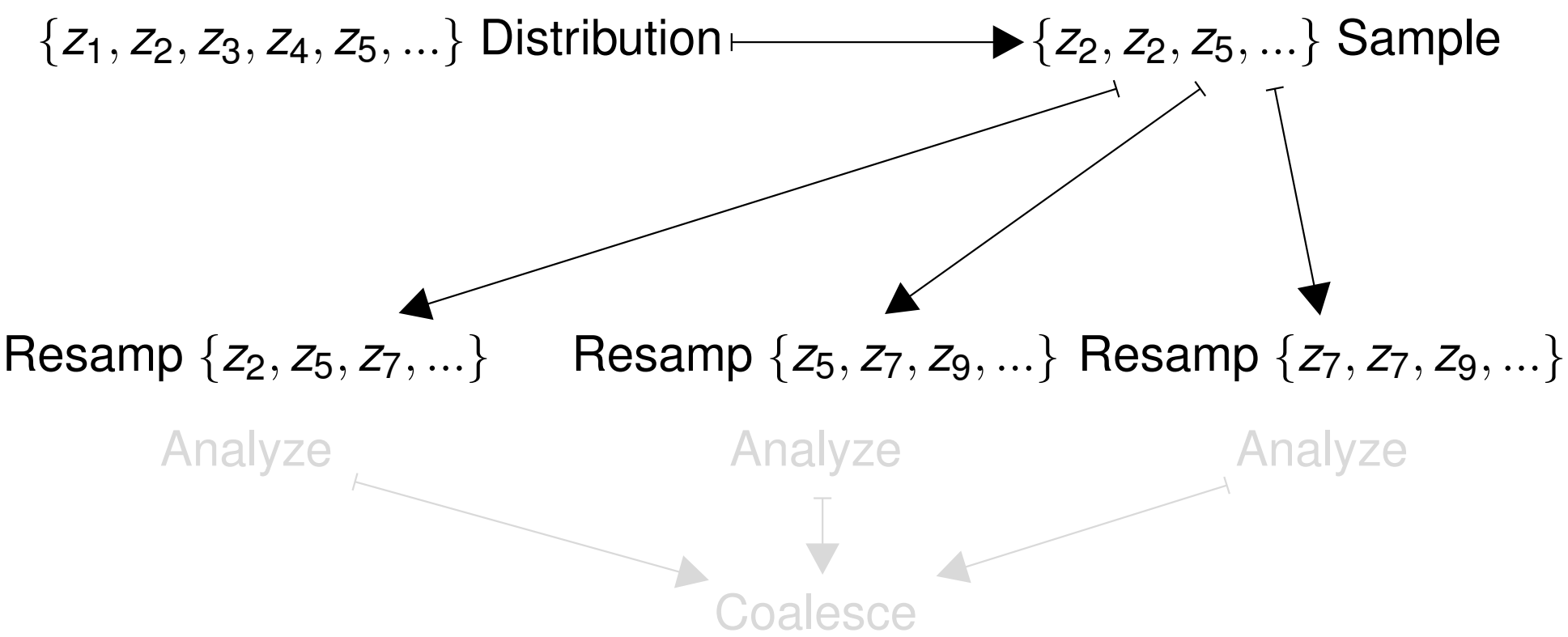

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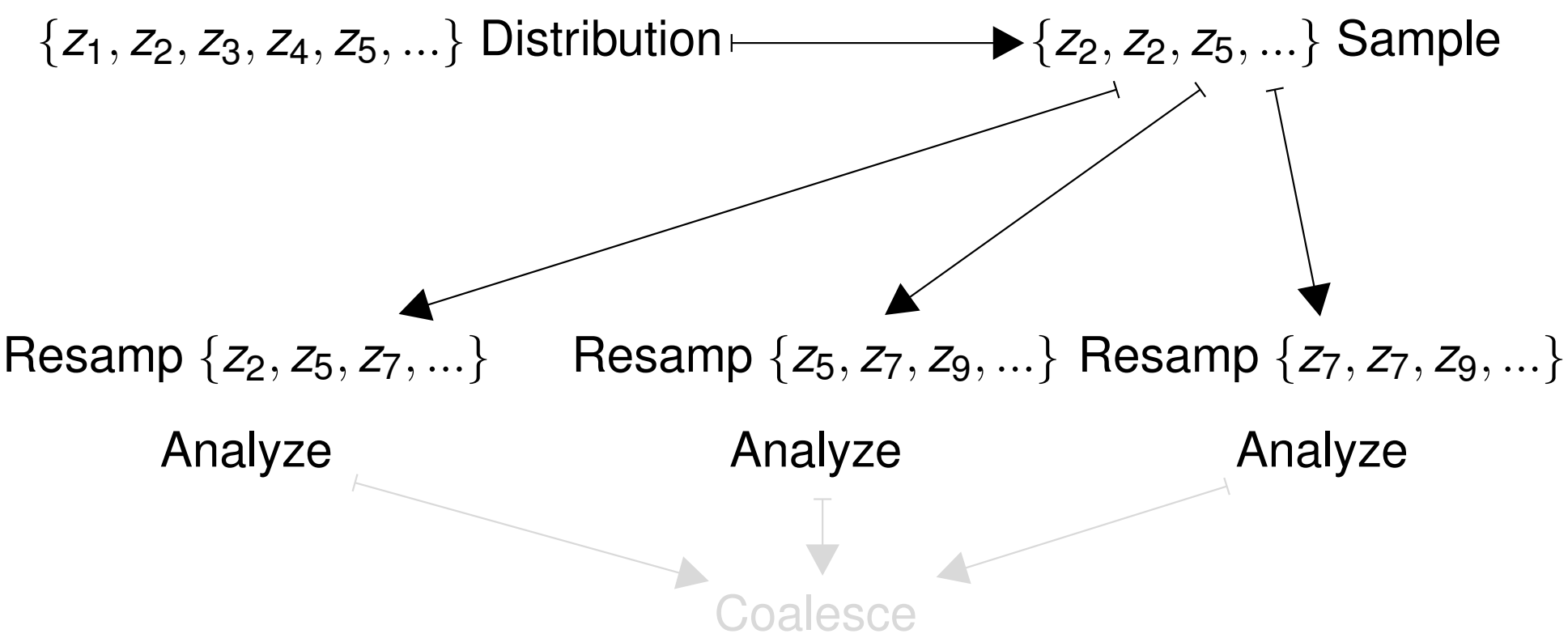

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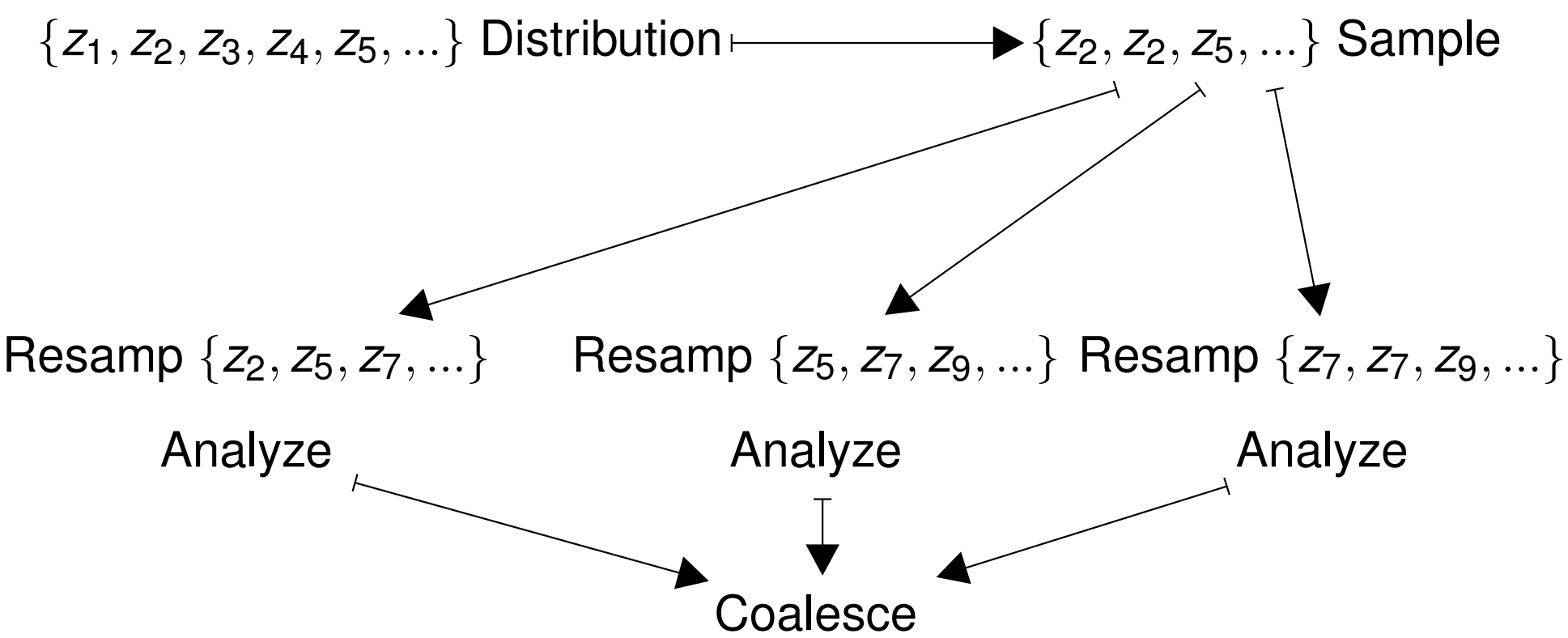


Statistical Bootstrapping

A Condor/Matlab implementation

Driver Creates distribution.

Driver Creates `submit` file.

Driver Runs `condor_submit`.

Workers Analyzes subset

Driver Processes results.

driver.m

```
dist_size = 100000;
d = rand(dist_size, 1) .* 500;
subset = d(floor(rand(1000,1) .*
100000));
save "subset" subset;
```

Statistical Bootstrapping

A Condor/Matlab implementation

Driver Creates distribution.

Driver Creates `submit` file.

Driver Runs `condor_submit`.

Workers Analyzes subset

Driver Processes results.

Generated submit_file

```
universe = vanilla
executable = worker.m
transfer_files = true
when_to_transfer_output = on_exit
transfer_input_files = subset
output = mean.$(PROCESS)
log = log
queue 5
```

Statistical Bootstrapping

A Condor/Matlab implementation

Driver Creates distribution.

Driver Creates `submit` file.

Driver Runs `condor_submit`.

Workers Analyzes subset

Driver Processes results.

driver.m

```
system("condor_submit file");
system("condor_wait log");
```

Statistical Bootstrapping

A Condor/Matlab implementation

Driver Creates distribution.

Driver Creates `submit` file.

Driver Runs `condor_submit`.

Workers Analyzes subset

Driver Processes results.

worker.m – All in parallel

```
load "subset" subset;
subset =
subset(floor(rand(10,1) .* 1000));
printf("%f ", mean(subset));
```

Statistical Bootstrapping

A Condor/Matlab implementation

Driver Creates distribution.

Driver Creates `submit` file.

Driver Runs `condor_submit`.

Workers Analyzes subset

Driver Processes results.

driver.m

```
while (jobs– > 0)
tmp = sprintf("mean.%d", jobs);
f = fopen(tmp, "rb", "native");
val = fscanf(f, "%f");
results(jobs + 1) = val;
endwhile
result = mean(results);
```

Running the example

Shell prompt

```
$ ./driver.m
Submitting job(s).....
Logging submit event(s).....
5 job(s) submitted to cluster 565262.
```

5 minutes later...

```
All jobs done.
mean of mean is 161.014978
```

DAGMan

DAGMan: Directed Acyclic Graph Manager

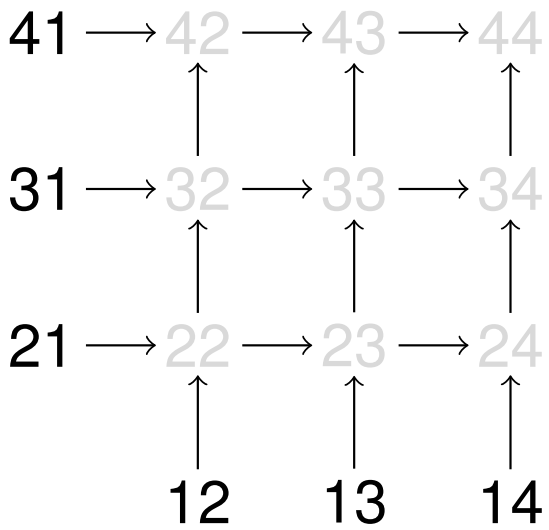
- Often there are dependencies between the individual jobs that make up your application.
- One job's output is another's input.
- The relationships between the different jobs are known a priori, and not generated dynamically during execution.
- Possibly there are many such relationships in your application.

DAGMan is intended for applications like this.

DAGMan
Example problem

Example

- 2-D Matrix of Condor jobs
- Each job has two inputs
  - From leftmost neighbor
  - From lower neighbor
- Initial conditions known
- Desire maximum concurrency



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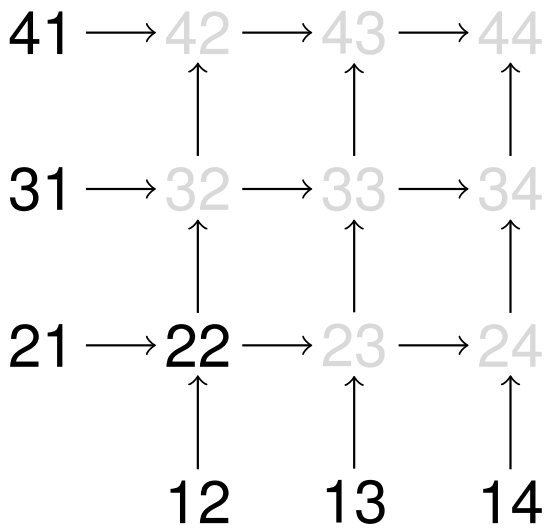

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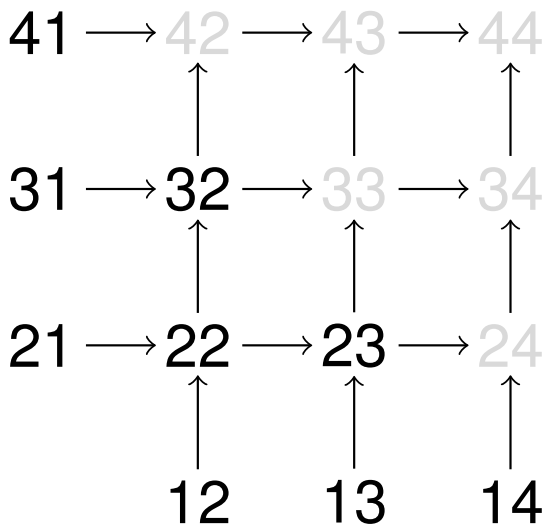

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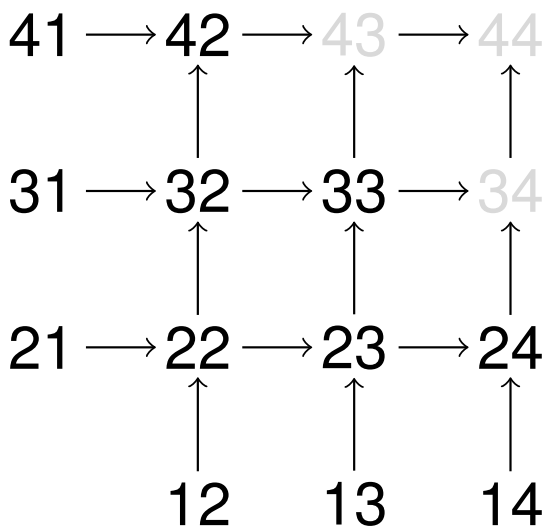

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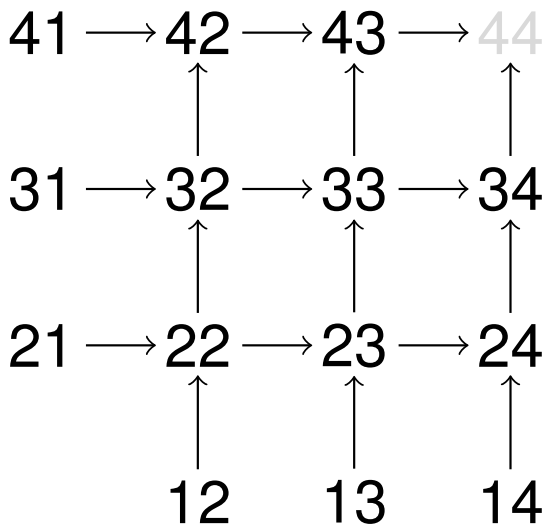

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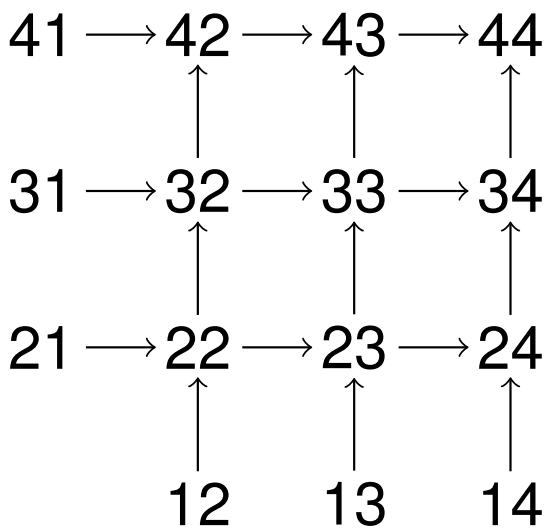


DAGMAN description file

- JOB section names each node and its submit file
- PARENT section describes dependencies
- VARS section names variable to expand in submit file

DAG file

```
JOB Node_1_1 node.sub
JOB Node_2_1 node.sub
JOB Node_2_2 node.sub
...
PARENT Node_1_2 Node_2_1 CHILD Node_2_2
...
VARS Node_2_2 in1="f12"
VARS Node_2_2 in1="f21"
VARS Node_2_2 out="f22" ...
```

submit

```
universe = vanilla

executable   = sum.pl
arguments    = $(IN1) $(IN2) $(IN3)

should_transfer_files = yes
when_to_transfer_output = on_exit

transfer_input_files = $(IN1), $(IN2), $(IN3)

output       = $(OUT)
log          = log

Notification = never
queue
```

Running dagman

submit

```
$ condor_dag_submit grid.dag
```

Condor and GAMS

Using the Grid support within GAMS

- A new feature of GAMS!
- GAMS itself writes submit files, calls condor_submit
- Uses Condor script to glue the pieces together

Condor and GAMS

Example code

New GAMS Commands

```
<model>.solvelink = 3
  ;do not wait for solve, just submit
<model>.handle  (set by the 'submitting' solver)

HandleStatus(handle)  =
  0 bad handle
  1 model ready to solve but no solution
  2 solution ready to be extracted

executeloadhandle model
; loads all equ and var info
```

Condor and GAMS

Running it

Shell Prompt

```
# gamskeep transgrid10.gms
```

Outline

Two Condor Shortcomings

- Condor doesn't run short jobs well.
  - lots of time required to schedule jobs in the pool;
  - time needed to transmit the executable/data/results.
- Condor doesn't deal directly with parallel algorithms.
  - Can have the process on the user's workstation generating waves of "worker" jobs to run in parallel, but
    - each worker job must be scheduled anew in the Condor pool, and
    - the master application has to handle all the details of scheduling, rescheduling after faults, managing input and outputs to workers, etc.

Master-Worker (MW) addresses these issues!

Master-Worker: Basic Ideas

- Master assigns tasks to the workers
- Workers perform tasks, and report results back to master
- Workers do not communicate (except through the master)

- Simple!
- Fault-tolerant
- Dynamic
- Programming model reusable across many applications.

Other Important Features!

- Data common to all tasks is sent to workers only once
- (Try to) Retain workers until the whole computation is complete—don't release them after a single task is done.

These features make for much higher parallel efficiency.

- We now need to transmit much less data between master and workers.
- We avoid the overhead of putting each task on the condor queue and waiting for it to be allocated to a processor.

MW

- Three abstractions in the master-worker paradigm: Master, Worker, and Task.
- The `MW` package encapsulates these abstractions
  - C++ abstract classes
  - User writes 10 functions (Templates and skeletons supplied in distribution)
  - The `MW`ized code will adapt transparently to the dynamic and heterogeneous environment
- The back side of `MW` interfaces to resource management and communications packages:
  - Condor/PVM, Condor/Files
  - Condor/Unix Sockets
  - Single processor (useful for debugging)
  - In principle, could use other platforms.

MW Classes

- MWMaster
  - `get_userinfo()`
  - `setup_initial_tasks()`
  - `pack_worker_init_data()`
  - `act_on_completed_task()`
- MWTask
  - `(un)pack_work`
  - `(un)pack_result`
- MWWorker
  - `unpack_worker_init_data()`
  - `execute_task()`

But wait there's more!

- User-defined checkpointing of master. (Don't lose the whole run if the master crashes.)
- (Rudimentary) Task Scheduling
  - MW assigns first task to first idle worker
  - Lists of tasks and workers can be arbitrarily ordered and reordered
  - User can set task rescheduling policies
- User-defined benchmarking
  - A (user-defined) task is sent to each worker upon initialization
  - By accumulating normalized task CPU time, MW computes a performance statistic that is comparable between runs, though the properties of the pool may differ between runs.

MW Applications

- MWFATCOP (Chen, Ferris, Linderoth) – A branch and cut code for linear integer programming
- MWQAP (Anstreicher, Brixius, Goux, Linderoth) – A branch-and-bound code for solving the quadratic assignment problem
- MWATR (Linderoth, Shapiro, Wright) – A trust-region-enhanced cutting plane code for two-stage linear stochastic programming and statistical verification of solution quality.
- MWKNAP (Glankwamdee, Linderoth) – A simple branch-and-bound knapsack solver
- MWAND (Linderoth, Shen) – A nested decomposition-based solver for multistage stochastic linear programming
- MWSYMCOP (Linderoth, Margot, Thain) – An LP-based branch-and-bound solver for symmetric integer programs

Wealth Accumulation

Given initial capital stock x_0, find $V(x_0)$

$$V(x_0) = \begin{cases} \max\limits_{(c_t, l_t)} & \sum_{t=0}^{\infty} \beta^t u(c_t, l_t) \\ s.t. & x_{t+1} = x_t + f(x_t, l_t) - c_t \end{cases}$$

- c_t and l_t are consumption and labor supply at time t
- capital evolves according to $x_{t+1} = x_t + f(x_t, l_t) - c_t$
- β is the discount factor and $u(c_t, l_t)$ is the utility given consumption c_t and labor supply l_t
- $V(x)$ is the *value function* for $x_0 = x$

Dynamic Programming

An optimization problem with infinitely many variables: c_t, l_t, x_t, $t = 0, 1, 2, \ldots$, so it's hard to attack it directly.

But we can use the *dynamic programming principle*, because the optimal objective $V(x_0)$ depends only on x_0 - not on any "past history" of x.

At the optimal values of x_t, c_t, l_t we have

$$\begin{aligned} V(x_0) &= u(c_0, l_0) + \beta \sum_{t=0}^{\infty} \beta^t u(c_{t+1}, l_{t+1}) \\ &= u(c_0, l_0) + \beta V(x_1) \\ &= u(c_0, l_0) + \beta V(x_0 + f(x_0, l_0) - c_0). \end{aligned}$$

We can use this formula to find V for many different values of x_0 simultaneously.

Bellman Equation for $V(x)$

We look for a function V that satisfies this relationship (for all x):

$$V(x) = \max_{(c,l)} u(c,l) + \beta V(x + f(x,l) - c).$$

This is the Bellman equation.

- The function V is unknown
- Parametric dynamic programming: Approximate $V(x)$ by $\hat{V}(x; a)$, and solve for the parameters a using the Bellman equation.
  - simplest representation: $\hat{V}(x; a) = \sum_{j=0}^{p} a_j x^j$
  - find $a \in R^{p+1}$ such that $\hat{V}(x; a)$ "approximately" satisfies the Bellman equation, on a finite grid of x values: $x^1, x^2, \ldots, x^n$. (Data Fitting.)

Value Function Iteration

Step 0. *Initialization.* Choose functional form for $\hat{V}(x; a)$ and approximation grid $X = \{x_1, \ldots, x_n\}$.
Make initial guess $\hat{V}(x; a^0)$ and choose $\epsilon > 0$.

Step 1. *Maximization step.* Fix $a^k = (a_j^k)_{j=1}^p$.
For $i = 1, \ldots, n$, compute
$v_i = T\hat{V}^k(x_i, a^k) = \max_{(c_i, l_i)} u(c_i, l_i) + \beta \hat{V}(x_i + f(x_i, l_i) - c_i, a^k)$

Step 2. *Data Fitting for a:* Fix c, l. Find a^{k+1} s.t.
$a^{k+1} = \arg\min_a \| \hat{V}(x, a) - v \|^2$

Step 3. *Convergence.* If $\| \hat{V}(x, a^{k+1}) - \hat{V}(x, a^k) \|_\infty > \epsilon$, set $k \leftarrow k + 1$ and go to Step 1; otherwise stop and report solution.

Value Function Iteration in MW

MASTER: *Initialization.* Choose functional form for $\hat{V}(x; a)$ and approximation grid $X = \{x_1, \ldots, x_n\}$.
Make initial guess $\hat{V}(x; a^0)$ and choose $\epsilon > 0$.

WORKER: *Maximization:* Fix $a^k = (a_j^k)_{j=1}^p$.
For $i = 1, \ldots, n$, compute (in parallel)
$v_i = T\hat{V}^k(x_i, a^k) = \max_{(c_i, l_i)} u(c_i, l_i) + \beta \hat{V}(x_i + f(x_i, l_i) - c_i, a^k)$

MASTER: *Data Fitting:* Fix c, l. Find a^{k+1} s.t.
$a^{k+1} = \arg\min_a \| \hat{V}(x, a) - v \|^2$

MASTER: *Convergence.* If $\| \hat{V}(x, a^{k+1}) - \hat{V}(x, a^k) \|_\infty > \epsilon$, set $k \leftarrow k + 1$ and go to Step 1; otherwise stop.

MW Implementation

Each task finds the optimal (c_i, l_i) for a batch of x_i's.

- Calls a simple FORTRAN code (to demonstrate that we can!) to do minimizations.
- Hot starting: the optimal (c_i, l_i) is usually a great starting point for (c_{i+1}, l_{i+1})—so report these values to the master for use at the next iteration.
- The task wrapper (C++) and the FORTRAN code communicate via files.

Good algorithms are still vitally important!

A smart, hard-to-parallelize algorithm often beats a dumb, pleasantly parallel algorithm.

`act_on_complete_task()` on the Master stores the v_i's (and the c_i and l_i values) as they arrive from the workers. When all workers have reported, it solves the least-squares problem (fitting step) to find a^{k+1}.

- Could still take a fitting step without waiting for all tasks to report (partial information) to avoid hangups if some workers go down.
- Could adapt size of task (number of x_i's in each task) to accommodate workers of different speeds.

How Big Can These Get?

Judd: These models can get very big!!!

- Investment Portfolio
  - d assets in the portfolio
  - $X_j = \{x_{j1}, \ldots, x_{jn}\}$ represents j-th asset's position
  - state space: $X = X_1 \times X_2 \cdots \times X_d$
  - transaction cost occurs when adjusting asset positions
- Dynamic Principal-Agent Problem
  - the CEO's performance is evaluated by multiple measures, e.g. stock price, annual profits, etc.
  - the company decides the CEO's compensation package
- Many other economic applications

MWGAMS

Running short-lived GAMS as a MW task

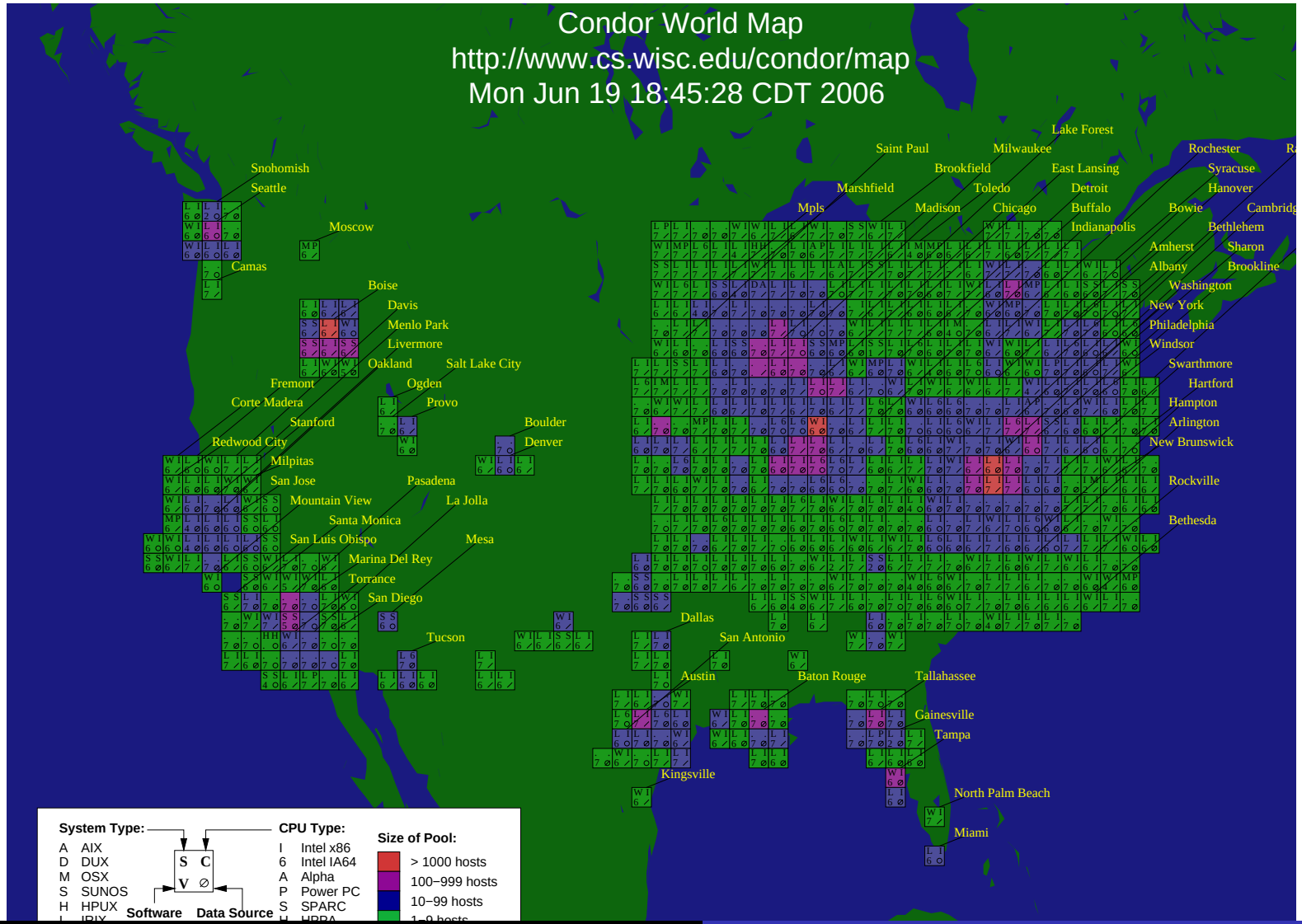
- MWGAMS is a MW application which runs GAMS in the worker
- Good for jobs with a lot of short optimization problems
- User writes entirely in GAMS – no C++ code at all

Summary

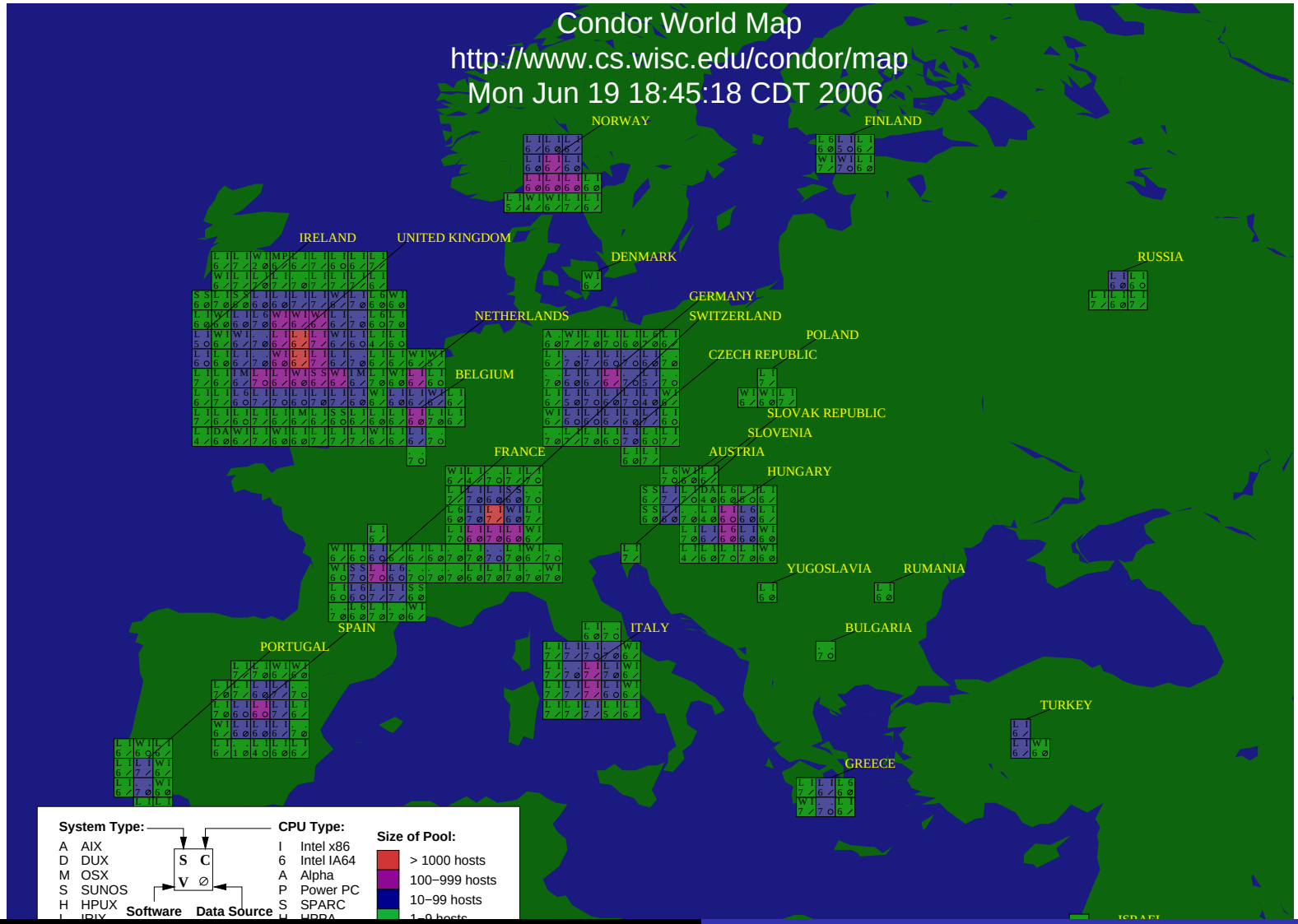
- Condor can easily manage dedicated and desktop machine
- Idle workstations can provide lots of compute cycles
- Master - Worker is a good way to run massively parallel applications

Condor team

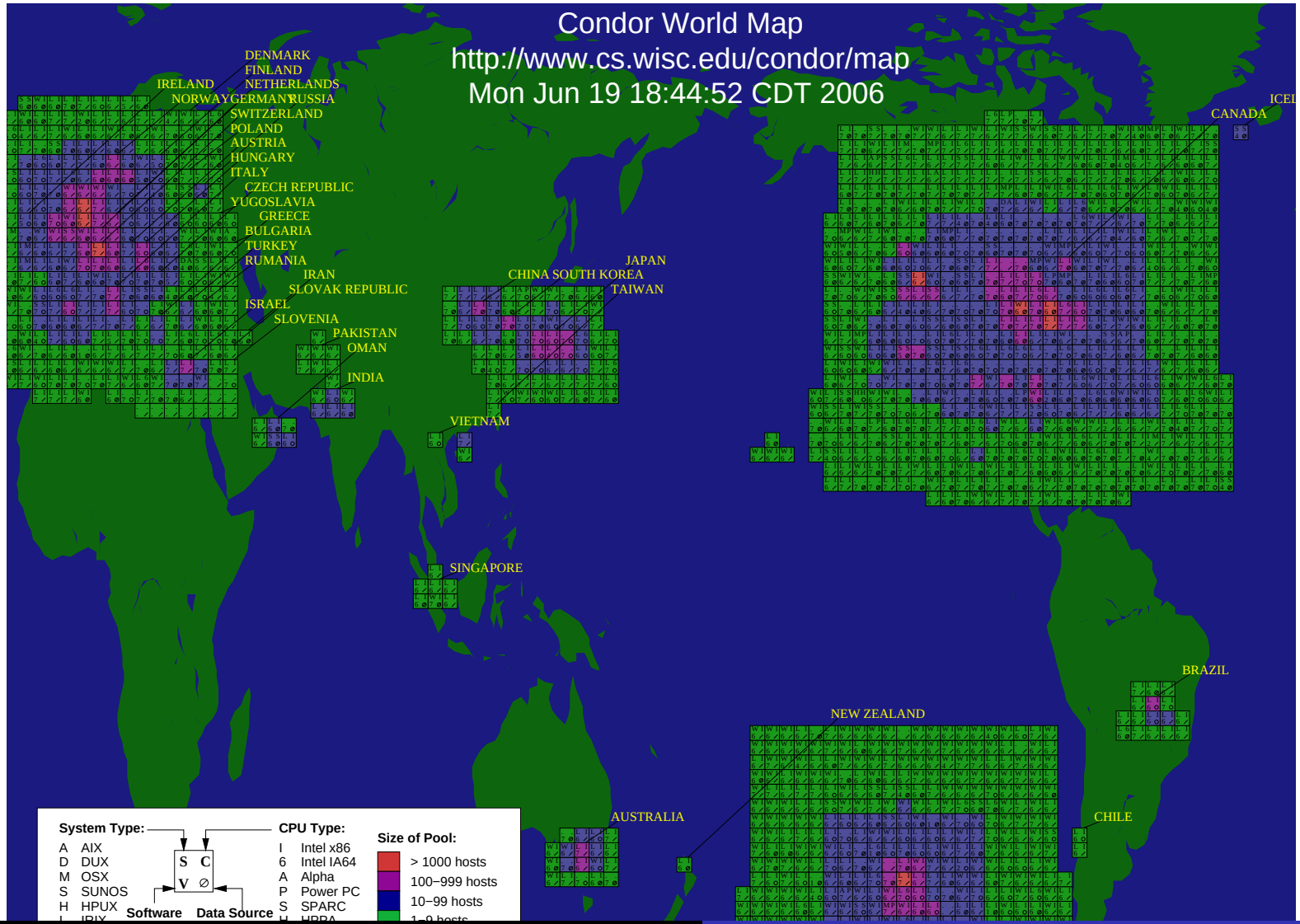
Condor in the US



Condor in Europe



Condor in the World



For more information

- Talk to Greg or Steve!
  - gthain@cs.wisc.edu
- Condor web site: `http://www.cs.wisc.edu`
- Condor-users mailing list (see web site)
- Condor Week 2008
- (If all else fails) 600 page condor manual
- Talk to Miron re: collaboration