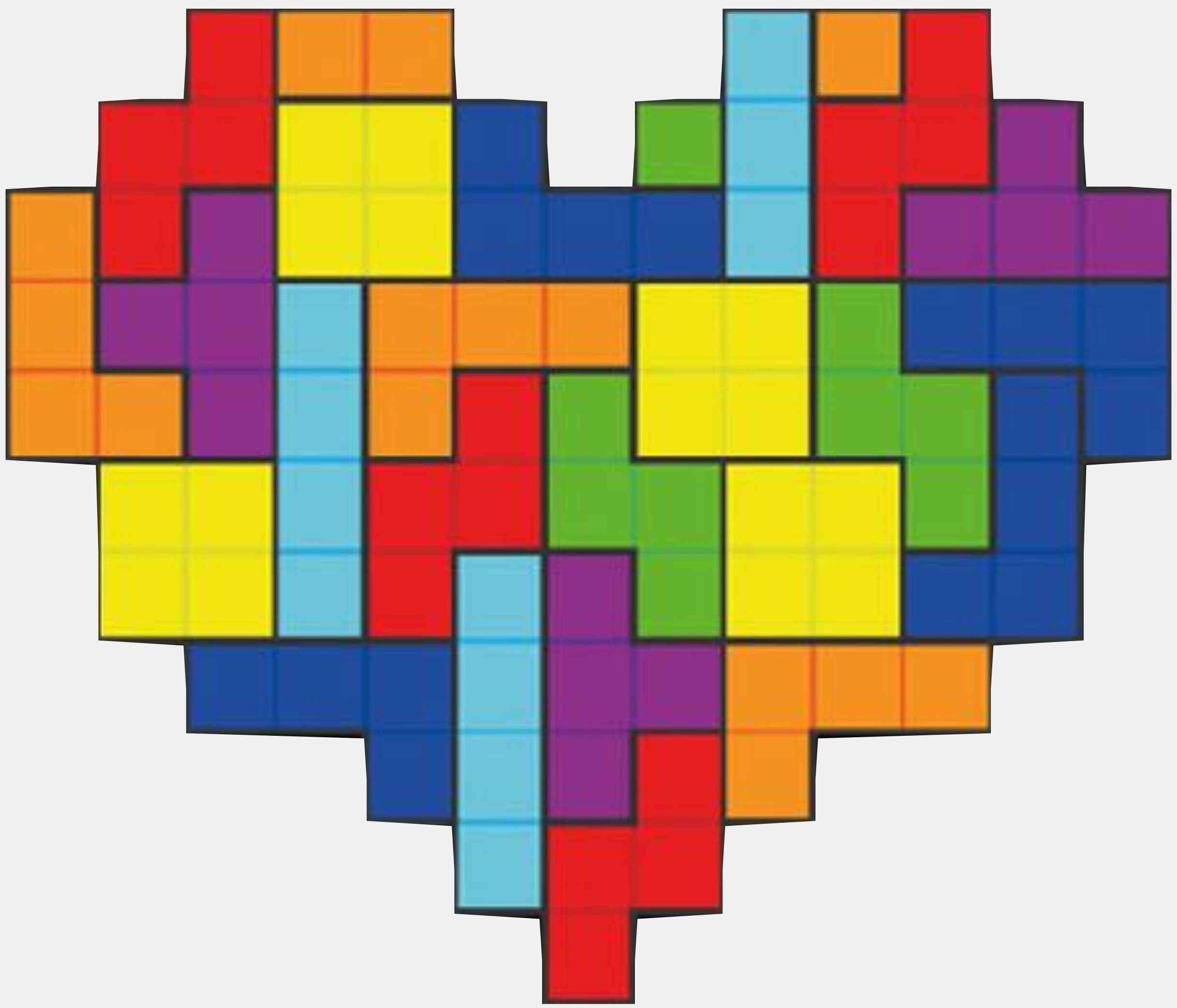
Placing Virtual Machines in a Cloud under Constraints



Fabien Hermenier
— placing rectangles since 2006

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fabien.hermenier@nutanix.com
https://fhermeni.github.io

UNIVERSITÉ DE NANTES

2006 - 2010

PhD - Postdoc

Gestion dynamique des tâches dans les grappes,
une approche à base de machines virtuelles

THE UNIVERSITY OF UTAH

2011

Postdoc

How to design a better testbed:
Lessons from a decade of network experiments

Université Nice Sophia Antipolis

2011 - 2016

Associate professor

VM scheduling, green computing

NUTANIX™

Entreprise cloud company

“Going beyond hyperconverged infrastructures”

VM scheduling, resource management
Virtualization

I am
from the (distributed) system community
not
from the CP community

Inside a private cloud

Clusters

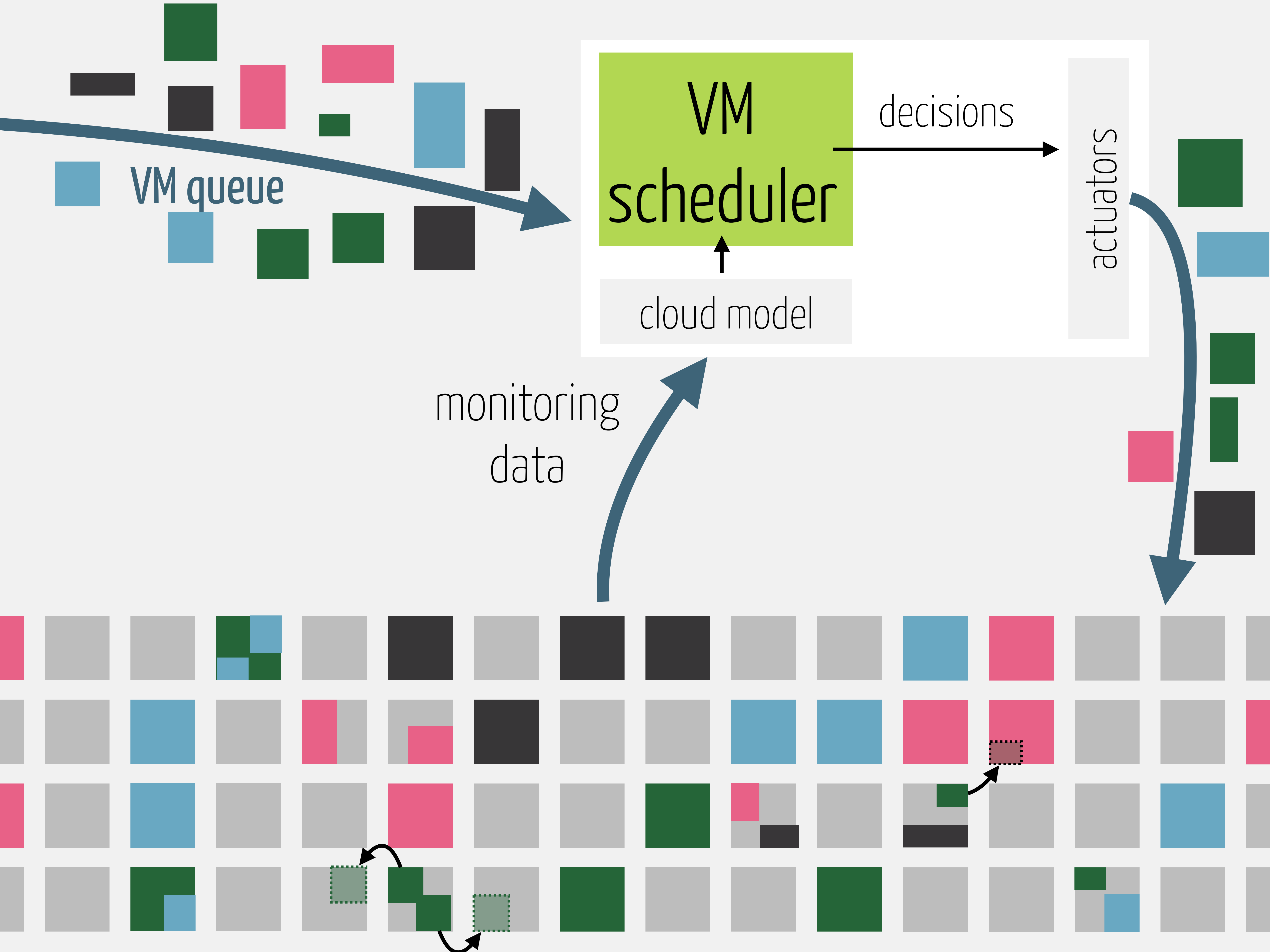
from 2 to *x* physical servers

isolated applications

virtual machines
containers

storage layer

SAN based: converged infrastructure
shared over the nodes: hyper-converged infrastructure



VM queue
VM scheduler
decisions
actuators
cloud model
monitoring data

VM scheduling

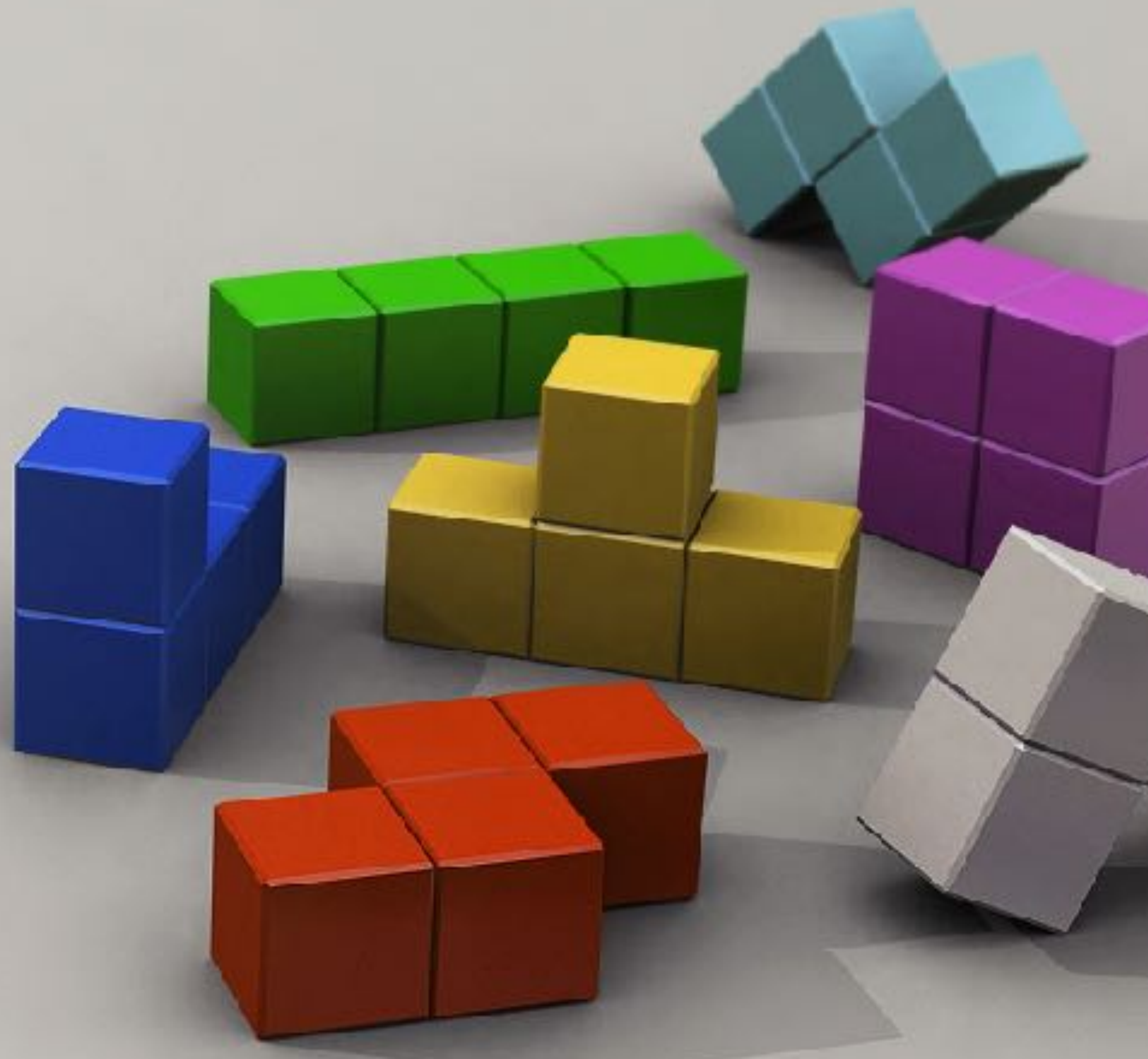
find a server to every VM to run

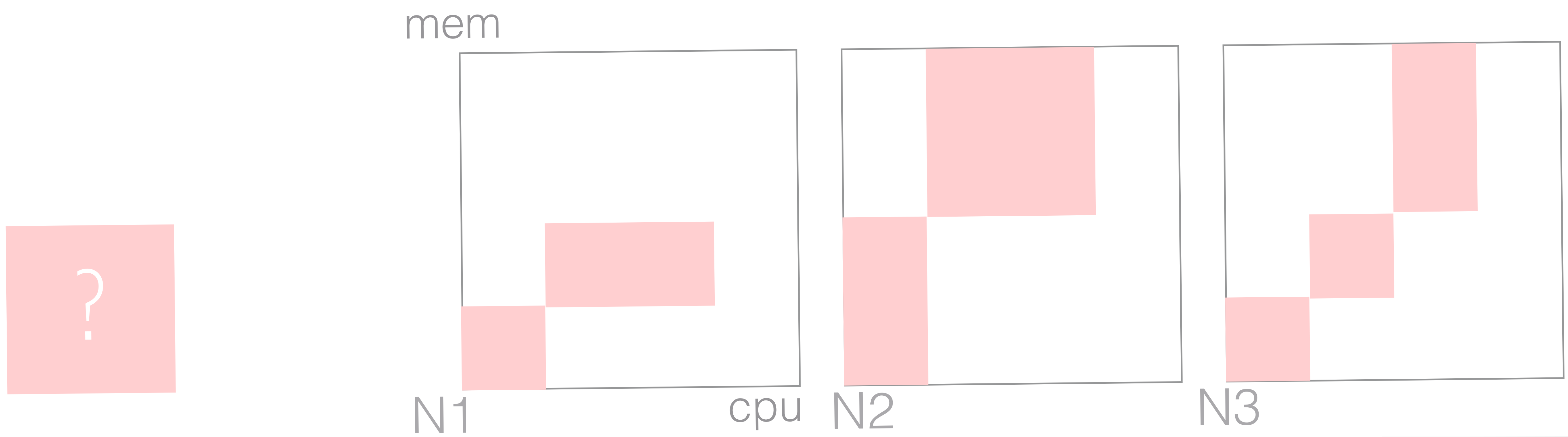
Such that

- compatible hw
- enough pCPU
- enough RAM
- enough storage
- enough whatever

While

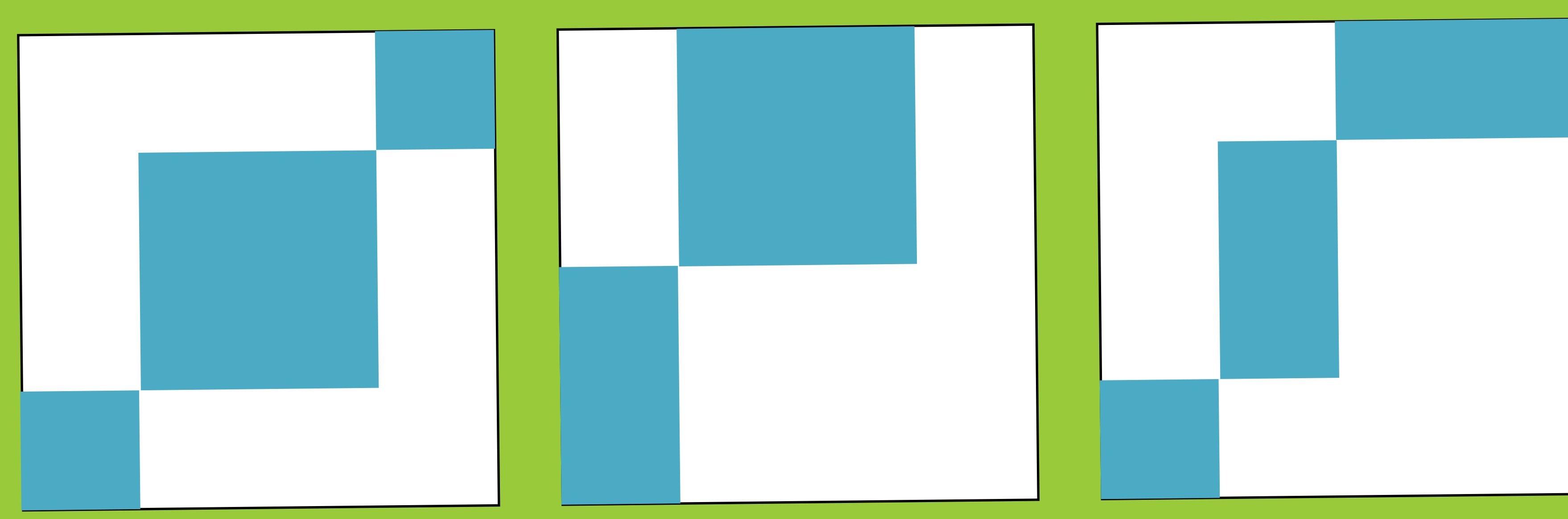
- min or max sth

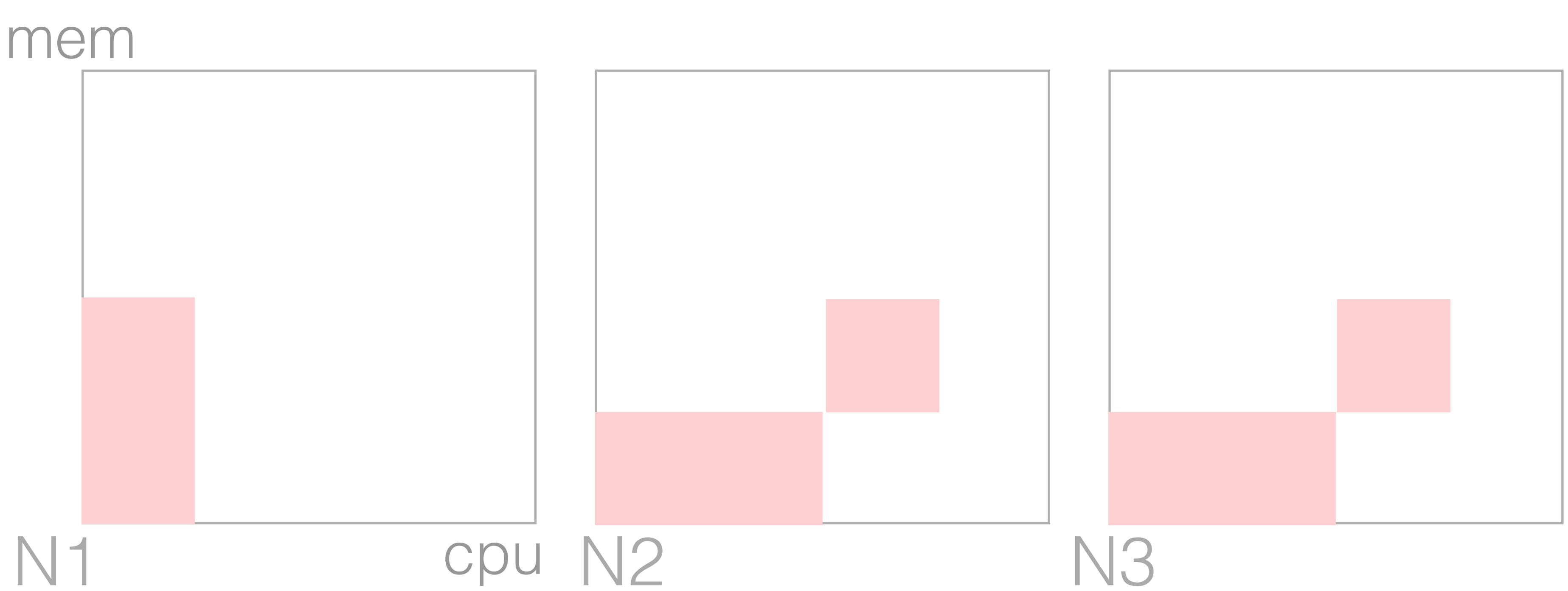




A good VM scheduler provides

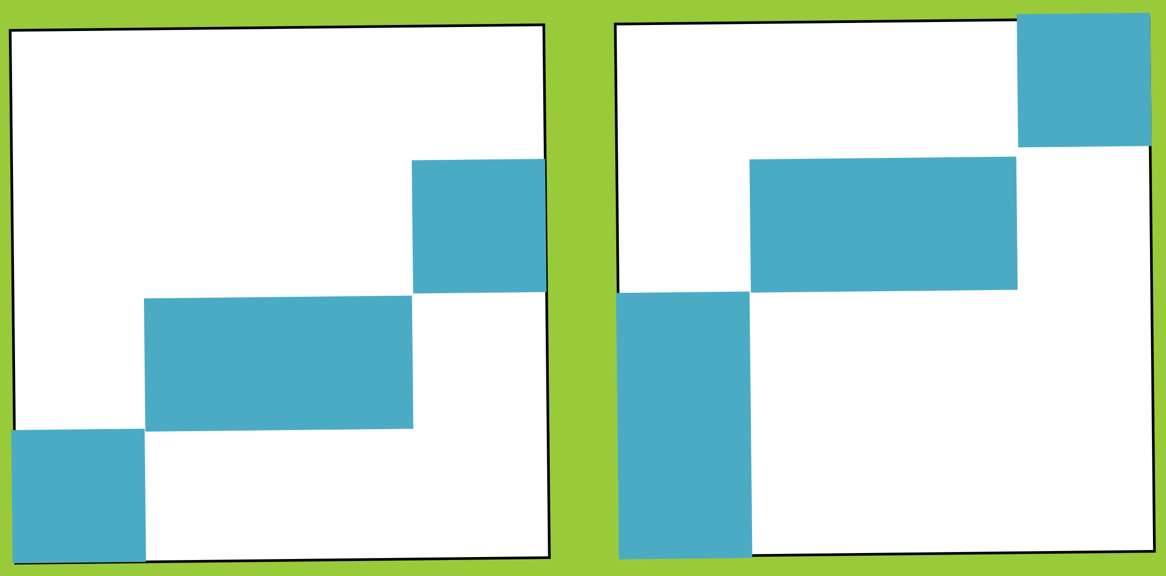
Bigger business value,
same infrastructure





A good VM scheduler provides

Same business value,
smaller infrastructure

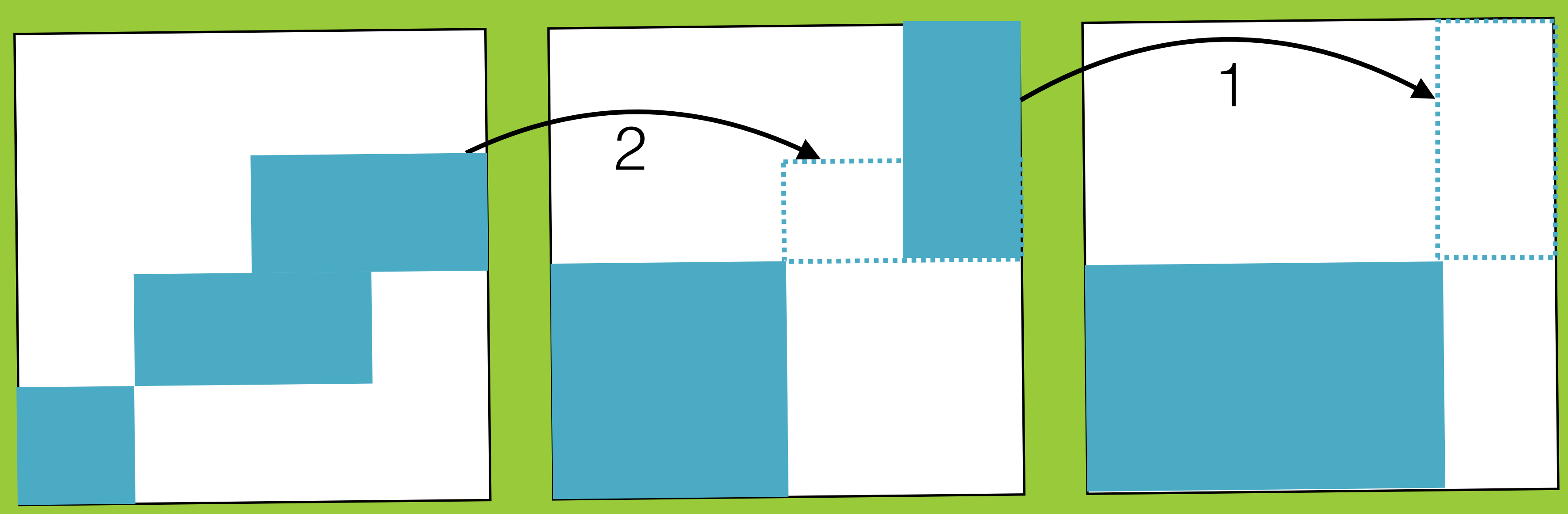


A good **dynamic** VM scheduler fixes issues online

hotspot mitigation

re-balancing

dynamic packing



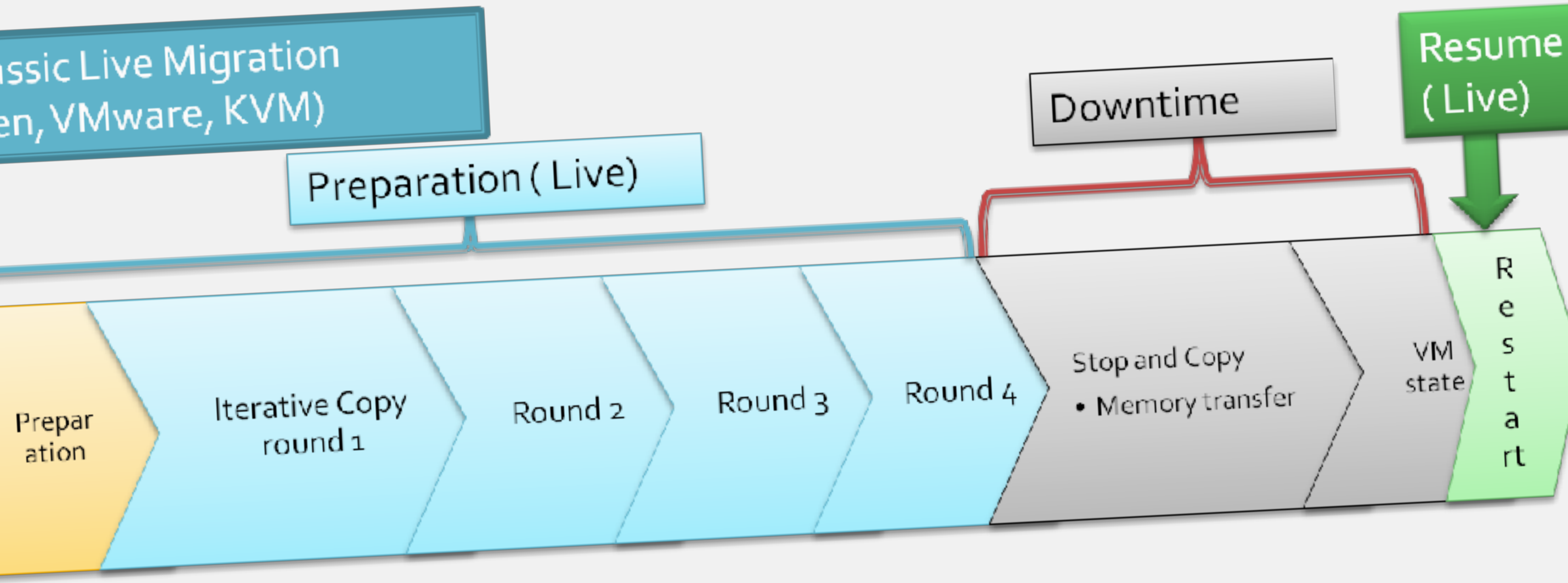
KEEP CALM AND CONSOLIDATE AS HELL

1 node = 

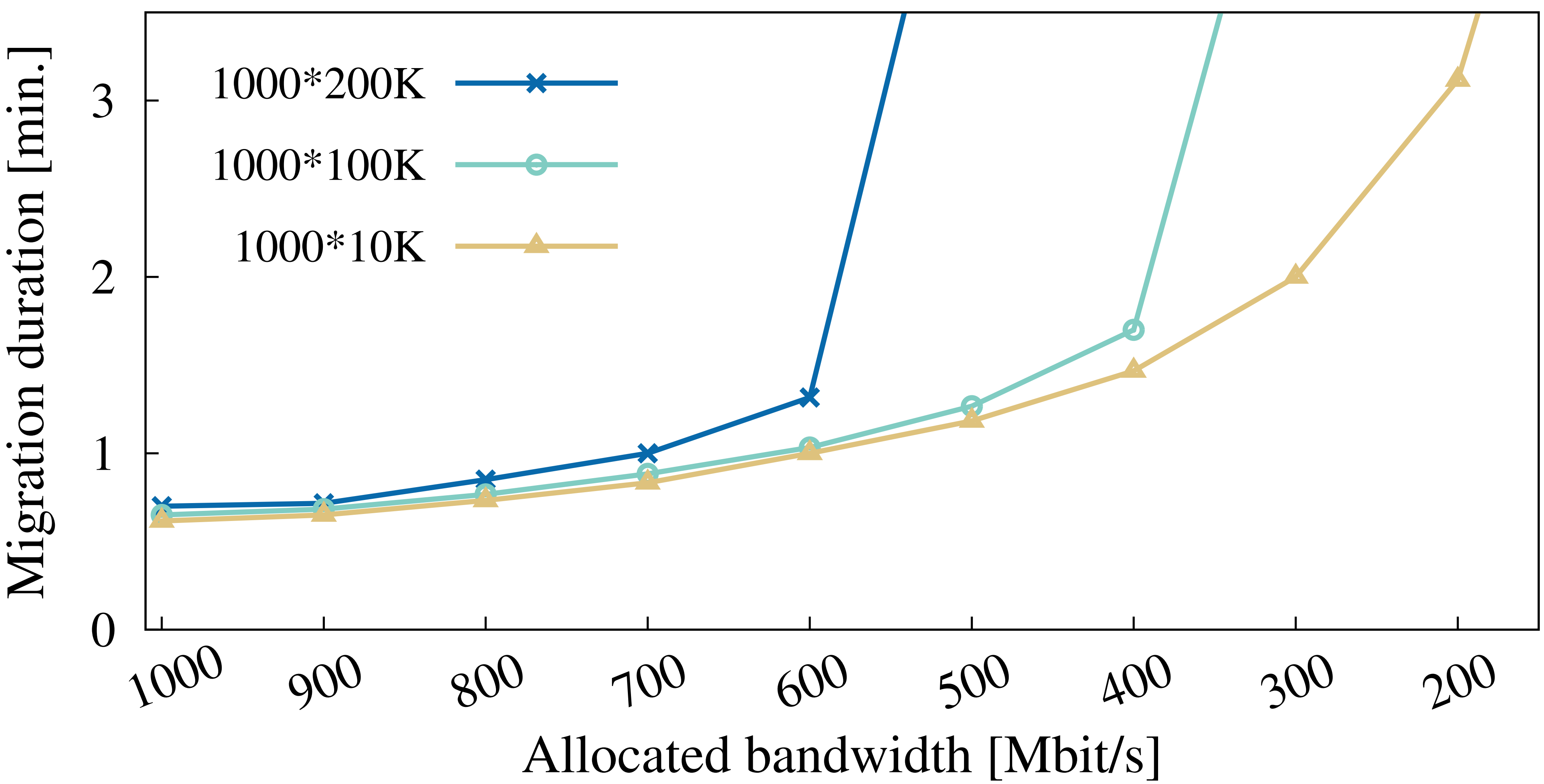
VDI workload:
12+ vCPU/1 pCPU

100+ VMs / server

2005: Live-migration of VMs



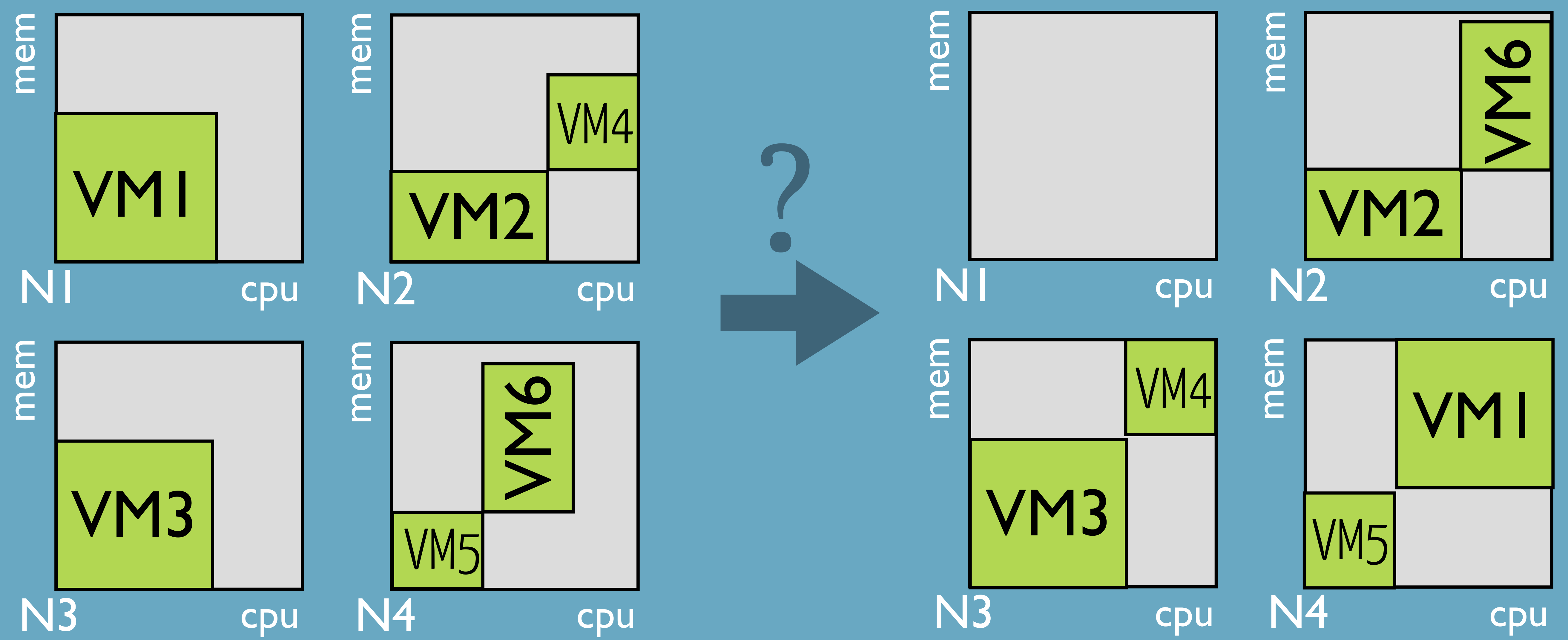
temporary,
resources are used on the source and
the destination nodes



Migrations are costly

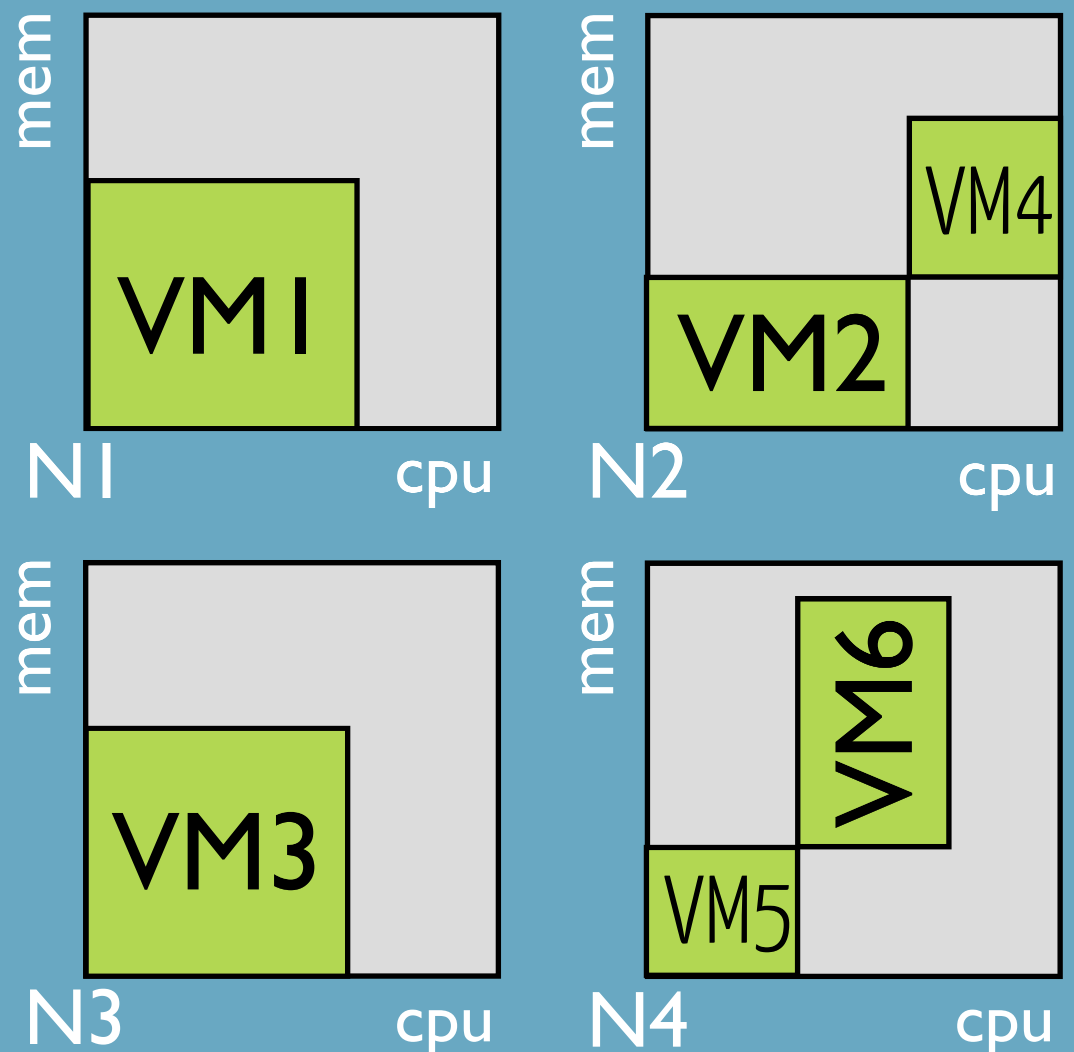
dynamic schedulers

dependency management



dynamic schedulers

dependency management

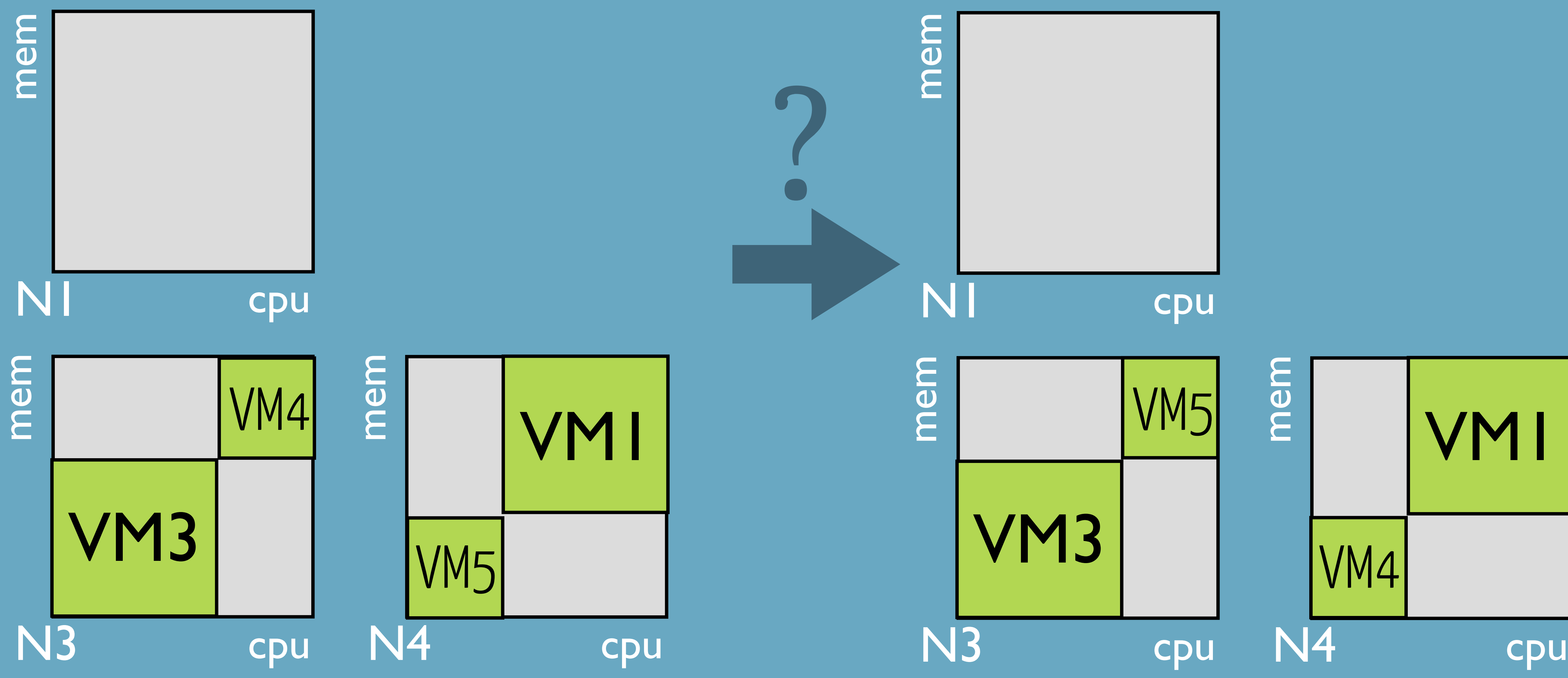


dynamic schedulers

cyclic dependencies

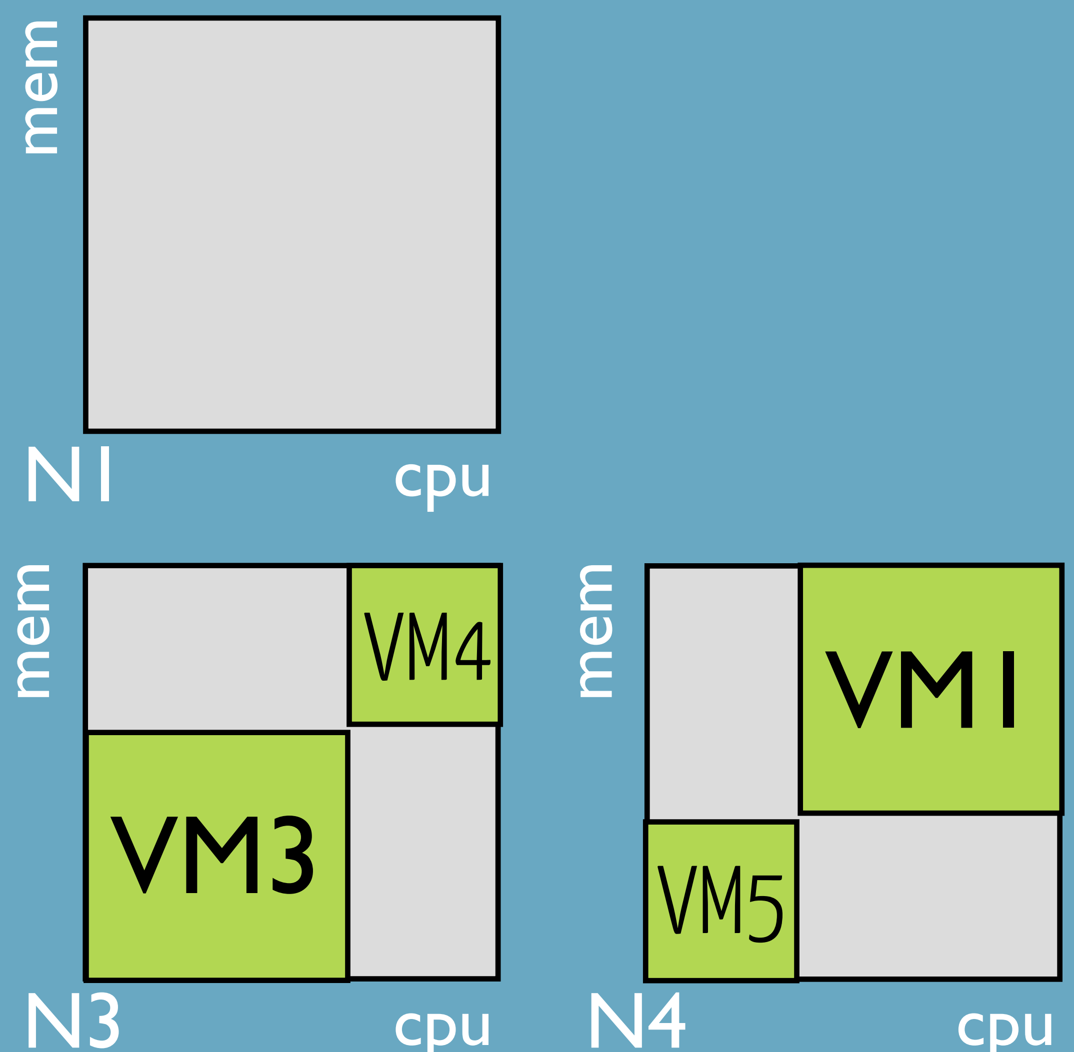
anti-affinity(VM3,VM4)
min(#onlineNodes)

anti-affinity(VM3,VM4)
min(#onlineNodes)



dynamic schedulers

cyclic dependencies

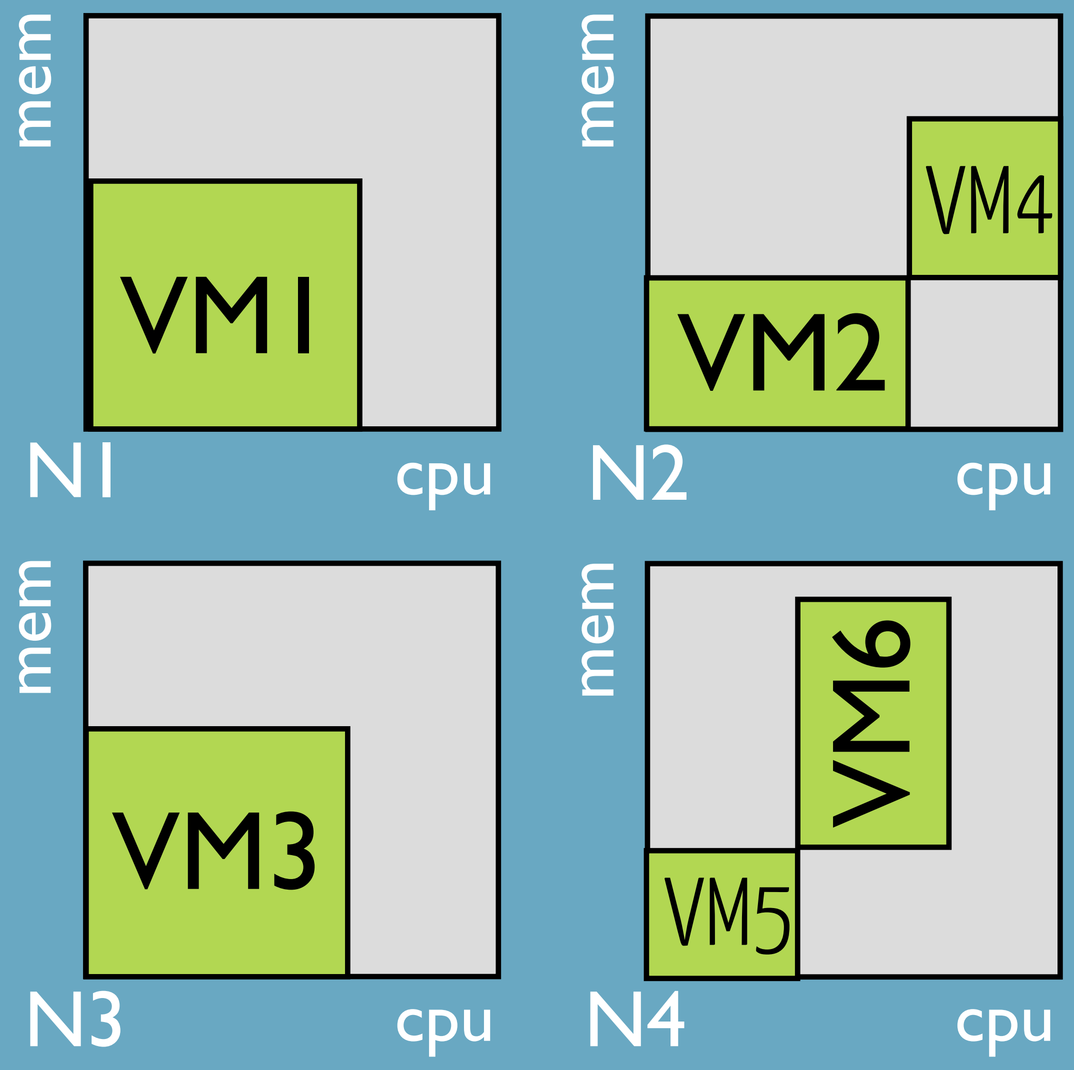


a pivot to break the cycle

fix or prevent the situation ?

dynamic schedulers

quality at a price

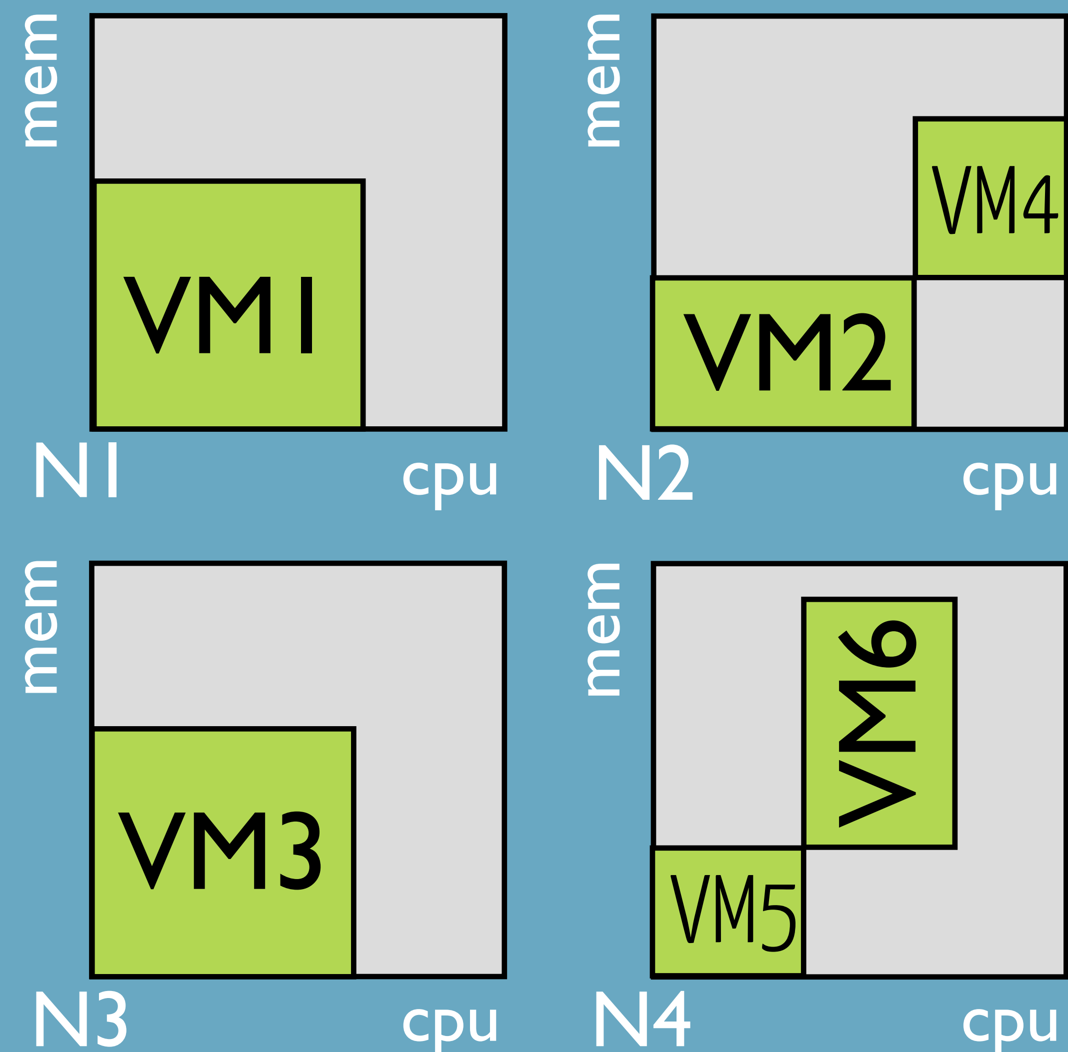


min(#onlineNodes) = 3

sol #1: 1m,2m,2m

dynamic schedulers

quality at a price



$min(\#onlineNodes) = 3$

sol #1: 1m,2m,2m

sol #2: 1m,2m
1m

lower MTTR
(faster)

static schedulers

consider the VM queue

deployed everywhere

fragmentation issues

dynamic schedulers

live-migrations to
address fragmentation

Costly
(storage, migration latency)

thousands of articles

over-hyped ?

but used in private clouds
(steady workloads ?)

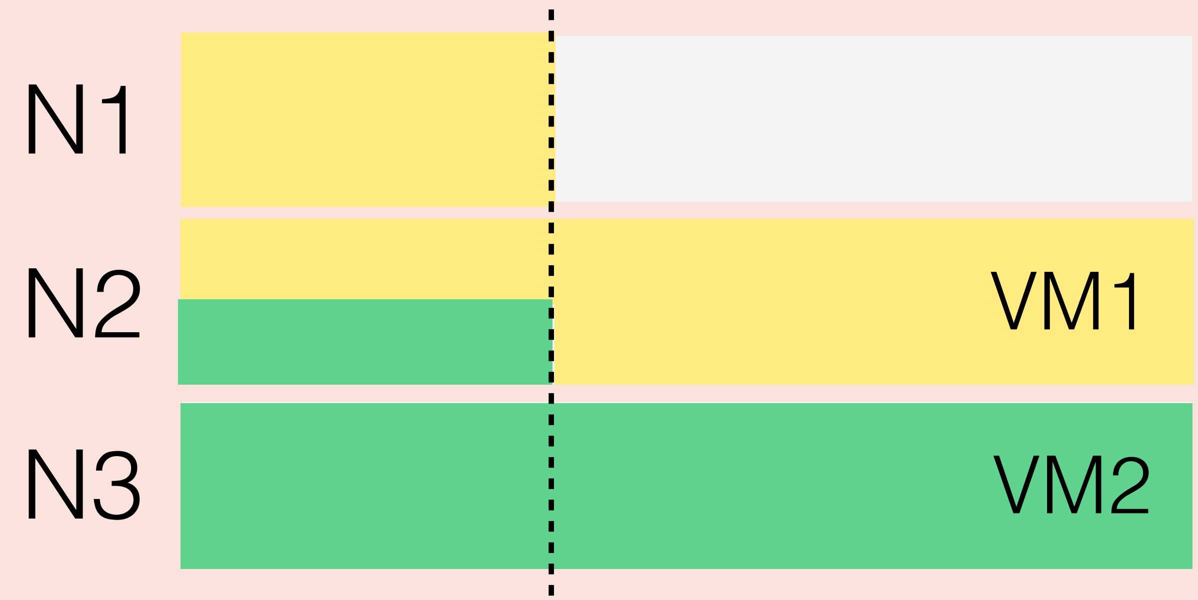
Placement constraints

customer or provider side

various concerns	performance, security, power efficiency, legal agreements, high-availability, fault-tolerance ...
dimension	spatial (placement) or temporal (scheduling)
enforcement level	hard or soft discrete or continuous
manipulated concepts	state, placement, resource allocation, action schedule, counters, etc.

discrete constraints

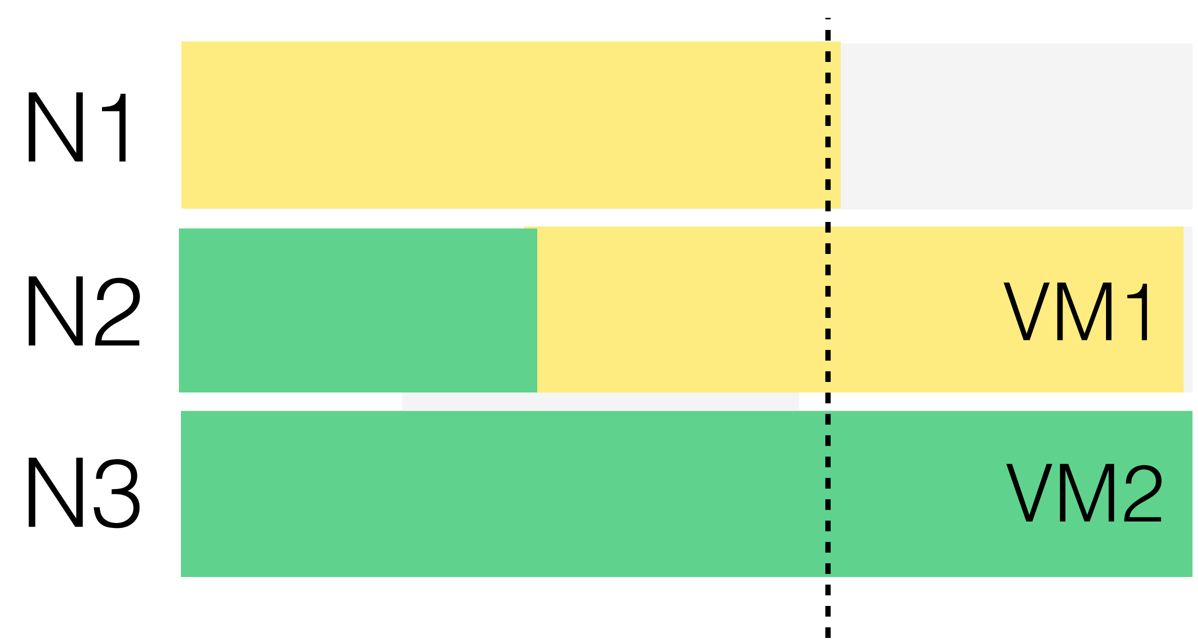
```
>>spread(VM[1,2])
ban(VM1, N1)
ban(VM2, N2)
```



“simple” spatial problem

continuous constraints

```
spread(VM[1,2])
ban(VM1, N1)
ban(VM2, N2)
```



harder scheduling problem
(think about actions interleaving)

hard constraints

`spread(VM[1..50])`

must be satisfied
all or nothing approach
not always meaningful

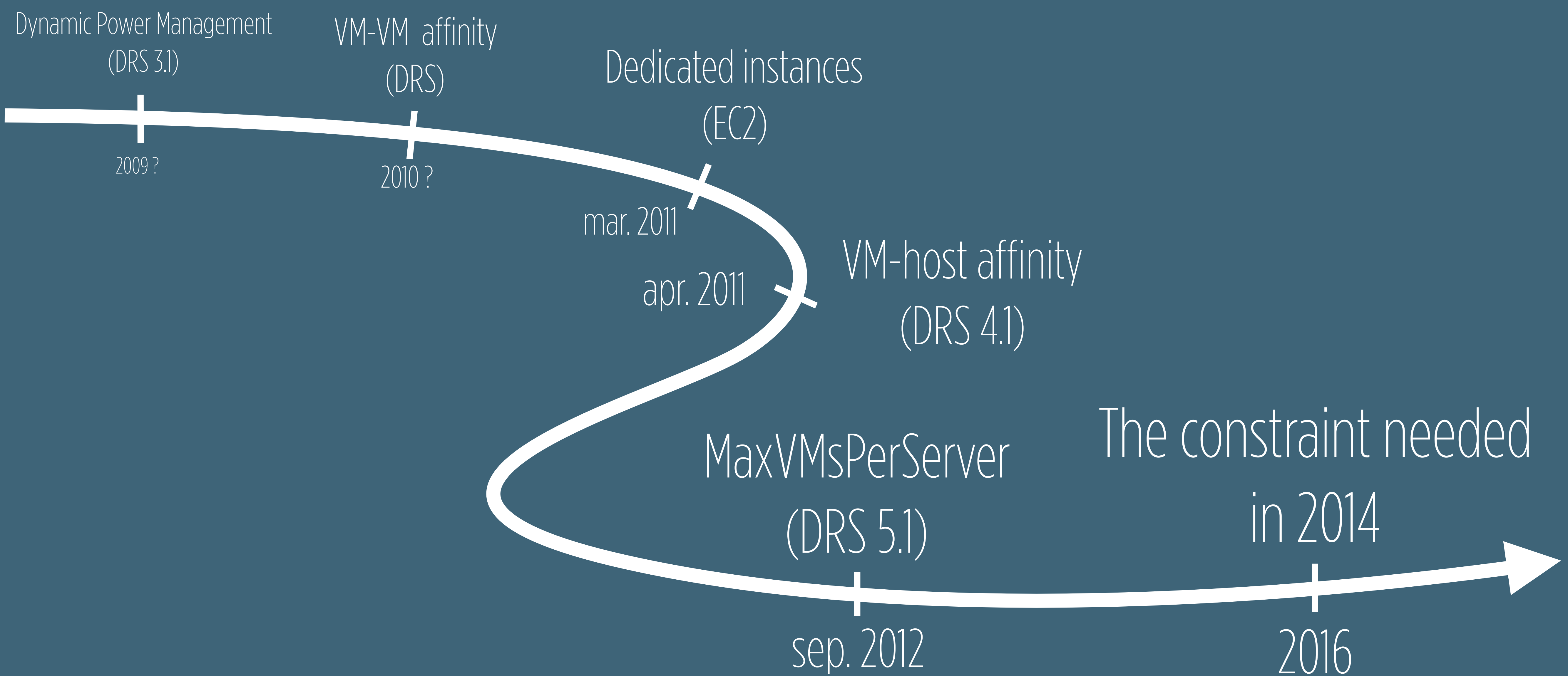
soft constraints

`mostlySpread(VM[1..50], 4, 6)`

satisfiable or not
internal or external penalty model

harder to implement/scale
hard to standardise ?

The constraint catalog evolves



the objective

provider side

$min(x)$ or $max(x)$

atomic objectives

$$min(penalties)$$

$$min(Total\ Cost\ Ownership)$$

$$min(unbalance)$$

$$\ldots$$

composite objectives

using weights

$$min(\alpha x + \beta y)$$

How to estimate coefficients ?

useful to model sth. you don't understand ?

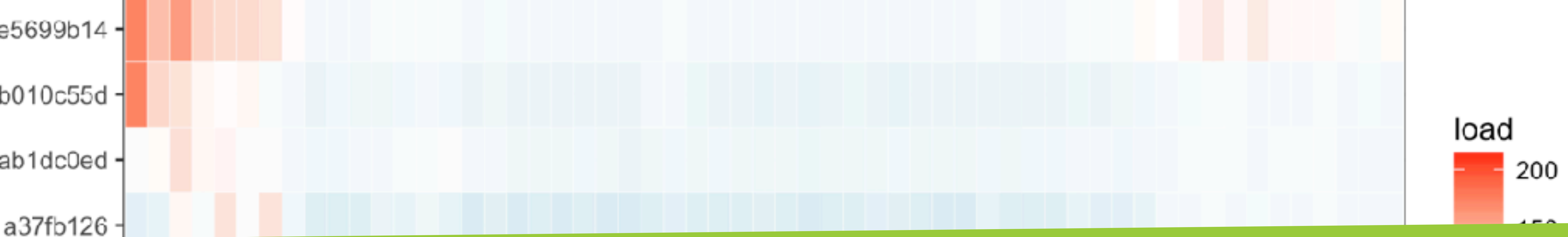
$$min(\alpha\ TCO + \beta\ VIOLATIONS)$$

€ as a common quantifier:

$$max(REVENUES)$$

Optimize or satisfy ?

min(...) or max(...)	threshold based
easy to say	domain specific expertise
hardly provable	verifiable
composable through weighting magic	composable



Acropolis Dynamic Scheduler mitigates hotspot

Trigger

Thresholds

85%

CPU

storage-CPU

Maintain

affinity constraints

Resource demand
(from machine learning)

Minimize

$\sum$ mig. cost

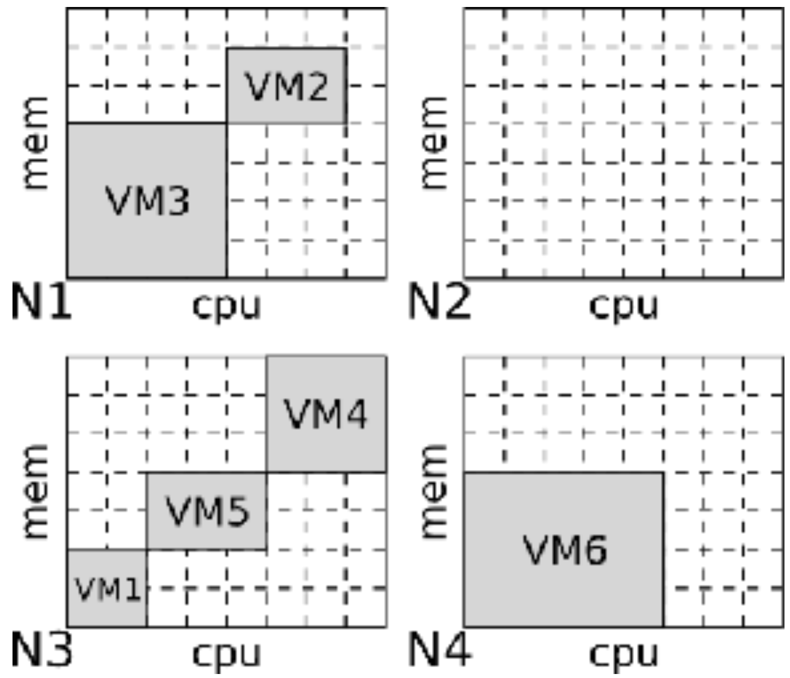
30 sec. timeout

128MB RAM max

BtrPlace

adapt the VM placement depending on pluggable expectations

network and memory-aware migration scheduler, VM-(VM|PM) affinities, resource matchmaking, node state manipulation, counter based restrictions, energy efficiency, discrete or continuous restrictions interaction though a DSL, an API or JSON messages

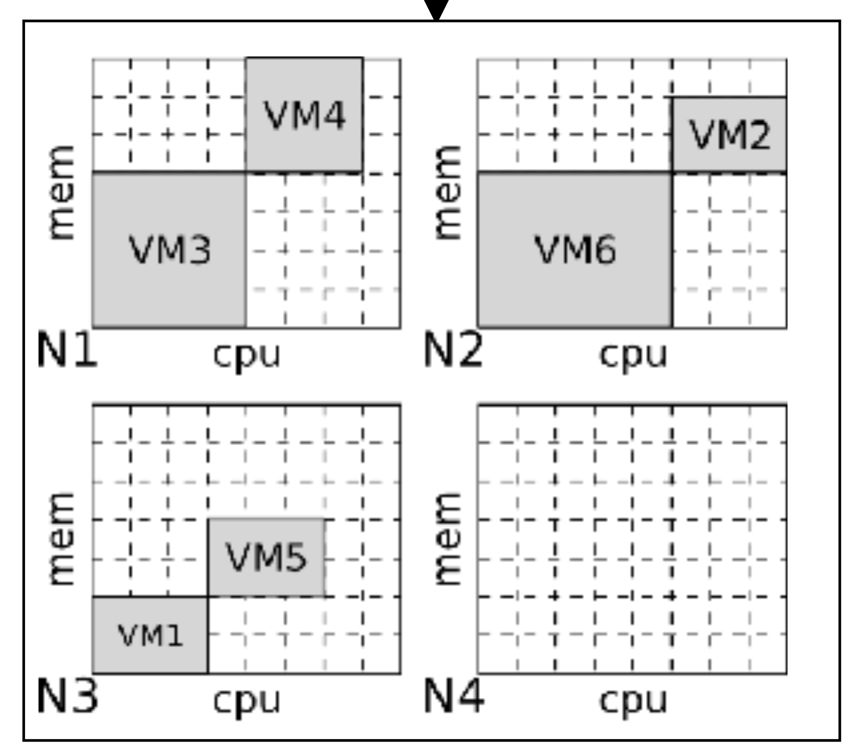



```
spread(VM[2..3]);
preserve(VM1,'cpu', 3);
offline(@N4);
```

BtrPlace

The reconfiguration **plan**

```
0'00 to 0'02: relocate(VM2,N2)
0'00 to 0'04: relocate(VM6,N2)
0'02 to 0'05: relocate(VM4,N1)
0'04 to 0'08: shutdown(N4)
0'05 to 0'06: allocate(VM1,'cpu',3)
```



P.S: From a theoretical to a practical schedule

duration may be longer
convert to an event based schedule

/!\ possible loss of quality but no alternative yet

```
0:3 - migrate VM4
0:3 - migrate VM5
0:4 - migrate VM2
3:8 - migrate VM7
4:8 - shutdown(N2)
```

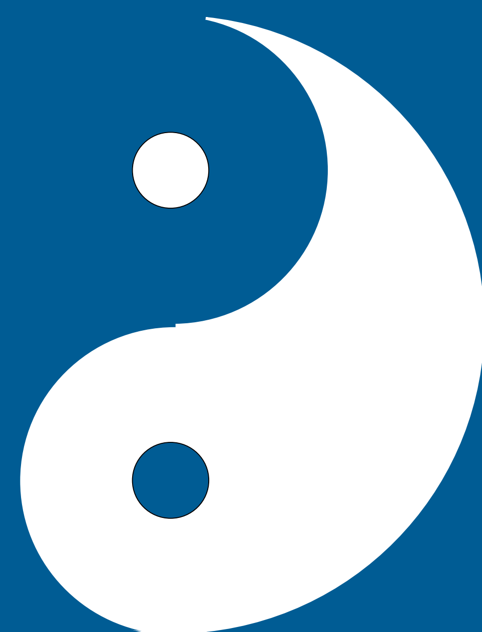
```
- : migrate VM4
- : migrate VM5
- : migrate VM2
!migrate(VM2) & !migrate(VM4): shutdown(N2)
!migrate(VM5):  migrate VM7
```

CHOCO

An Open-Source java library
for constraint programming

$$
\begin{aligned}
\mathcal{X} &= \{x_1, x_2, x_3\} \\
\mathcal{D}(x_i) &= [0,2]\,, \forall x_i \in \mathcal{X} \\
\mathcal{C} &= \begin{cases} c_1 : x_1 < x_2 \\ c_2 : x_1 + x_2 \geq 2 \\ c_3 : x_1 < x_3 \end{cases}
\end{aligned}
$$

deterministic composition
high-level constraints



the right model
for the right problem

Entropy

http://entropy.gforge.inria.fr

BtrPlace

2006 2011 2017

From how it worked to how it works

Consequences of trying to understand

2006 - 2009

Entropy

http://entropy.gforge.inria.fr

No knowledge in CP: Collaboration with the Nantes team

2 phases approach: 1 problem for the placement (VMPP),
1 for the “schedule” (VMRP)

(Faster & better than 1 phase + weighting magic)

[vee 2009]

2006 - 2009

Entropy an Autonomic VM Manager for Clusters

http://entropy.gforge.inria.fr

The placement problem (VMPP)

VMs are idle or burning the CPUs

Old-school `bin-packing`
H_i bit vectors + `bool_channelling`

$$\mathcal{R}_p \cdot H_i \leq \mathcal{C}_p(n_i) \quad \forall n_i \in \mathcal{N}$$
$$\mathcal{R}_m \cdot H_i \leq \mathcal{C}_m(n_i) \quad \forall n_i \in \mathcal{N}$$

`Multi-knapsack` constraint + dynamic programming
(Thanks Xavier Lorca & Hadrien Cambazard)

Symmetry breaking for items not fitting

Minimize `#nodes` using `atmost_nvalue`
(green computing hype)

2006 - 2009

Entropy an Autonomic VM Manager for Clusters

http://entropy.gforge.inria.fr

The replacement problem (VMRP)

VMPP variation:

`atmost_nvalue, #nodes` as a constant

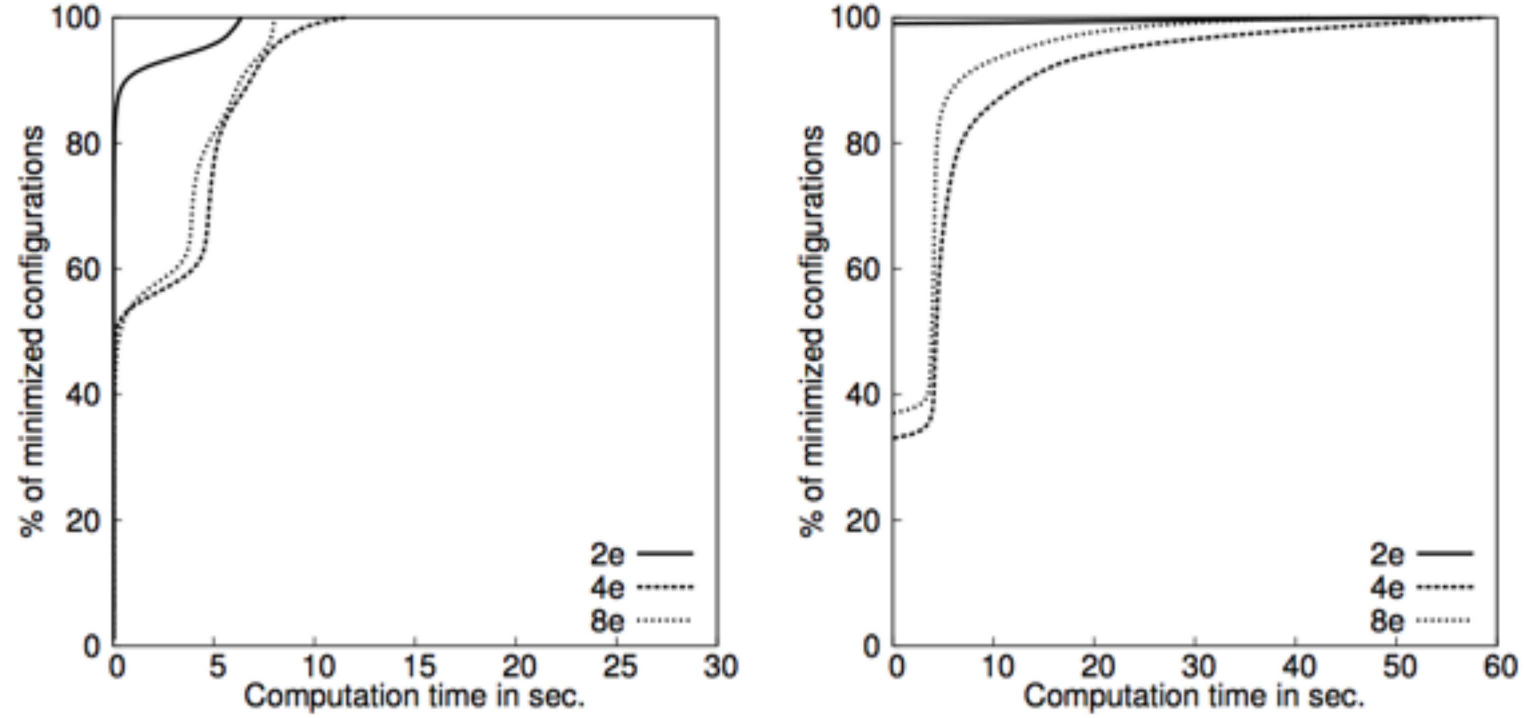
`migration_duration: [0, K], 0 iff stays`

dependency_management & cost function:
hard coded inside a propagator

min (sum of the end moment of migrations)

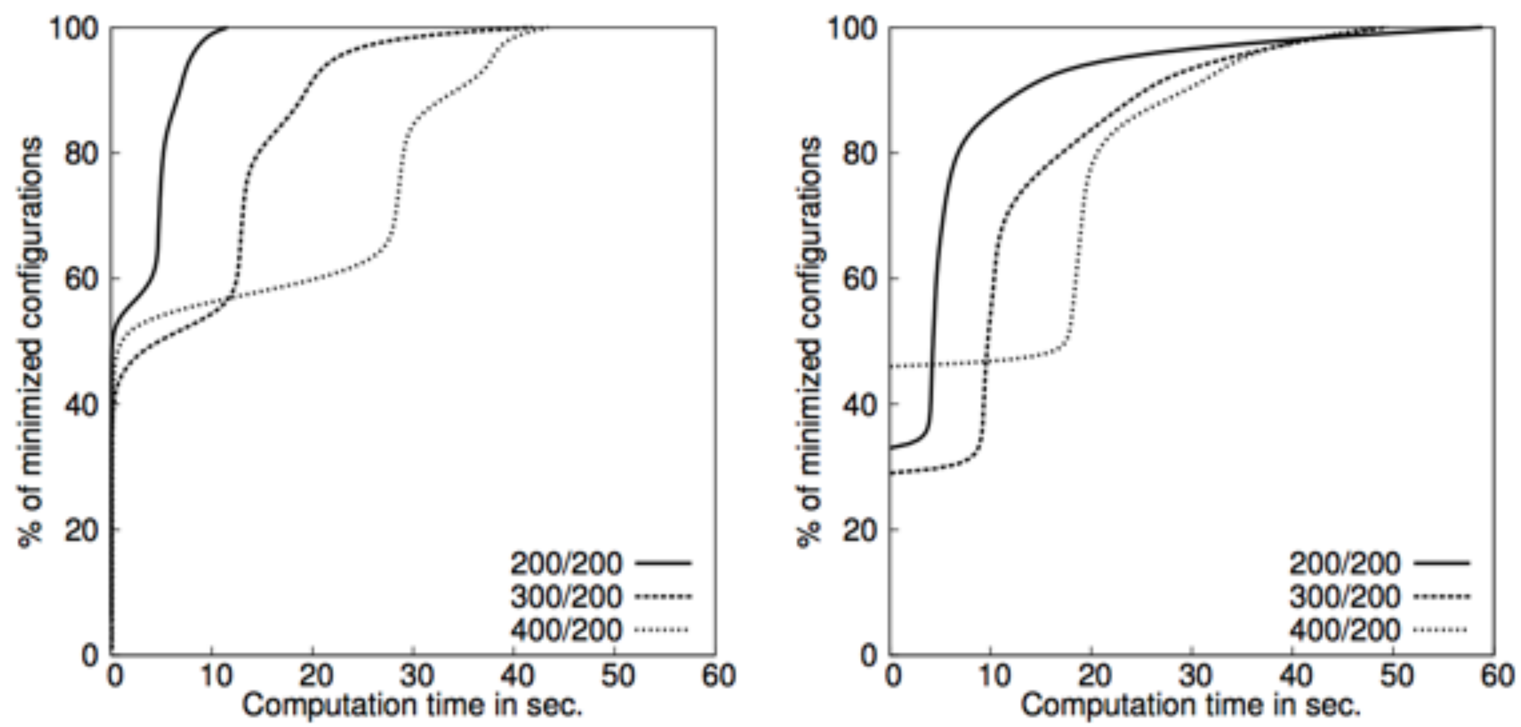
Symmetry breaking
50% faster

200 VMs/ 200 nodes



(a) VMPP (b) VMRP

Global perf
2 minutes for a local opt.



(a) VMPP (b) VMRP

Reviewing Entropy design

Scheduling heuristic prevents control

hard-coded but vital heuristic inside a propagator
not optimisation friendly

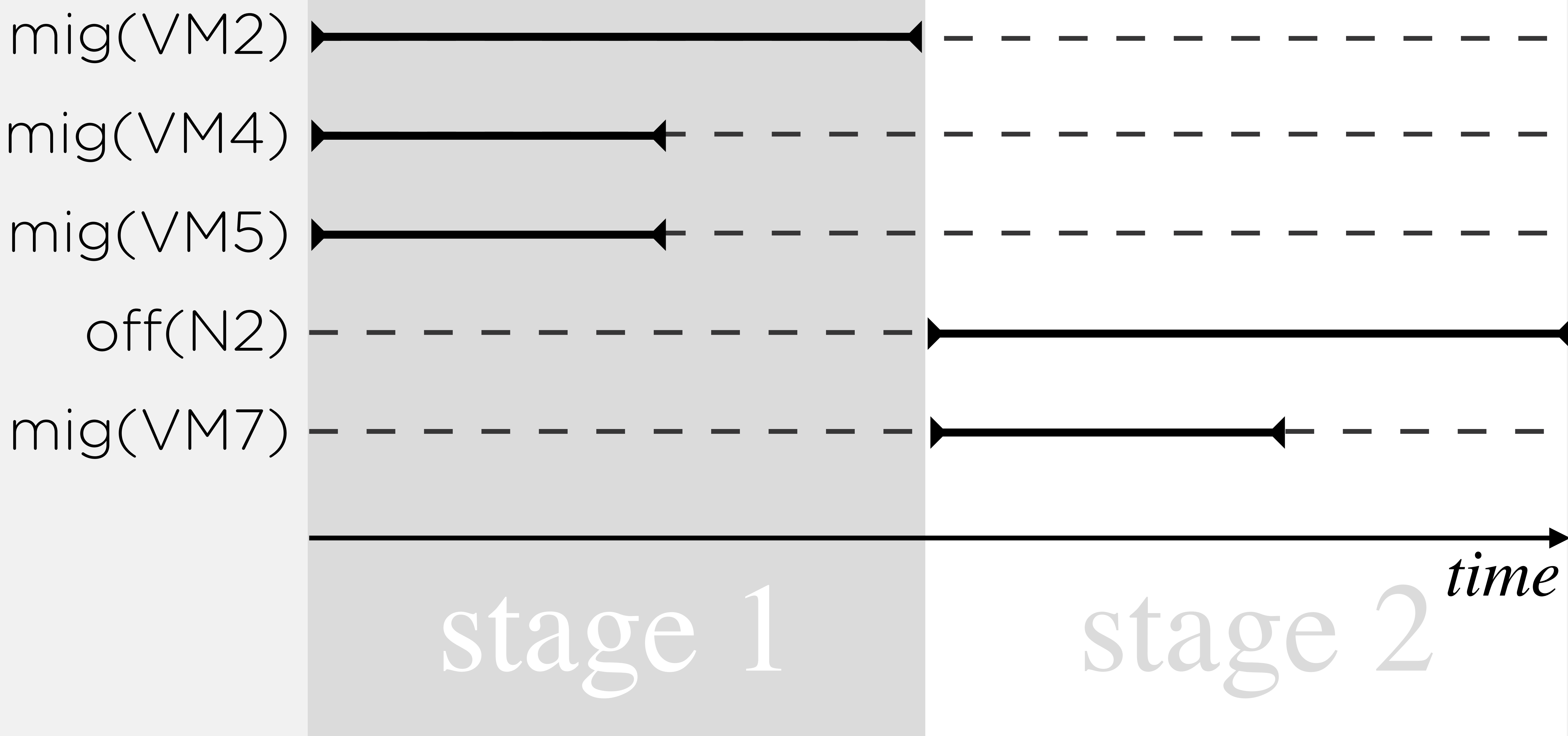
Scalability issue

model-level: n*m binary variables, 5k VMs/100 servers: 500k bool vars
memory level: see above (4GB RAM in 2006)

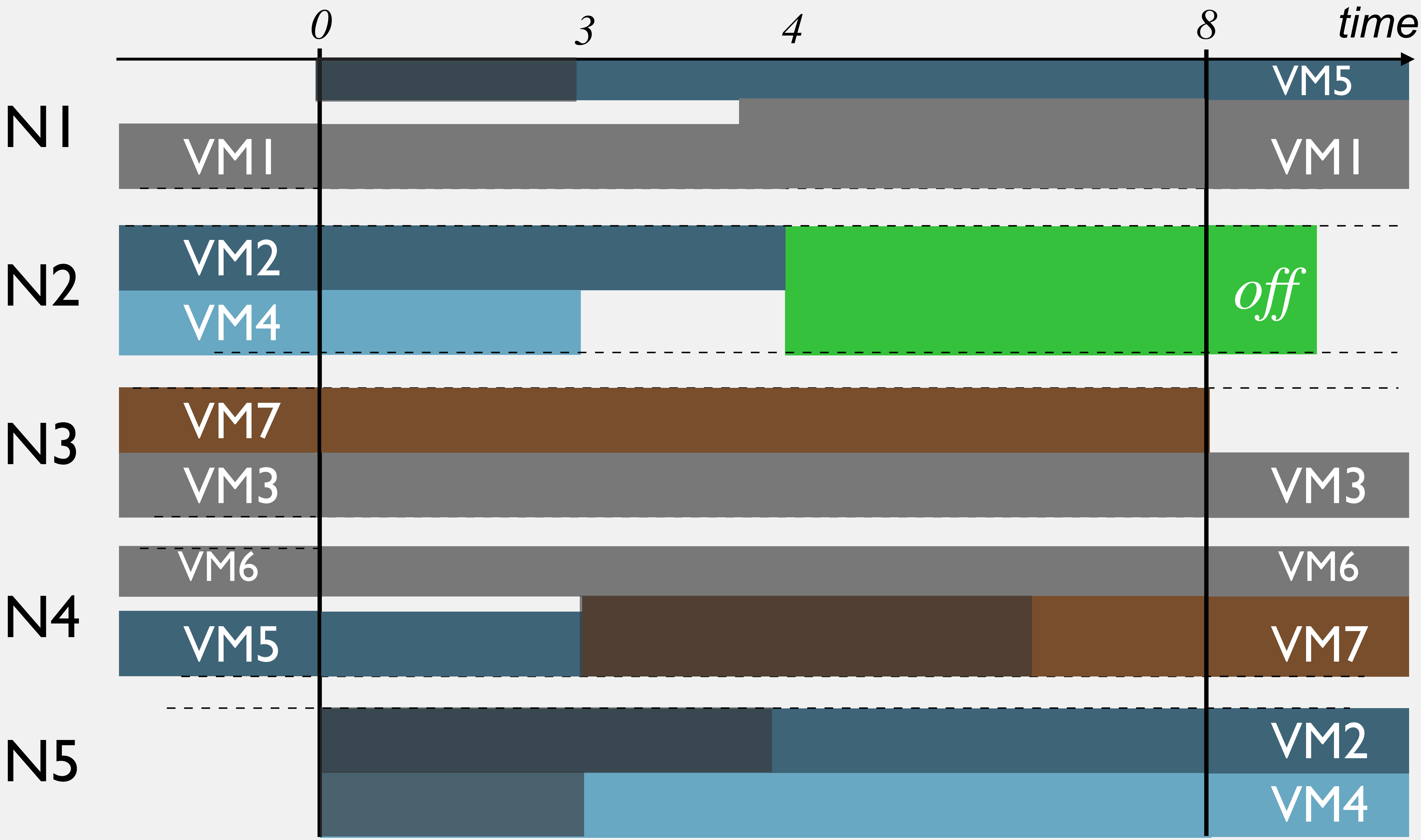
Objective issue

No one really cares about `min(#nodes)`
`min(#migration)` dominates

coarse grain staging delay actions



2010+ : let schedule properly

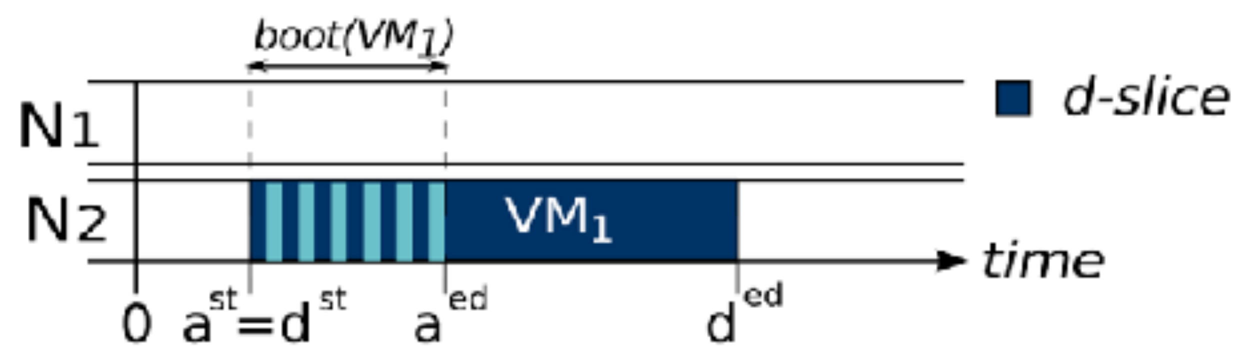


Resource-Constrained Project Scheduling Problem

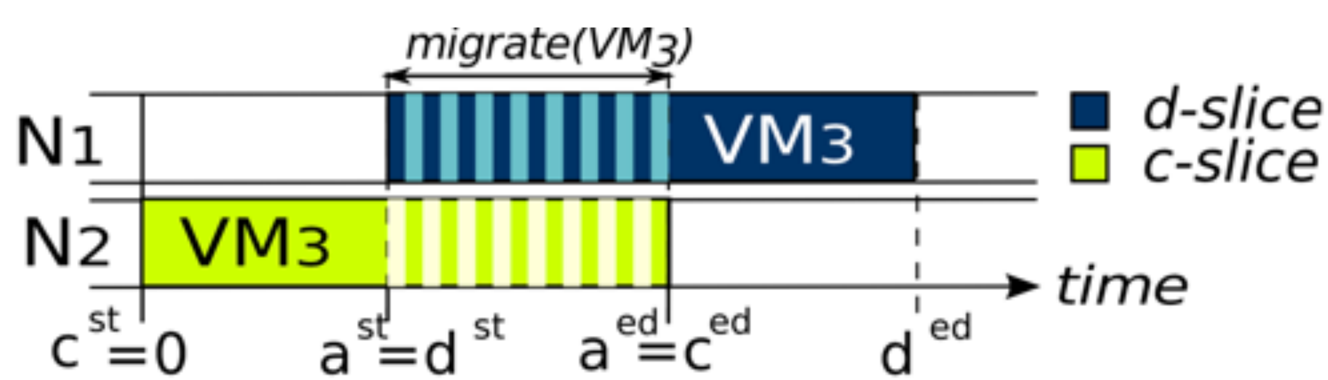
Tasks to model resource consumption

Every action modelled from its impact over resource

Booting a VM:
Place a task on the node



Migrating a VM:
2 tasks (source and destination)
Tasks co-locate if the VM stays
(impact the overlapping period)



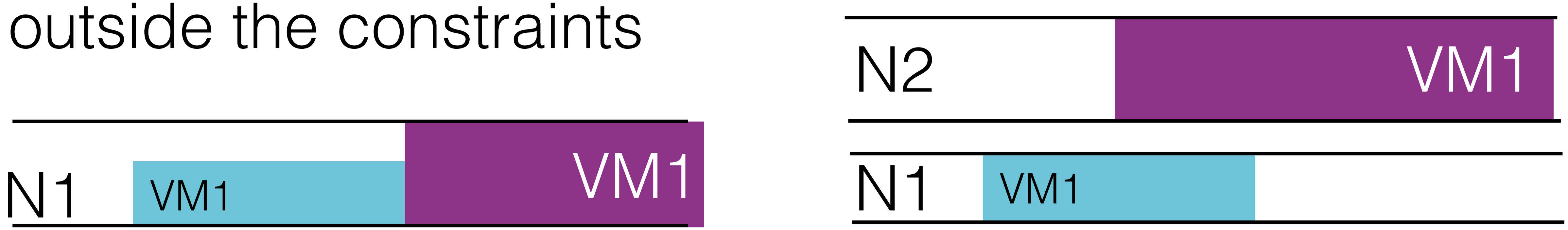
Original implementation

Using Choco "cumulativeS" constraint (1 per resource)

(Thanks Arnaud Malapert)

Regular cumulative constraints + binary variables to state if the tasks is in.

Conditional non-overlapping modeled outside the constraints



No more cyclic dependencies

Prevent the situation in place of fixing it. Should not happen anyway

Enough perf for a Poc. Not enough for being good enough

First implementation falls with more than 10 nodes

From cumulativeS to *myCumulative*

Problem: overkill filtering

2 kind of tasks: starts at 0 (c-task) or ends at makespan (d-task)

Problem particularities:

A VM migration is modelled using 1 c- and 1 d-task

no overlap when there is no migration

Moving to a home-made implementation

(thanks Sophie Demassey)

active only once the Items are placed

From myCumulative to myCumulative 2

Booting || halting the node:
No longer modelled using tasks

First implementation by my own
hackie, incorrect, big fail

Second implementation by Sophie Demassey
big win

Quick improvement by my side
semi-win: bug found 2 years later (over-filtering)

2011+ : let pack properly

From 1 bin packing per dimension
to one xD vector packing

Originally:

- same filtering but less events, less memory
- get rid of the knapsack filtering from profiling observation
- no more bool vector. Useless.

Now:

- knapsack is back again (see later).
- start to consider cardinality dimension as a pivot

Un-effective tryout: static or dynamic big-items

BtrPlace becomes a CP solver dedicated to VM management

A primary problem to model a reconfiguration
Extensions to bring additional concerns
Constraints to manipulate

BtrPlace core CSP

models a reconfiguration plan

1 model of transition per element

action durations as constants *

$$boot(v \in V) \triangleq \begin{array}{l} D(v) \in \mathbb{N} \\ st(v) = [0, H - D(v)] \\ ed(v) = st(v) + D(v) \\ d(v) = ed(v) - st(v) \\ d(v) = D(v) \\ ed(v) < H \\ d(v) < H \\ h(v) \in \{0, .., |N| - 1\} \end{array}$$

$$relocatable(v \in V) \triangleq \ldots$$
$$shutdown(v \in V) \triangleq \ldots$$
$$suspend(v \in V) \triangleq \ldots$$
$$resume(v \in V) \triangleq \ldots$$
$$kill(v \in V) \triangleq \ldots$$
$$bootable(n \in N) \triangleq \ldots$$
$$haltable(n \in N) \triangleq \ldots$$

Views bring additional concerns

new variables and relations

ShareableResource(r) ::=

$$\forall n \in \mathcal{N}, \sum_{v \in \mathcal{V}, host(v)=n} cons(v,r) \leq capa(n,r)$$

Network() ::= …

Power() ::= …

High-Availability() ::= …

$$spread(X \subseteq \mathcal{V}) \triangleq \forall (a,b) \in X, host(a) \neq host(b)$$

$$lonely(X \subseteq \mathcal{V}) \triangleq \bigcup_{v \in X} host(v) \not\subseteq \bigcup_{v \in \mathcal{V} \setminus X} host(v)$$

...

Constraints state new relations

Constraint	Loc.	Constraint	Loc.	Constraint	Loc.
spread	50	root	11	preserve	10
among	40	lonely	17	overSubscription	40
ban	20	quarantine	40	offline	10
fence	58	capacity	64	noIdles	10
gather	11	splitAmong	31		

CP expressivity leads to concise code

2009 - 2011

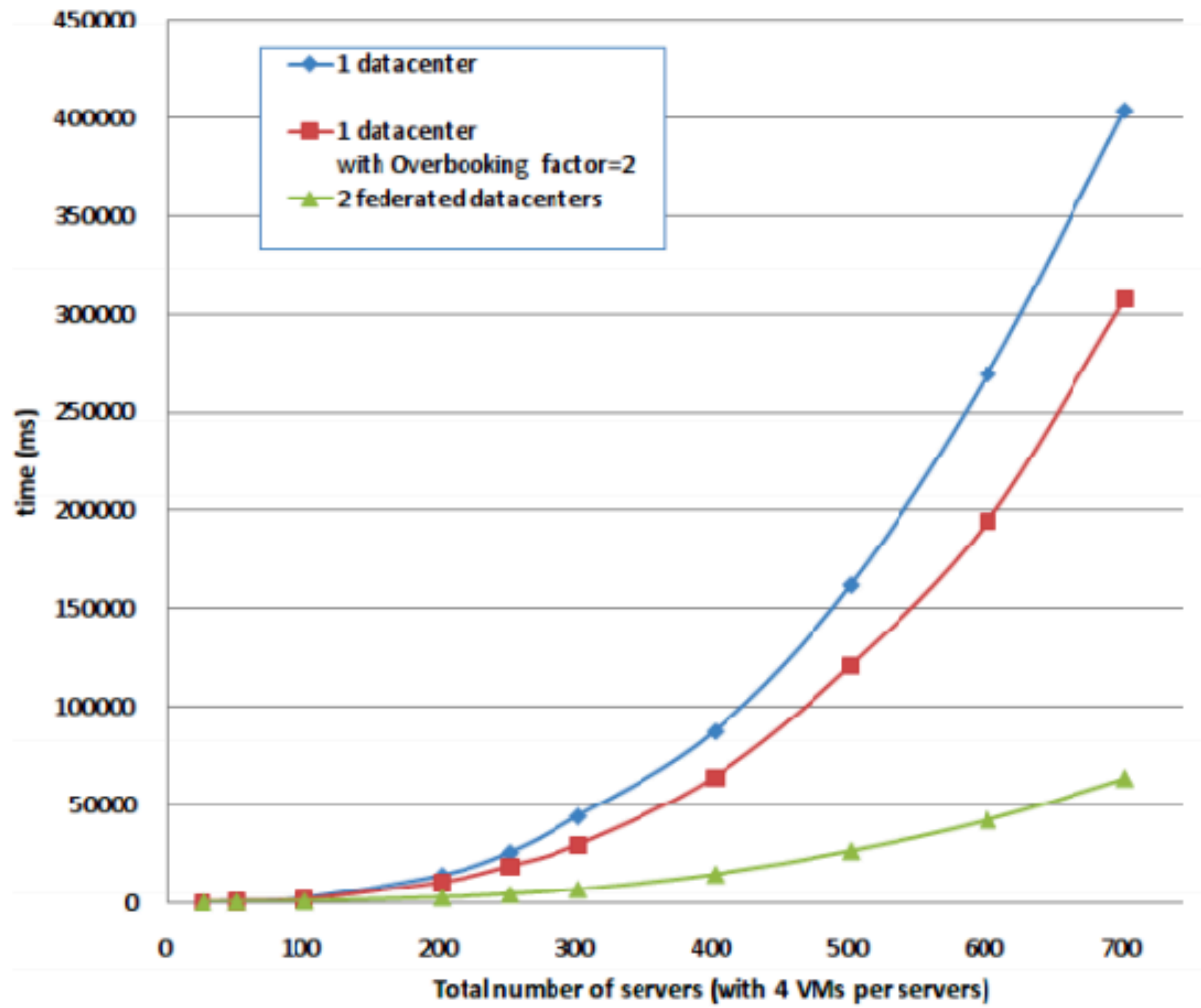
FIT4green aims at contributing to ICT energy reducing efforts by creating a energy-aware layer of plug-ins for data centre automation frameworks.

2010: switch from their heuristic to Entropy/BtrPlace.
homemade (very fine grain) objective
Involved as a contributor

[e-energy 12]

2.8k VMs, 700 servers

400 sec. to the 1st solution



“Houston (Fabien), we got a problem, CP is sloowww

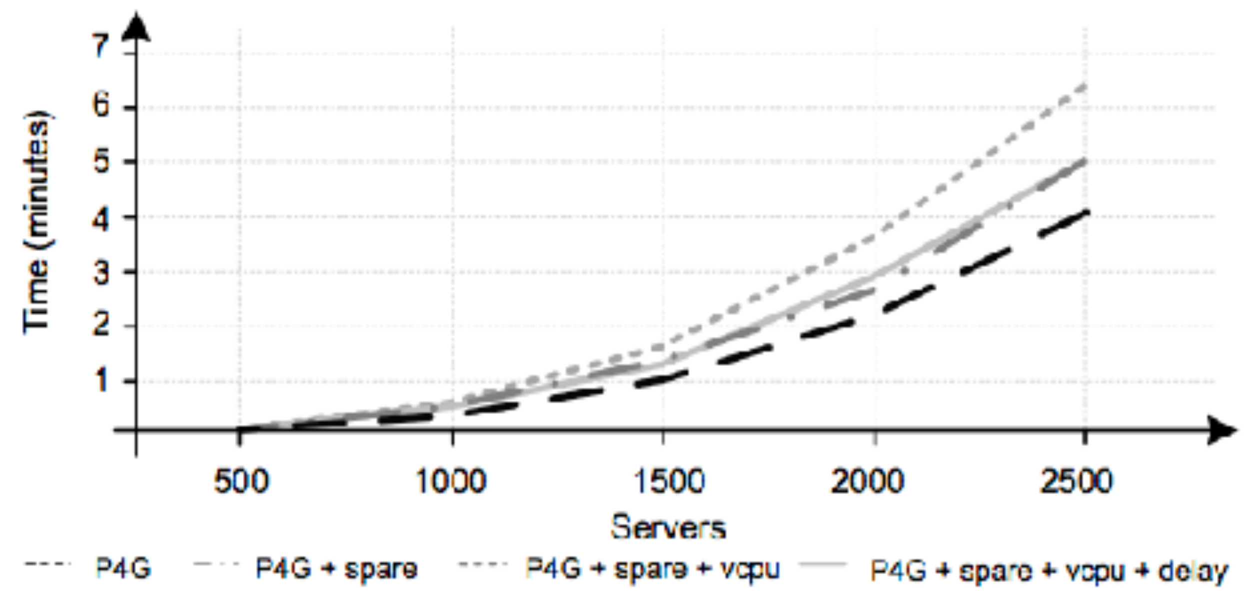
95%+ in search heuristic

no value gettable O(1), O(n) at least

One cache later:

from 400 to 20 sec.

[adhoc network 12]



Lesson learned

1/ CP was not slow, they did not try to understand the issue

2/ The fix is not good/disruptive/innovative. Normal due to the context

3/ Their opinion did not change as they forgot about the fix.

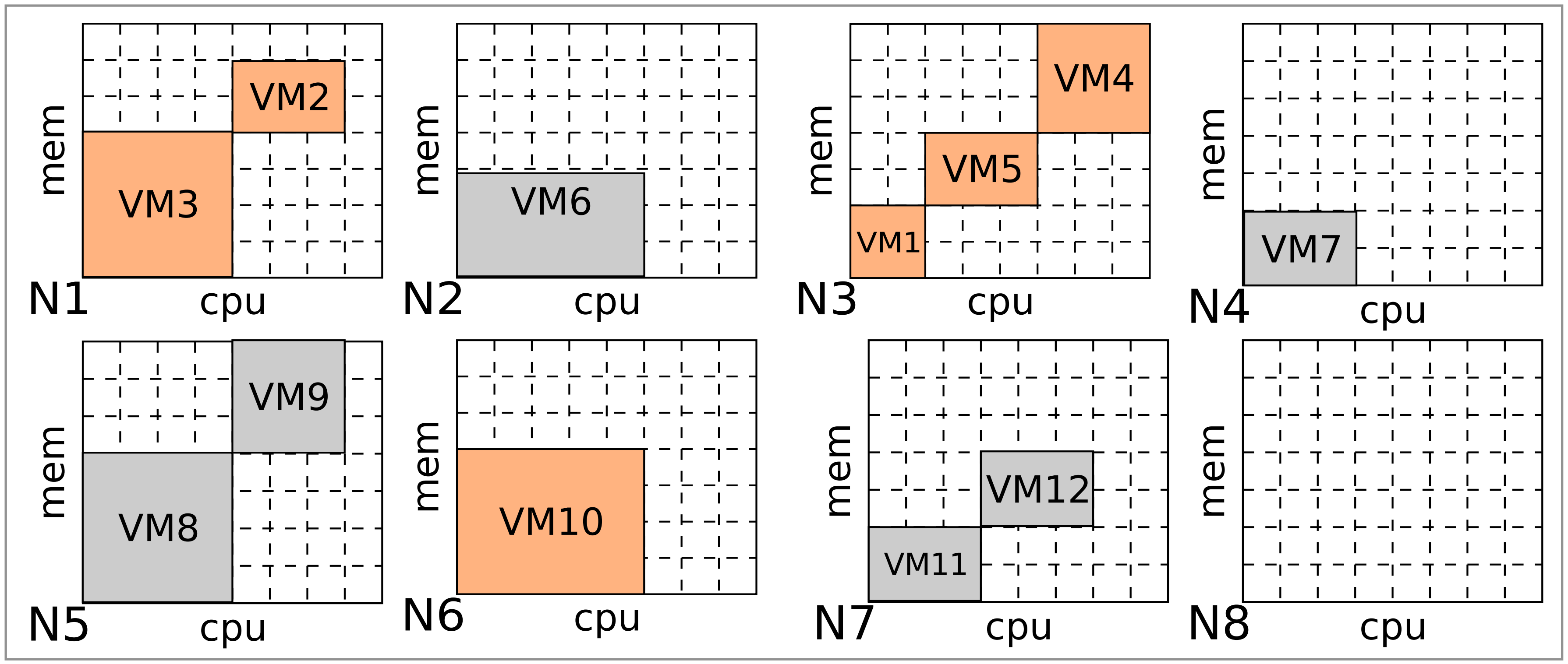
2011: better knowledge of the problem

There is no anarchy in a data center
load spike, failures: local issue

The data center is not a single space
Technical limitations create *autonomous regions*

Static instance analysis to the rescue

static model analysis 101




```
spread({VM3,VM2,VM8});
lonely({VM7});
preserve({VM1},'ucpu', 3);
offline(@N6);
ban($ALL_VMS,@N8);
fence(VM[1..7],@N[1..4]);
fence(VM[8..12],@N[5..8]);
```

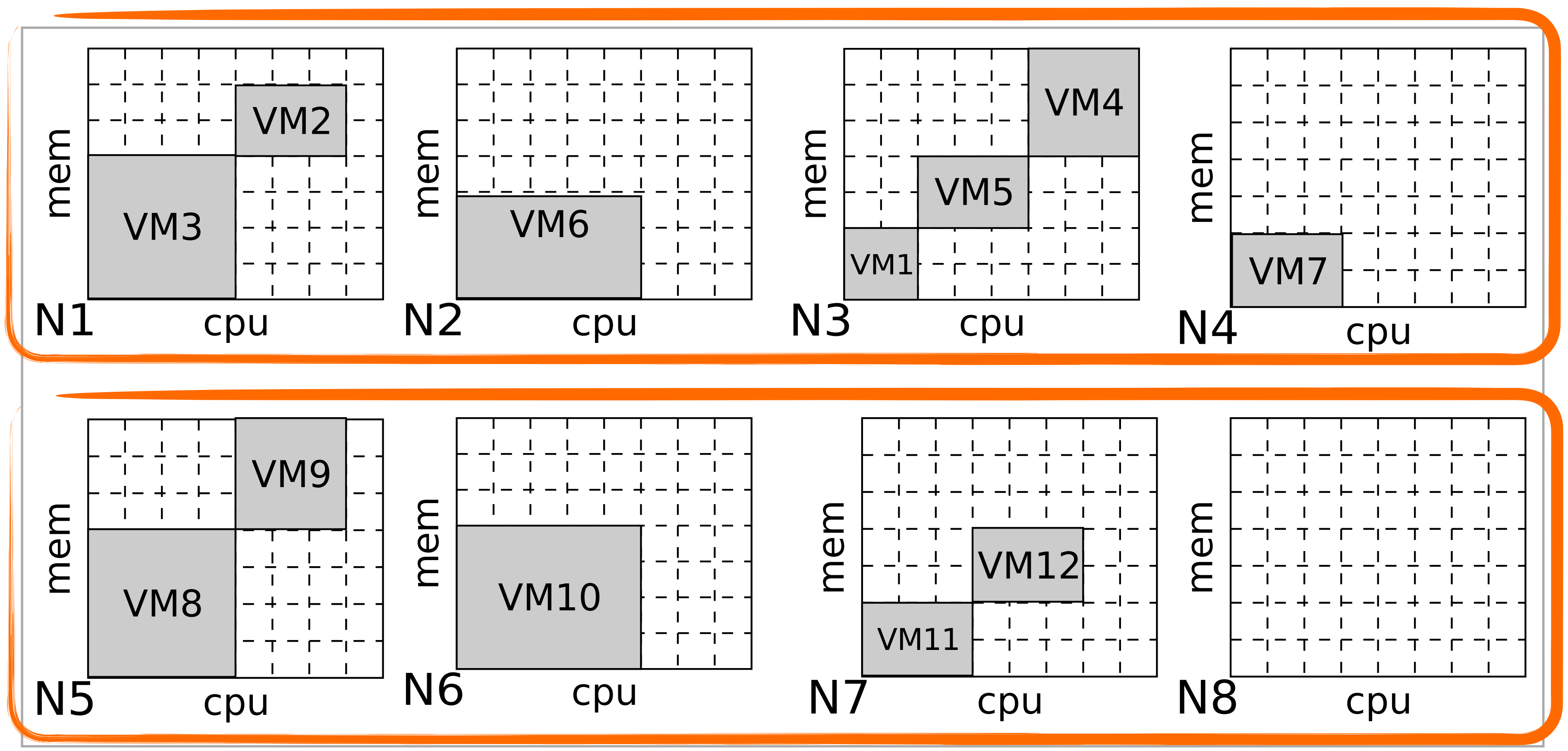
scheduler.doRepair(true)

manage only supposed mis-placed VMs

Pre-place “well placed VM”

beware of under estimations !

static model analysis 201

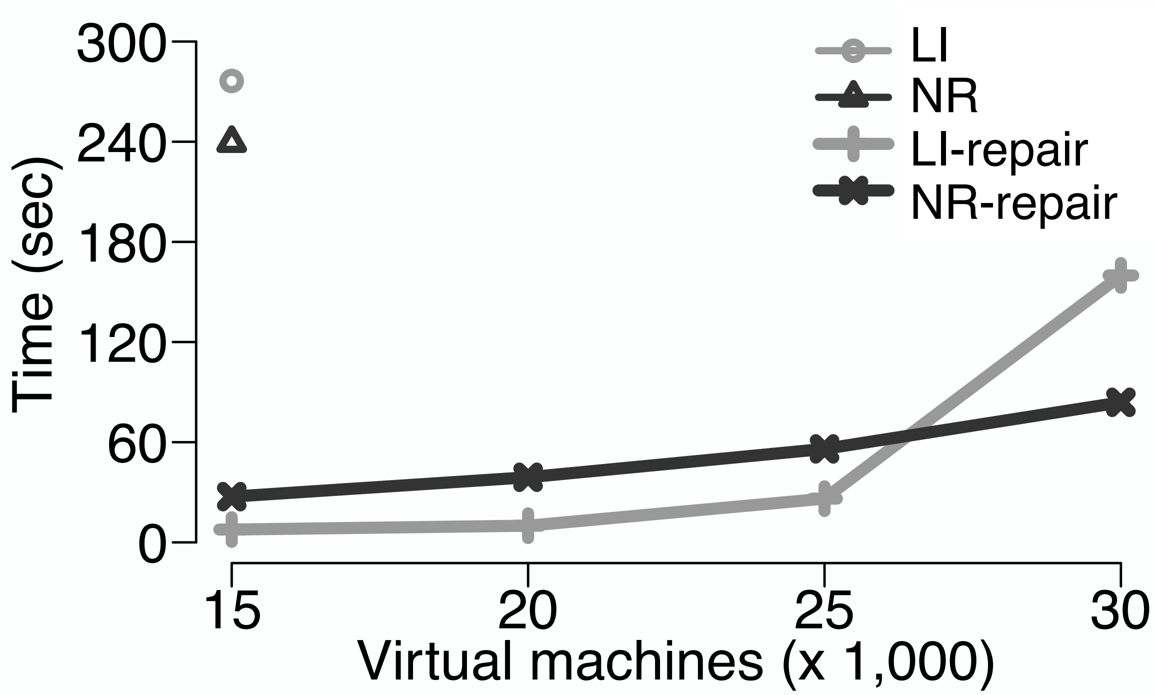



```
spread({VM3,VM2,VM8});
lonely({VM7});
preserve({VM1},'ucpu', 3);
offline(@N6);
ban($ALL_VMS,@N8);
fence(VM[1..7],@N[1..4]);
fence(VM[8..12],@N[5..8]);
```

```
s.setInstanceSolver(
  new StaticPartitioning())
```

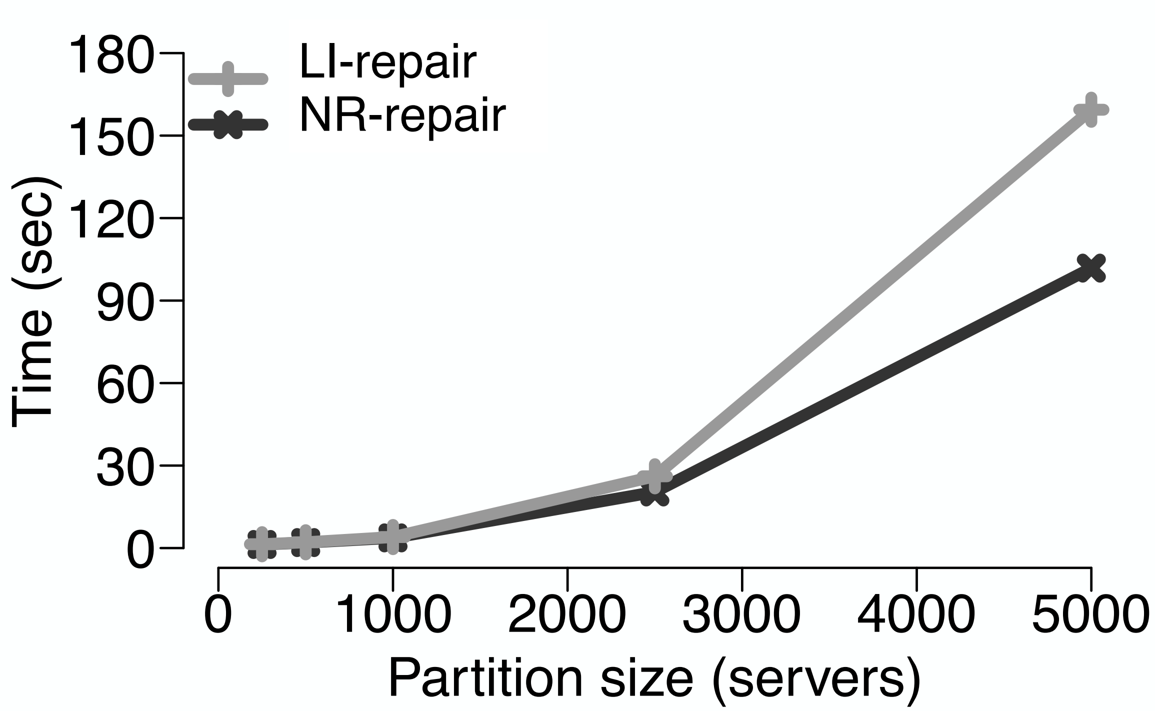
independent sub-problems solved in parallel

beware of resource fragmentation !



Repair benefits

5 times less VMs to consider
10 times faster at least
no impact on the solution quality



Partitioning benefits

2 times smaller, 4 times faster
no impact on the solution quality

2011: The hype of set variables

(Better knowledge of the model & the solver)

In choco bin packing

In the user-API to state the items in every bin

Embed a channeling to the placement variables

In side constraints

Lonely: 2 sets of VMs must be on disjoint set of nodes.

using the *set_disjoint* constraint

[CP 2011, industry track]

Results

From 2 to 6k VMs on 1k servers

Table 1: Impact of the consolidation ratio on the solving process.

Ratio	Rebuild Mode					Repair Mode				
	solved	obj	nodes	fails	time	solved	obj	nodes	fails	time
2:1	100	452	2034	352	42.2	100	381	163	0	3.5
3:1	94	1264	3119	3645	75.2	100	749	394	0	8.4
4:1	65	3213	4574	11476	129.3	100	1349	836	0	18.7
5:1	10	7475	6878	47590	241.2	100	2312	1585	44	37.7
6:1	0	-	-	-	-	86	4092	2884	2863	71.5

From 2k5 VMs/500 servers to 10kVMs/2k servers

Table 2: Impact of the datacenter size on the solving process (repair mode).

Set	#servers	#VMs	solved	obj	nodes	fails	time
x1	500	2,500	100	1160	805	13	7.0
x2	1,000	5,000	99	2321	1594	17	36.2
x3	1,500	7,500	99	3476	2374	43	105.5
x4	2,000	10,000	100	4635	3171	15	217.0

[RR report: “CP 2011” back to work]

In bin packing

- set variables used to iterate only. Overkill
- switch to internal bitsets + channelling with the placement variables

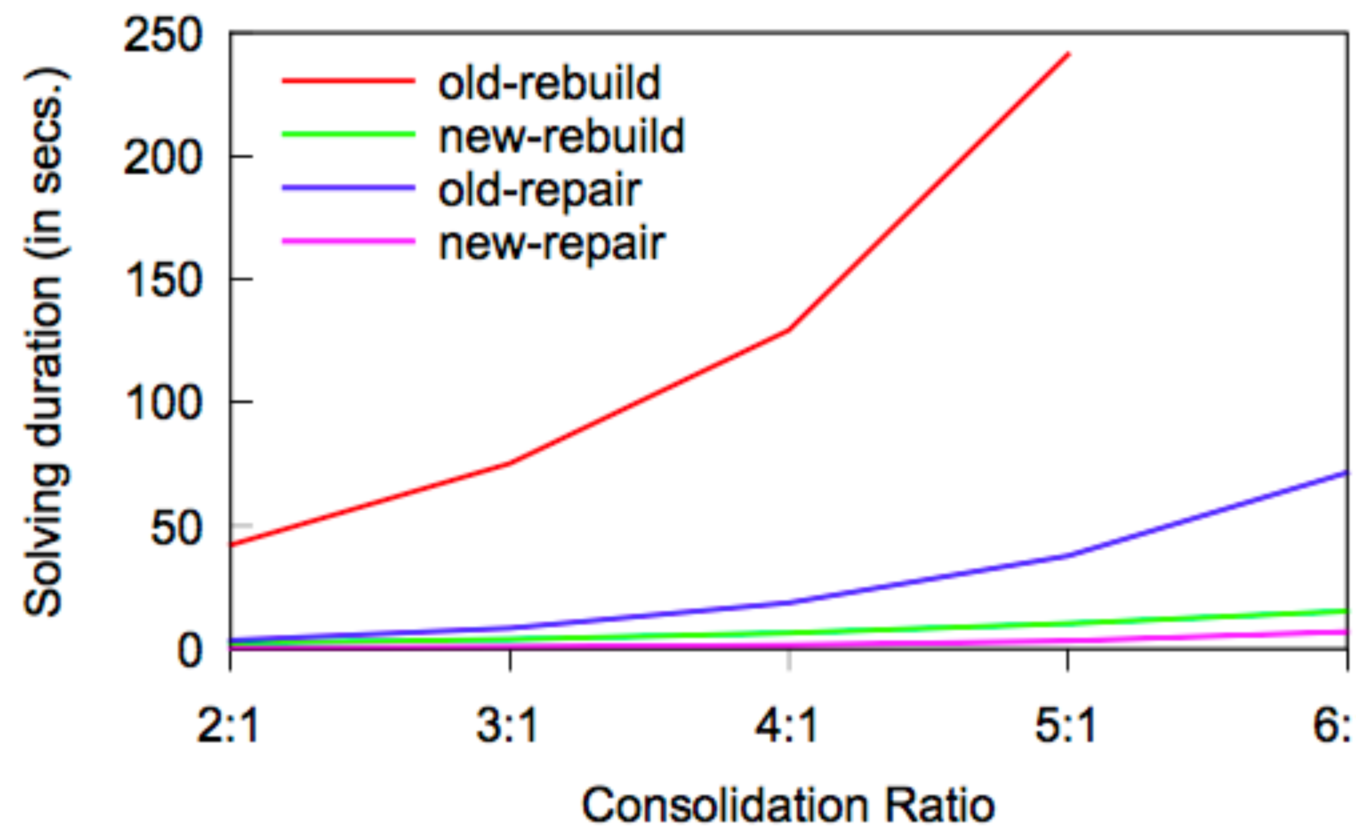
In side constraints

- set variables are overkill as the list of VMs is known
- switch to 2 list of placement variables

Side change in a heuristic

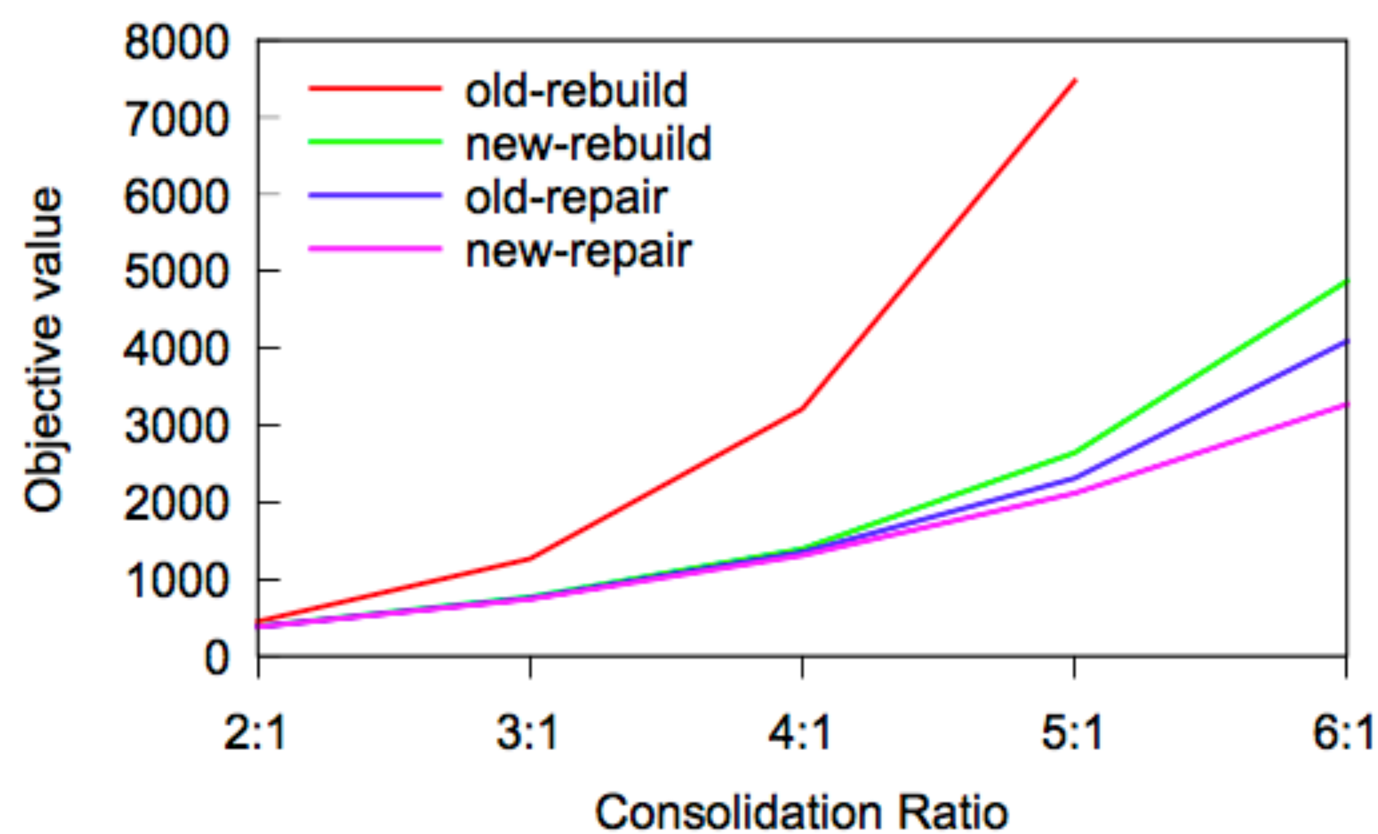
- Fix a bug that ignored the first-fail
- Improve the scheduling heuristic to branch on VMs going to leaf node

Up to a x20 speedup
No more backtracks
At least 1 sol for every instance
(Better score)



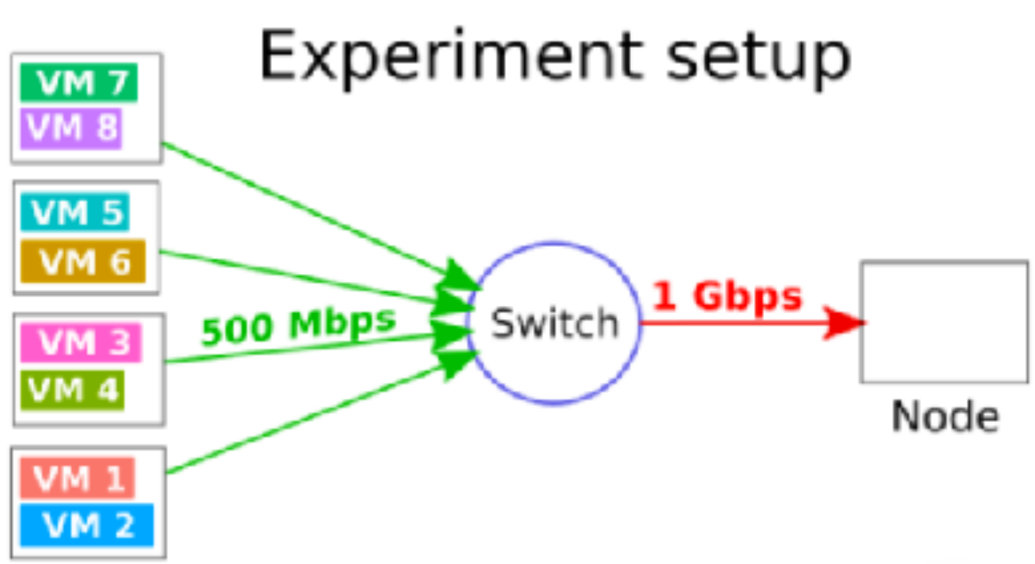
Nothing interesting for a publication (at least in my domain)

Before, the model was overkill

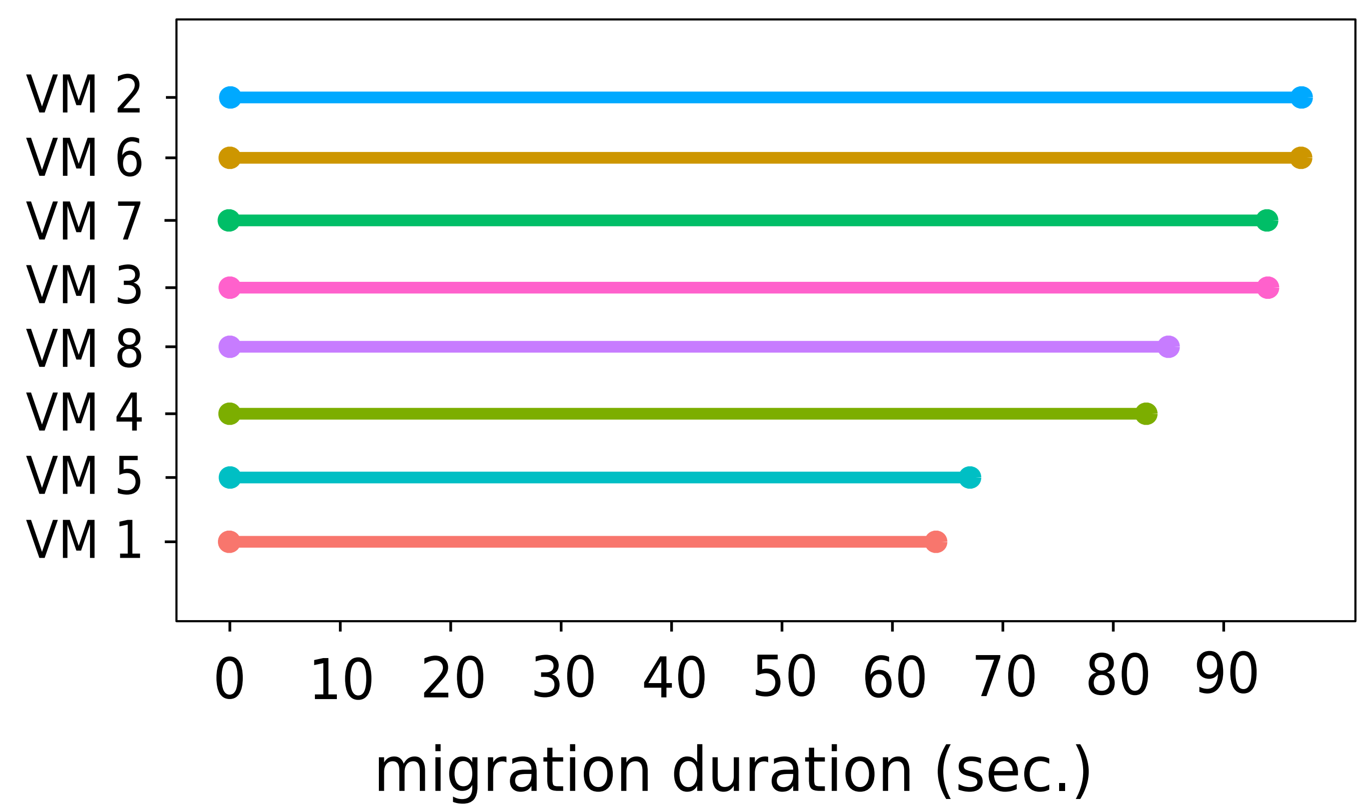


2013-2016

looking for a better migration scheduler
[Vincent Kherbache work]



[btrplace vanilla, entropy, cloudsim, ...]

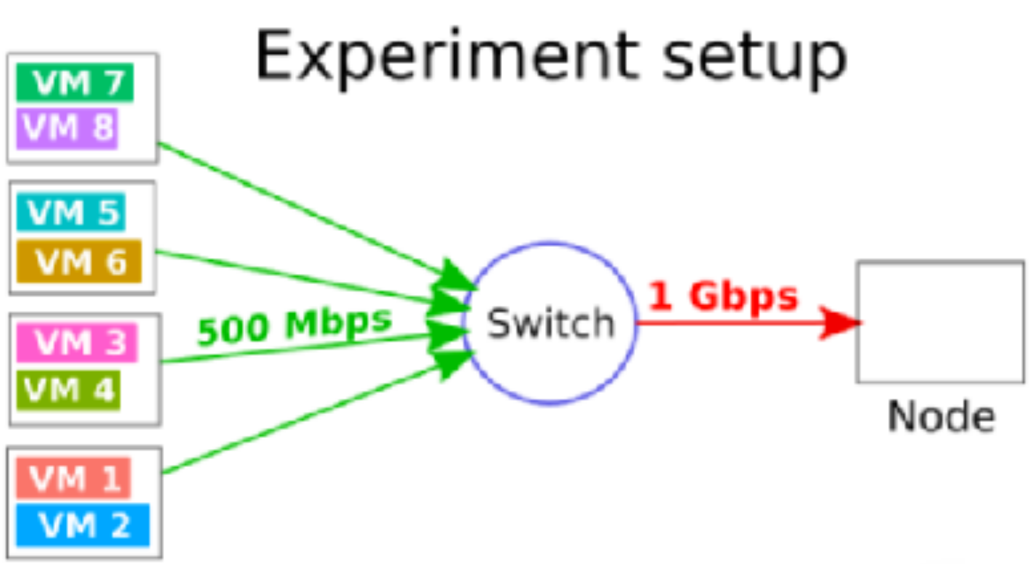


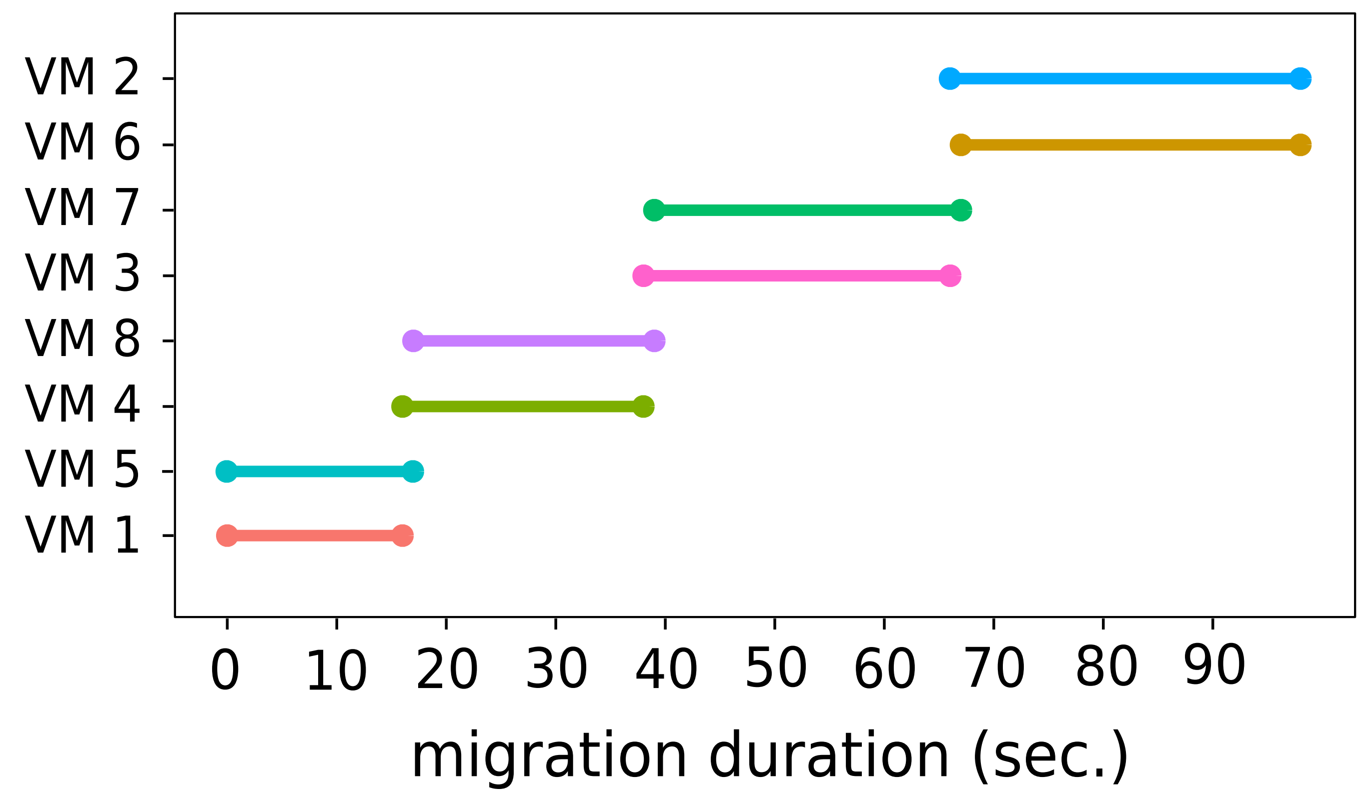
network and workload blind

2013-2016

looking for a better migration scheduler

btrplace + migration scheduler [UCC 15, TCC 17]





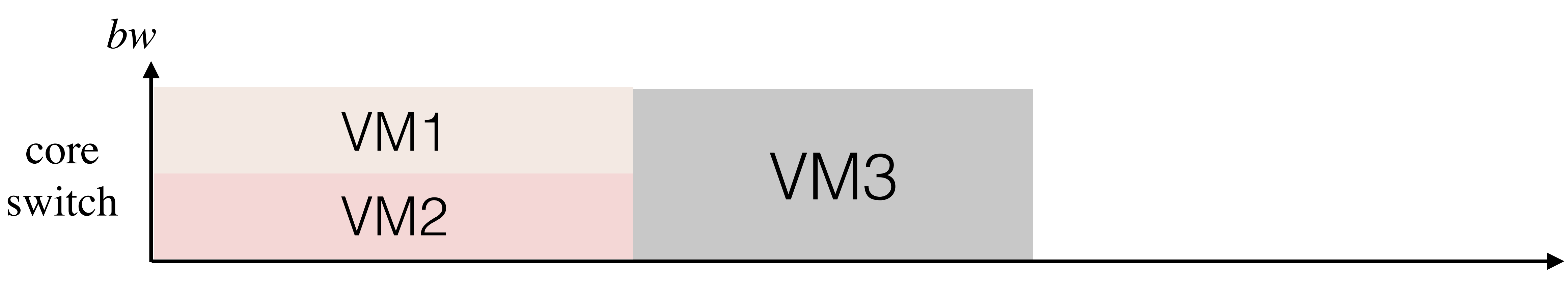
network and workload aware

Coding effort

Network Model — heterogeneous network
1 cumulative constraint per network element; +/- 300 sloc.

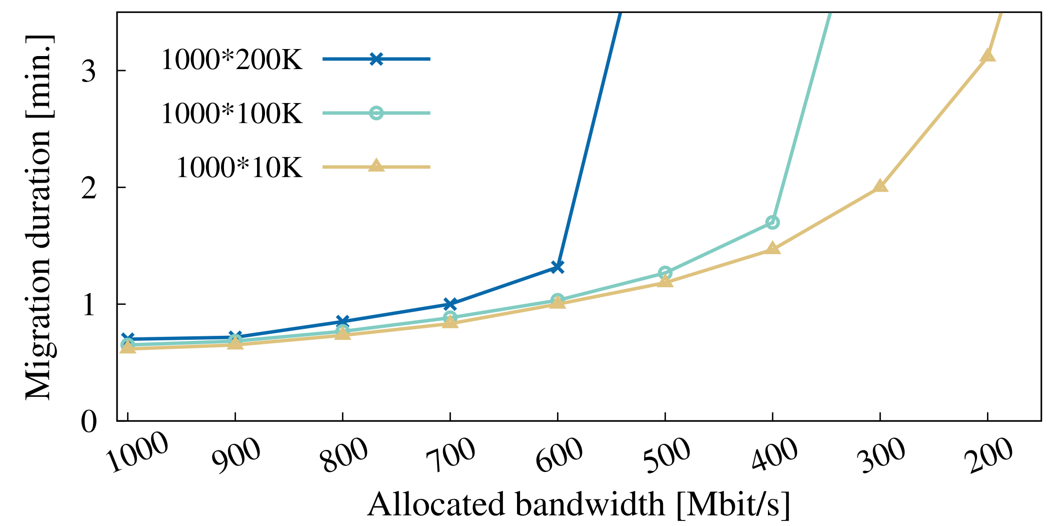
Migration Model — memory and network aware
+/- 200 sloc.

Constraints Model — restrict the migration models
+/- 100 sloc.



Migration Model

Phase 0 (6 mo.)
observe, experiment



Phase 1 :
mathematical model
(Few months)

$$d_{CP}(m) = \frac{CP_s}{bw(m) - CP_r}$$

$$d_{HP}(m) = \frac{HP_s}{bw(m)} + \frac{HP_s - (D \times bw(m))}{bw(m) - HP_r}$$

$$d_{CP}(m) + d_{HP}(m) = \frac{CP_s - \left((D \times bw(m)) - HP_s\right)}{bw(m) - CP_r} + \frac{HP_s}{bw(m)}$$

$$d(m) = d_{min}(m) + d_{CP}(m) + d_{HP}(m) + D$$

Phase 2 : CSP models

Try 1 - maths to CSP 101

Division, truncation issues
does not scale

Try 2: chunk based bandwidth allocation

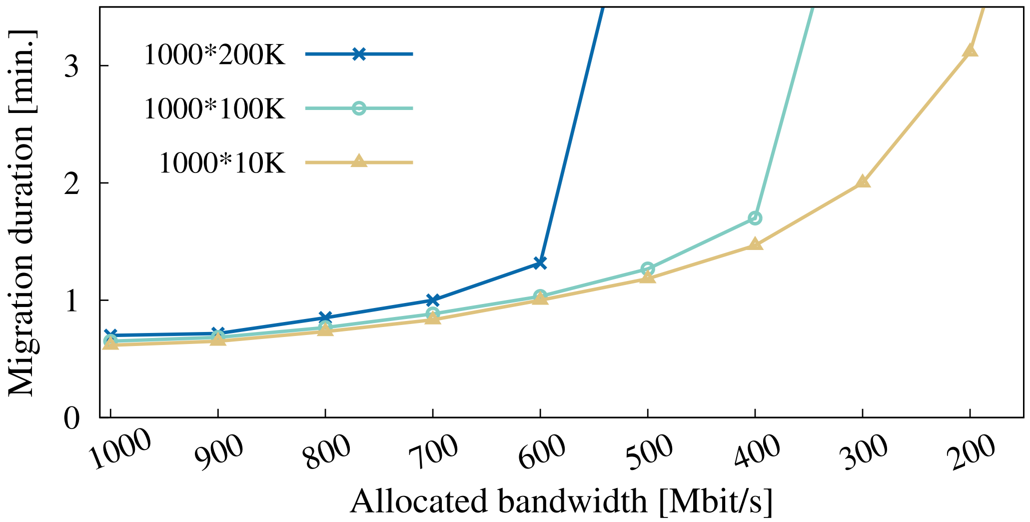
e.g. : 250, 500,7 50, 1Gb

table constraint

better scalability

Try 3: … why slowing down migrations ?

Force max bandwidth
The duration as a constant

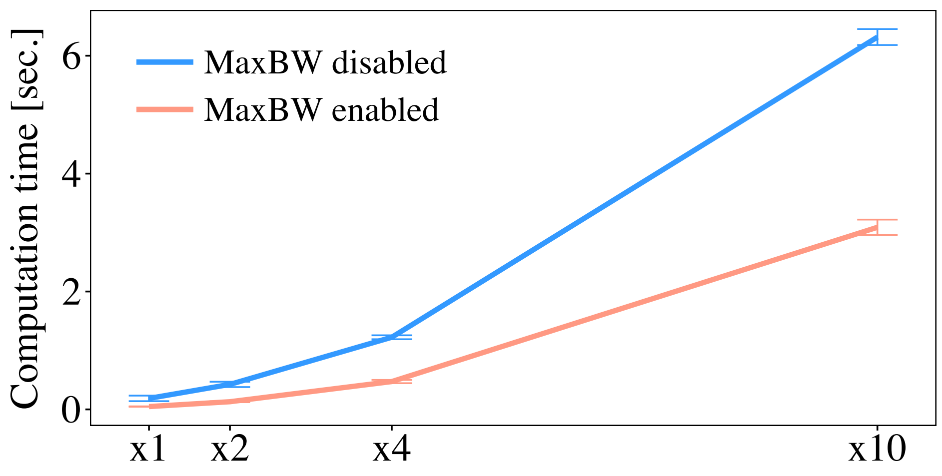


Evaluating the benefits of “max bandwidth”

Scale	*MaxBandwidth* option disabled	enabled
x1	65%	100%
x2	22%	100%
x4	83%	100%
x10	62%	100%

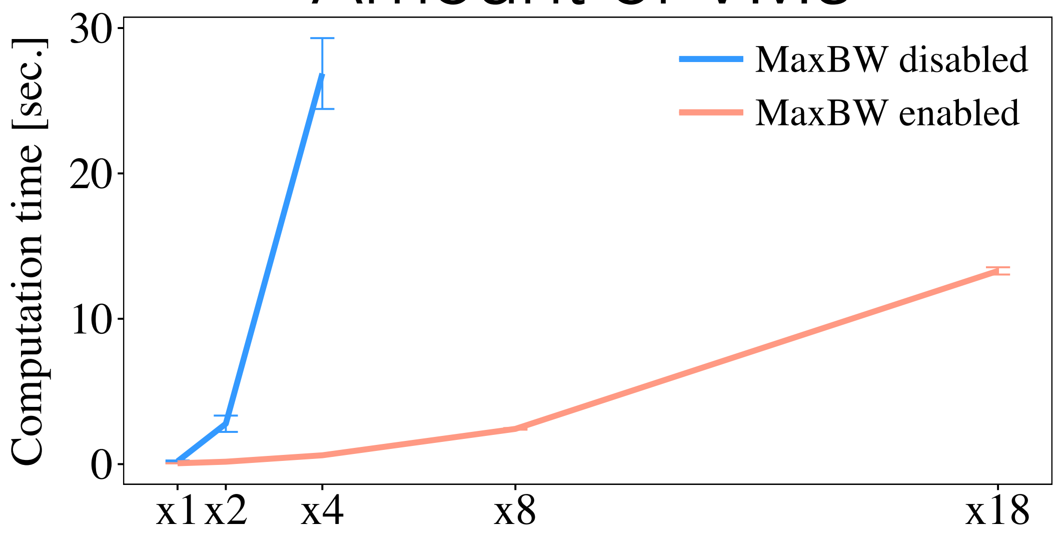
Scale	*MaxBandwidth* option disabled	enabled
x1	66%	100%
x2	57%	100%
x4	47%	100%
x8	0%	100%
x18	0%	100%

Infrastructure size



960 VMs,
20x24 nodes

Amount of VMs



1728 VMs,
2x24 nodes

Placement + migration scheduler

Back to 2006 solving workflow :D

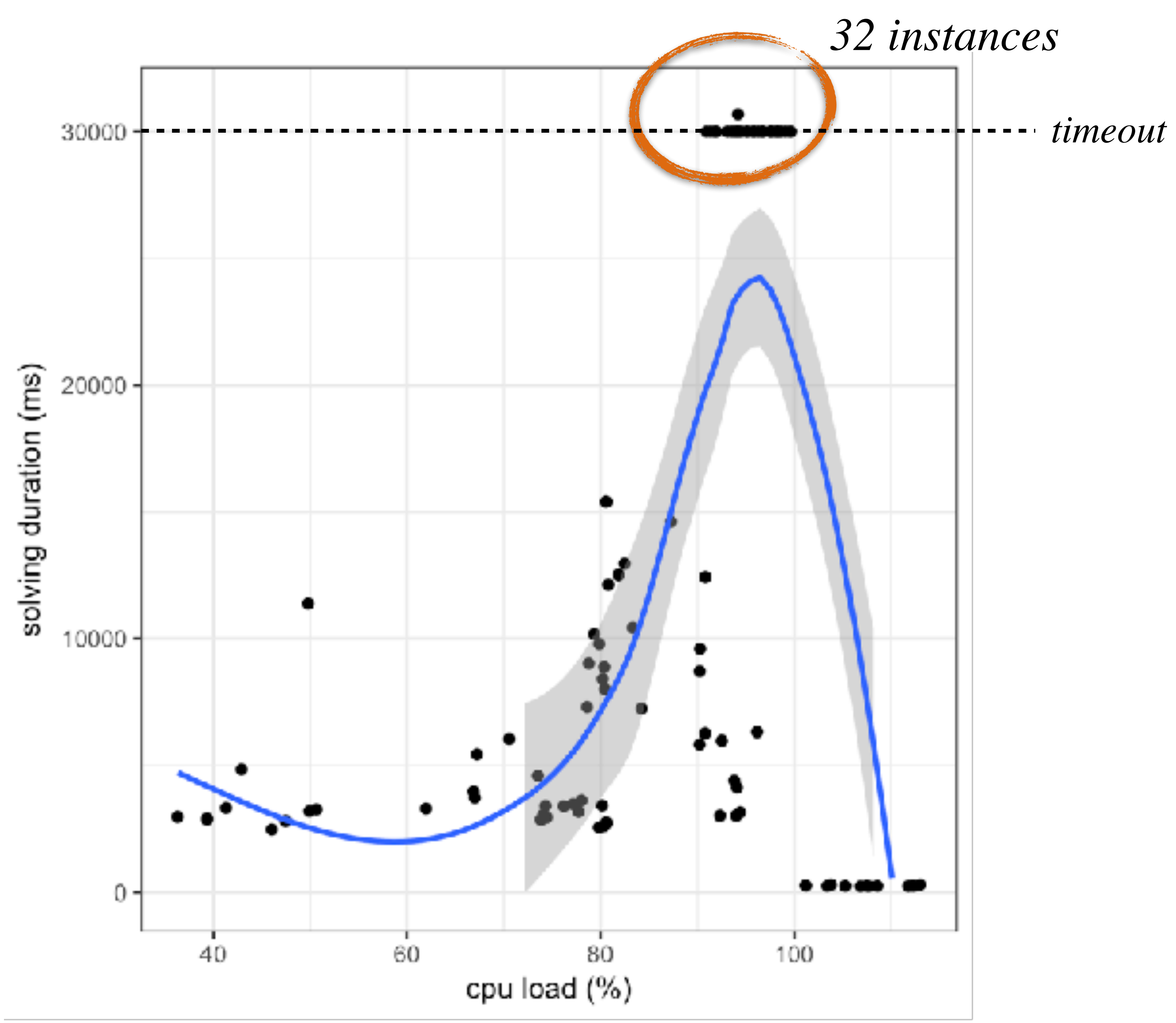
Phase 1: placement & old schedule
Phase 2: new scheduler (requires the route)

Not sure about the need to consolidate the phase
Can’t saturate the network
Workarounds exist

2017

The story of the knapsack

The right filtering algorithm for the right workload



very high load
small but hard instances

ok when non-solvable
but no evidence

knapsack filtering

simple to understand, to develop

“Iterate over the candidate items and filter out the oversized”

called after every assignment

O(n) worst case complexity

dsc. sorting items helps …

but costly with several dimensions

Sort items per dimension inside the constraint

Indirection tables to ensure compatibility with the core model

knapsack filtering

Strong filtering iff packing objective
high load
big items

Low filtering when balance objective
low load
small items

With sorted item, memory usage increases with the dimensions

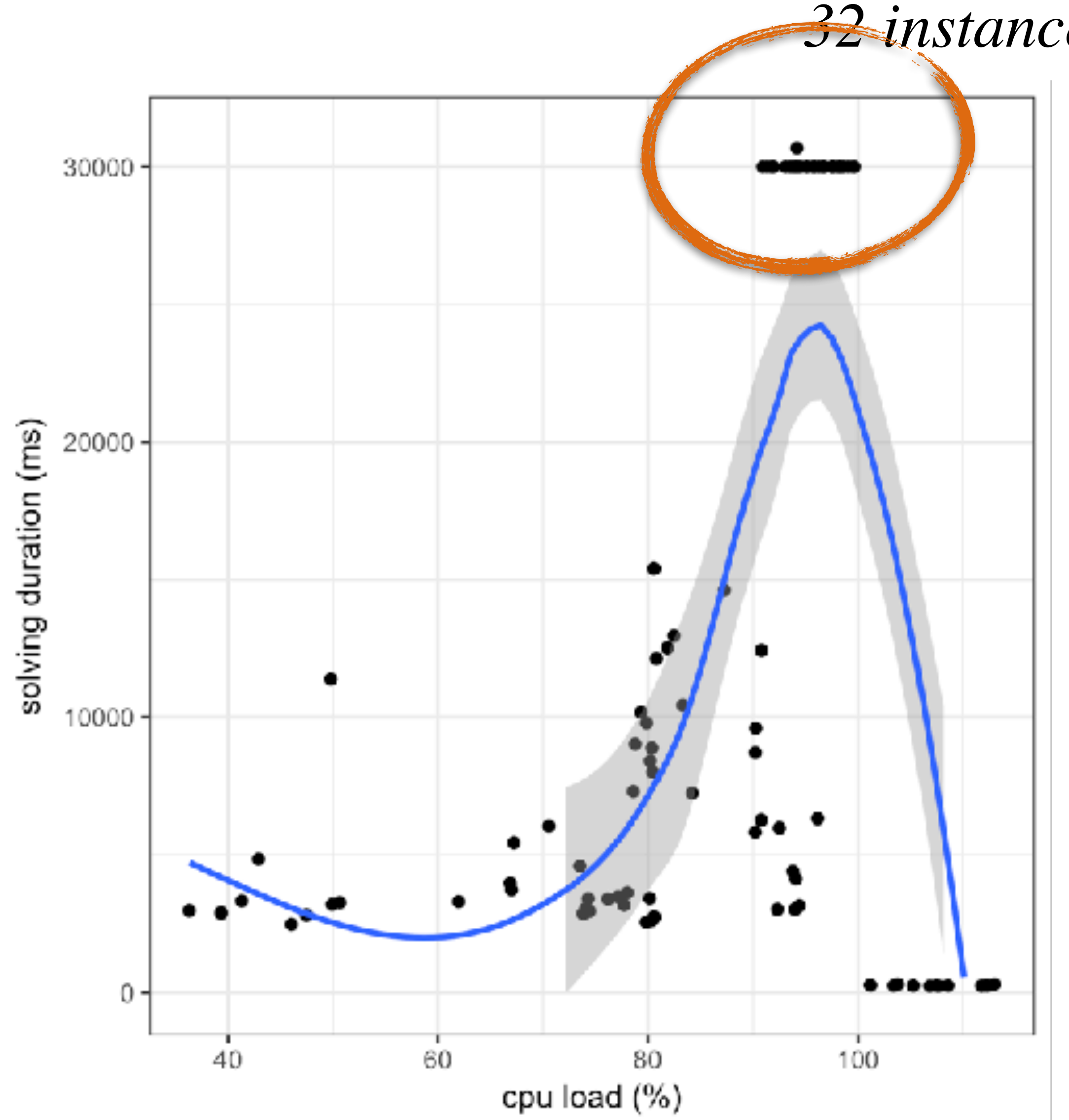
Overhead > benefits

Triggered Knapsack

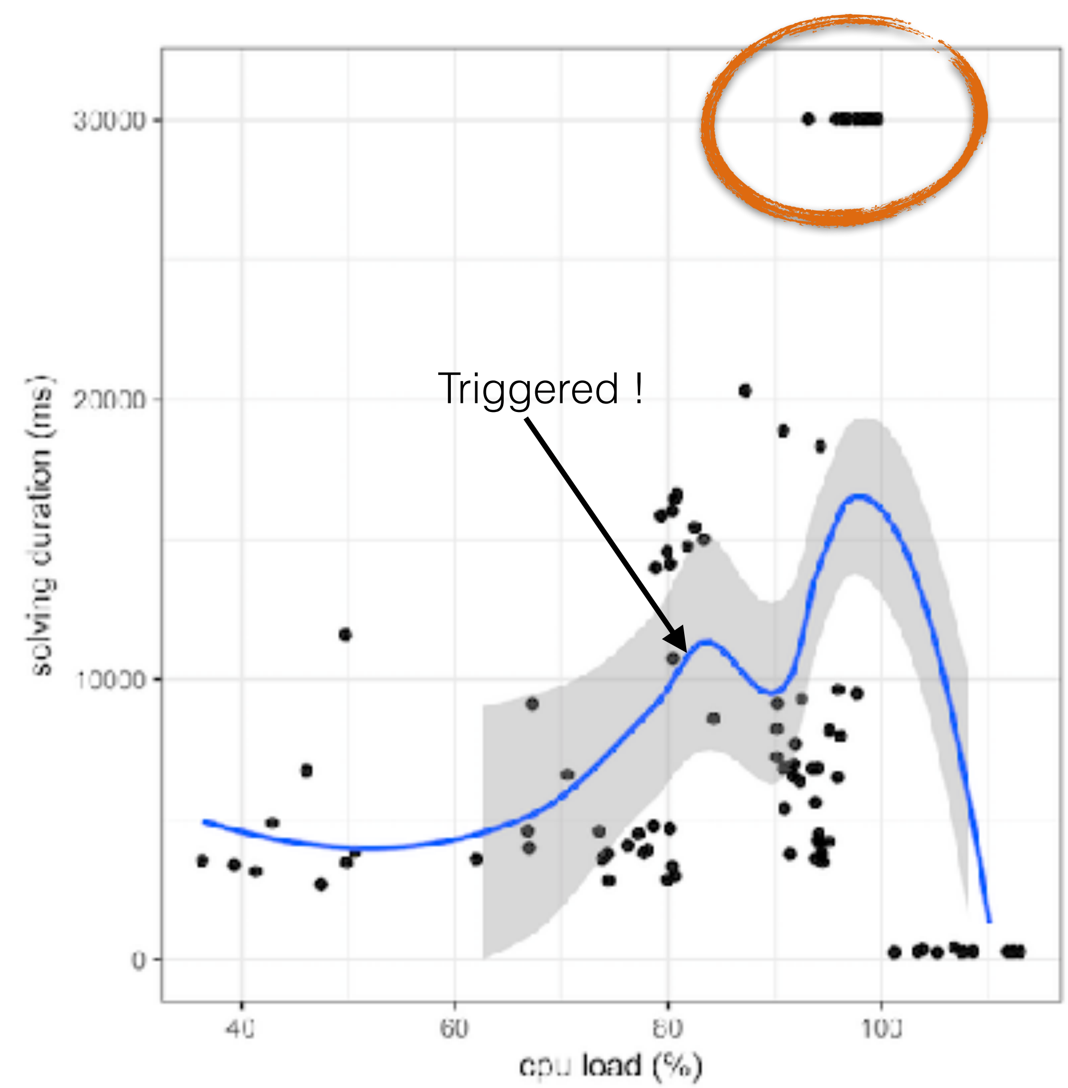
Triggered if the residual < biggest item

bigger constants

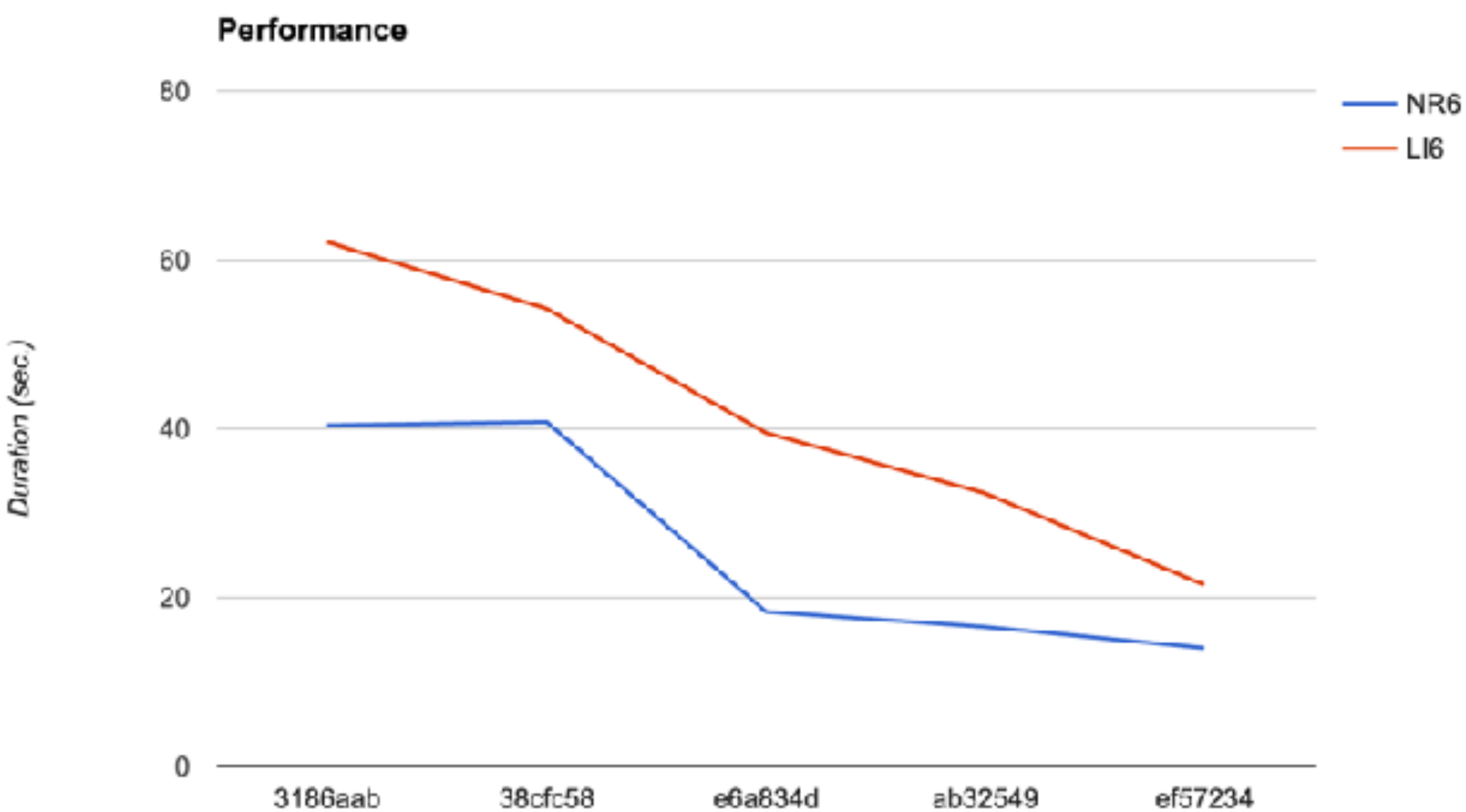
32 instances



16 instances



Review everything



understand the workload,
tune the model
tune the solver
tune the heuristics

38cfc58: [Choco.4 FirstFail] heuristic from the O(n) avg. legacy first fail to a O(n) worst case (iterates from the last instantiated variable, stop when Dom size == 2)

e6a834d: [task scheduling] simplistic local entailment. Stop early if all variables are instantiated

ab32549: [vector packing] cap cardinalities wrt. resource usage

ef57234: [memory] allocate memory per chunk to prevent increase with copy

STOP

RECAP

I am
from the (distributed) system community
Not
from the CP community

Composability is gold

Fit the way we think, we work, we upgrade

Take care of flexibility overhead

Multi expertise required

Domain expertise
CSP / solver expertise
Engineering expertise

global constraints are effective

But re-usability has its limits

“The right model/filtering for the right problem”

“The granularity is good when going finer does not change the decisions”

— Fabien Hermenier, right now

A regular dev writing a constraint ?

Deterministic event-based programming

- Error prone, no one like

Hard to debug

- Jump to the 36th instance of constraint X, at the 217th search nodes, in the 47th. awakeOnRem

Unusual reasoning

Wish list of one
CP enthusiast

Help me at modeling, developing, checking

redundancy checkers,
effectiveness checkers,
convenient programming model,
debugger,
...

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