The Open Cloud eXchange
Mechanisms for Efficient Cloud Markets

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Web and InterNetworking Group
http://www.cs.bu.edu/groups/wing

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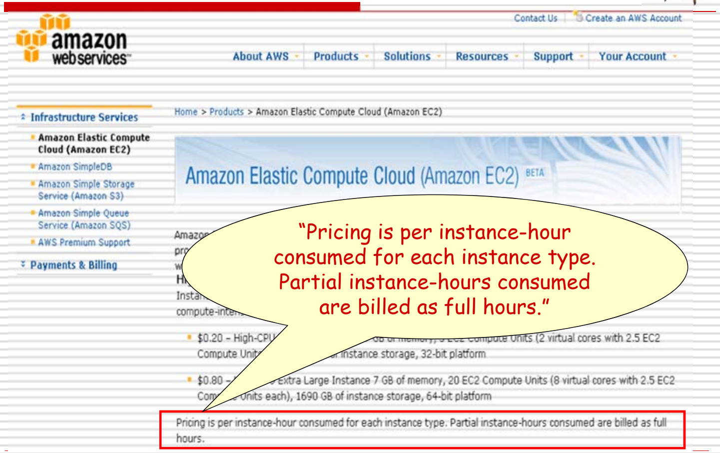
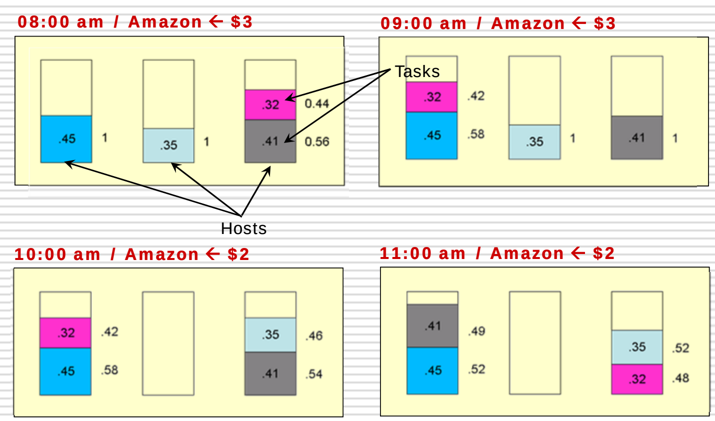
Cloud Computing: A Paradigm Shift

- Holistic system (social) view is passé
  - Tenants make resource acquisition decisions; no incentive to be fair or friendly to others
  - IaaS providers have no incentive to minimize tenant costs; they only react to market pressure
  - Challenge is to design the mechanisms that engender trust in the cloud marketplace
- Marketplace mechanisms
  - Fixed pricing for reserved resources
  - Fixed pricing for shared resources
  - Dynamic pricing for reserved resources

Fixed pricing for exclusive resources



Marketplace Implications?



(Cloud) Colocation Games

- IaaS cloud providers offer fixed-sized instances for a fixed price
- Provider's profit = number of instances sold; no incentive to colocate customers
- Virtualization enables colocation to reduce costs without QoS compromises
- Customers' selfishness reduces the colocation process to a strategic game

Colocation Games: Questions

- Does it reach equilibrium?
- If so, how fast?
- If so, at what price (of anarchy)?
- How about multi-resource jobs/hosts?
- How about multi-job tasks?
- How about job/host dependencies?
- How could it be implemented?
- How would it perform in practice?
- ...

Colocation Game: Model

- A hosting graph $G=(V,E)$
  - V & E labeled by capacity vector R and fixed price P
- Workloads as task graphs $T_i=(V_i,E_i)$
  - V_i & E_i labeled by a utilization vector W
- Valid mappings
  - $V_i \rightarrow V$ & $E_i \rightarrow E$: $\Sigma W \leq R$; supply meets demand
- Shapley Cost function
  - Cost P of a resource is split among workloads mapped to it *in proportion to use*

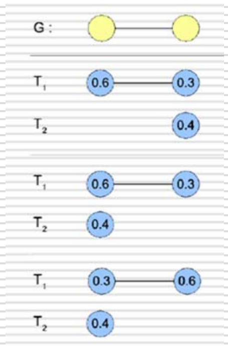
$$c_M(T_i) = \sum_{j \in \{V_i, E_i\}} P_j \frac{w_{ij}}{U_j}$$

The General Colocation Game (GCG)

- GCG is a pure strategies game:
  Each workload is able to make a (better response) "move" from a valid mapping M into another M' so as to minimize its own cost
- Example applications:
  - Overlay reservation, e.g., on PlanetLab
  - CDN colocation, e.g., on CloudFront

General Colocation Game: Properties

- GCG may not converge to a Nash equilibrium
- Theorem:
  Determining whether a GCG has a Nash Equilibrium is NP-Complete (by reduction to 3-SAT problem)
- Need more structure to ensure convergence



Colocation Games: Variants

- Process Colocation Game (PCG):
  Each workload consists of a single vertex (process) that needs to be assigned to a single host with only one capacitated resource
- Multidimensional PCG (MPCG):
  Same as PCG but with multi-capacitated resources
- Example applications:
  - VM colocation, e.g., on a Eucalyptus cluster
  - Streaming server colocation

Colocation Games: Variants

- Parallel PCG (PPCG):
  Task graph consists of a set of disconnected vertices (independent processes), each with multidimensional resource utilization needs
- Uniform PPCG:
  Same as PPCG but with identical resource utilization for all processes
- Example applications:
  - Map-Reduce paradigm
  - MPI scientific computing paradigm

Colocation Games: Theoretical results

- PCG converges to a Nash Equilibrium under better-response dynamics
- PCG converges to a Nash Equilibrium in $O(n^2)$ better-response moves, where $n = |V|$
- Price of Anarchy for PCG is 3/2 when hosting graph is homogeneous and 2 otherwise
- MPCG converges to a Nash equilibrium under better-response dynamics
- Uniform PPCG converges to a Nash equilibrium under better-response dynamics
- ...

PCG: Better Response

Best-Response moves require knowledge of utilizations of all processes – not practical

Local Better-Response solution:

1. Select a random target hosting node and obtain process utilizations of all processes on that node
2. Determine if a cost-reducing "legal" move to that node is possible – an NP-hard Knapsack problem
   - Dynamic Programming solution in pseudo-polynomial time for small number (100s) of processes/host [DPKP]
   - Breadth-First branch & bound Search heuristic [BFS]
   - Depth-First branch & bound Search heuristic [DFS]

PCG: Performance Evaluation

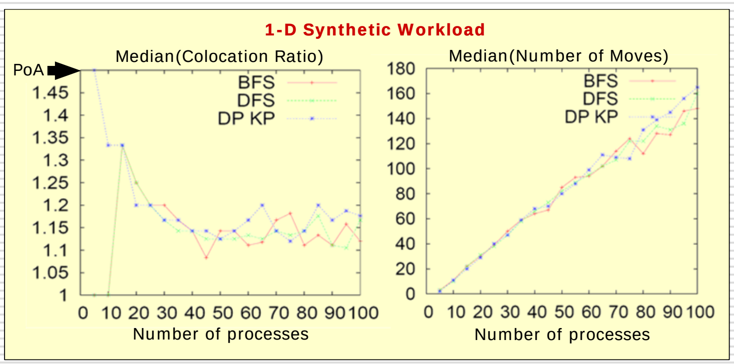
Workloads

- Trace-driven: CoMon PlanetLab Traces
  - Real hosting environment with 3-dimensional resource utilizations
  - Infeasible to compute optimal colocation
- Synthetic: Perfectly Packable
  - Allows systematic exploration of the space
  - Optimal colocation is known by construction

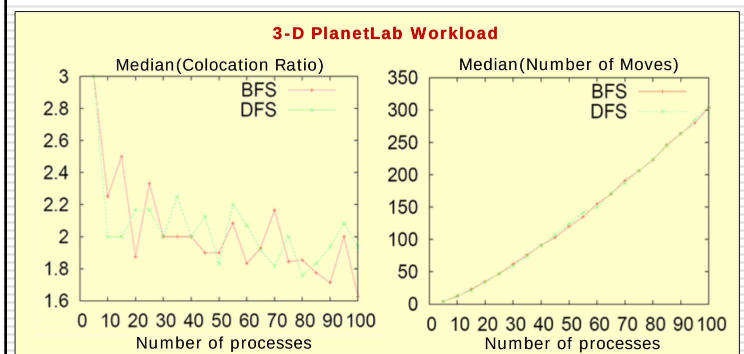
Metrics (over 100 experiments)

- Colocation Ratio (bounded by PoA)
  - How inefficient is the resulting colocation compared to optimal or best?
- Number of moves (not migrations) until NE is reached
  - How much churn (overhead) to be expected?

PCG: Synthetic baseline results



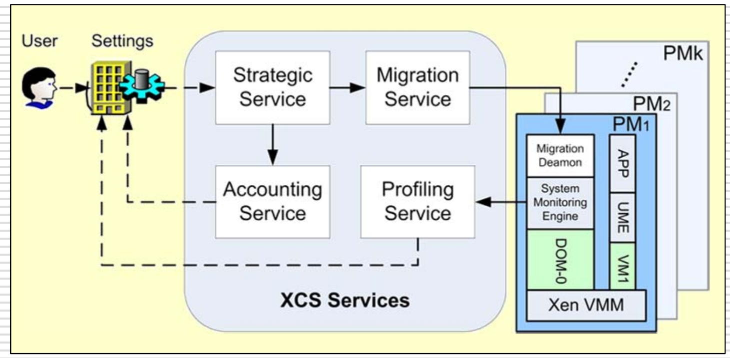
MPCG: PlanetLab baseline results



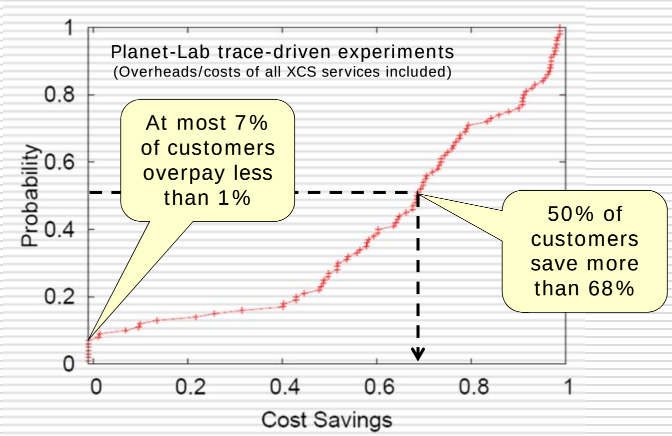
The CloudCommons prototype

- API for Strategic Services
  To facilitate colocation, e.g., allow users to find each other, compute strategic responses, …
- API for Operational Services
  To enforce outcomes of colocation, e.g., migration, reconfiguration, accounting, …
- Implementation over Xen
  Xen Colocation Services (XCS)

CloudCommons: XCS Architecture



CloudCommons: Benefit to Customers

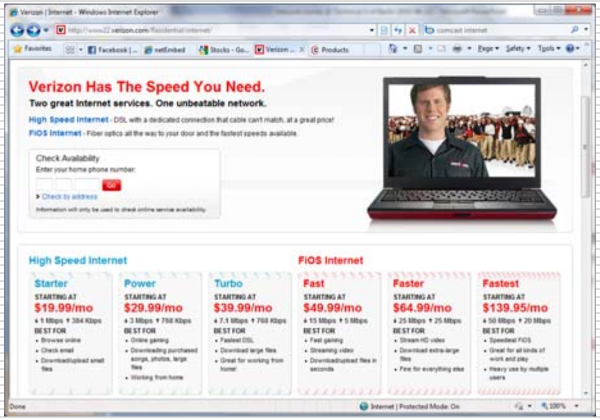


How do we depart from prior work?

- Cooperative cost-sharing games†‡#
  - Find coalition where nobody gains by leaving
  - Computationally hard
  - Applied to best-effort routing problems
  - Player cost not use based; unjustifiable

† V. Misra, S. Ioannidis, A. Chaintreau, and L. Massoulié. *Incentivizing Peer-Assisted Services: A Fluid Shapley Value Approach*. In SIGMETRICS 2010.
‡ H. Chen and T. Roughgarden, T. *Network design with weighted players*. In SPAA 2006.
# E. Anshelevich, A. Dasgupta, J. Kleinberg, E. Tardos, T. Wexler, and T. Roughgarden. *The price of stability for network design with fair cost allocation*. In FOCS 2004.

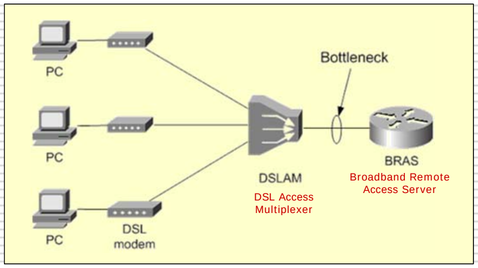
Fixed pricing for shared resources



The perils of the fixed pricing model

- It's here to stay; metered pricing rejected
- Implications:
  - Customer has no incentive to save bandwidth
  - ISP cost depends on peak demand – 95/5 rule
  - Reigning in bandwidth hogs is incompatible with Net Neutrality
- Must devise mechanisms that take ISPs out of the "traffic shaping" business

DSLAM "last-mile" architecture



Traffic shaping done at BRAS

Solution: Create a marketplace

- Recognize the two types of user utilities:
  - Interactive Traffic (IT)
    - Browsing, VoIP, Video, Messaging, Gaming, …
    - Limited bandwidth; highly sensitive to response time
  - Fluid Traffic (FT)
    - P2P, Network backup, Netflix/software downloads, …
    - Open-ended bandwidth; less sensitive to response time
- Create a marketplace:
  1. Give users rights to DSLAM bandwidth, and
  2. Let users trade IT & FT allocations over time

The Marketplace

- **Each user gets a fixed budget per epoch**
  - Budget (B_i) proportional to level of service
  - An epoch is a fixed number of time-slots, e.g., 1 day = 288 5-min slots
- **Trade & Cap**
  - User engages in a pure strategies game that yields a schedule for its IT sessions
  - User acquires as much FT bandwidth as its remaining budget would allow

Trading Phase: Strategy Space

- **Session:**

  An IT session is the sequence of slots during which an IT application is active
- **Slack:**

  User may have flexibility in scheduling IT sessions; slack specifies the number of slots that an IT session is allowed to be shifted back/forth
- **Strategy Space:**

  The set of all possible arrangements of IT sessions within allowable slack define the strategy space for a user

Trading Phase: Cost Function

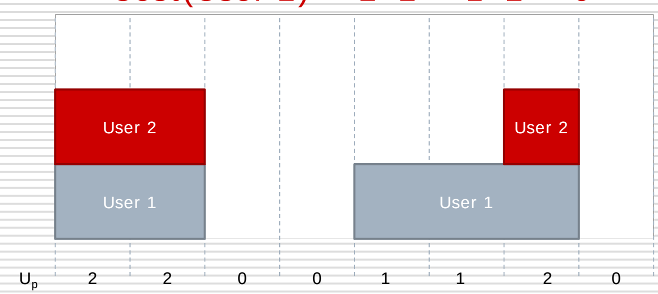
- Let x_{ik} be the bandwidth used in slot k by a chosen IT session schedule for user i.
- The cost incurred by user i is given by:

$$c_i = \sum_{k \in slots} x_{ik} \cdot U_k = \sum_{k \in slots} x_{ik} \left(\sum_{j \in users} x_{jk} \right)$$

- Cost of user i depends on the choices made by other users – hence the game!

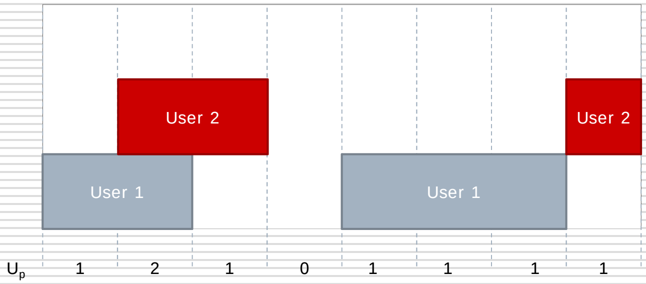
Trading Phase: Illustration

Cost(User 2) = 2*2 + 1*2 = 6



Trading Phase: Illustration

Cost(User 2) = 1*2 + 1*1 + 1*1 = 4



Trading Phase: Best Response

- BR of user i is the schedule of IT sessions that minimizes its cost c_i
- Computing BR is NP-hard, equivalent to solving a generalized knapsack problem
- Dynamic programming solution is pseudo-polynomial in the product of the number of sessions and number of slots
- Scales well for all practical settings – 100s of users and 100s of slots

Trading Phase: Findings

- Provably converges to Nash Equilibrium, even in presence of constraints
- For n users, Price of Anarchy is n, but in practice below 2, especially for n>10
- Experimentally, large reduction of peak utilization, even with small flexibility

Capping Phase: Best Response

- BR of user i is to maximize total FT allocation

$$w_i = \sum_{k \in slots} w_{ik}$$

subject to the budget constraint

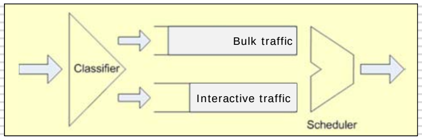
$$\sum_{k \in slots} w_{ik} \cdot \left(U_0 + \sum_{j \in users} w_{jk} \right) = B_i - c_i$$

Capping Phase: Findings

- Computing BR is efficient using Lagrange Multipliers method
- Provably, converges to a unique global (social) optimum that maximizes the FT allocations of all users
- Experimentally, smoothes the aggregate IT+FT traffic to any desirable level controlled by a "resistance parameter" R

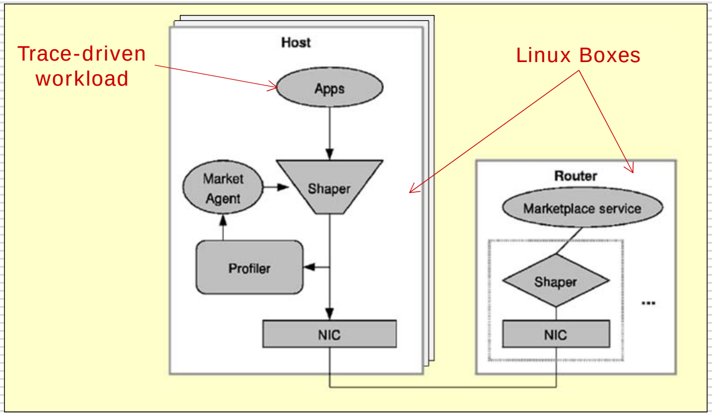
Trade & Cap: Implementation

- On Client Side (e.g., DSL Modem):
  - + Strategic agent to execute Trade & Cap
  - + Operational service to profile, classify, and shape



- ISP Side (e.g., DSLAM or BRAS):
  - + Support exchange between strategic agents
  - + Enforce total traffic/slot/user from Trade & Cap

Trade & Cap: Implementation



Trade & Cap: Implementation notes

- User Input:
  - As simple as checking box to join marketplace, and as elaborate as micromanaging RT slacks
  - May set a fraction of "budget" as insurance
- Client-side Profiler:
  - May be explicitly controlled by applications (or user settings)
- Client-side Traffic Shaper:
  - Work-conserving (not reservation based) Linux Hierarchical Token Bucket (HTB)
  - Allows FT to use underutilized RT bandwidth

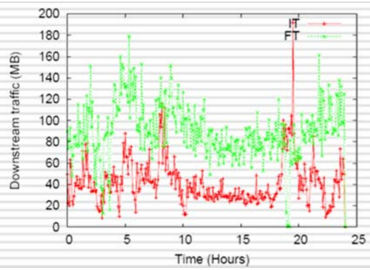
Experimental Evaluation

Workload

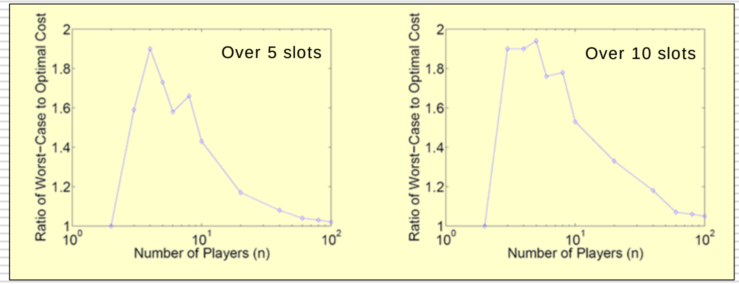
Derived from WAN traces of MAWI project

- Identify users from volume and direction of flows to known ports (e.g., most traffic destined to port 80)
- Identify user IT sessions using thresholds on per-IP traffic intensities over time
- Slack introduced using various models (e.g., fixed, proportional, etc.)

Period	2009-03-31 00:00 – 2009-03-31 23:59
Total packets	1,551,089,845
TCP packets	1,194,409,653
UDP packets	4,321,852
Total TCP bytes (payload)	924,540,189,060



Trading Phase: Experimental PoA

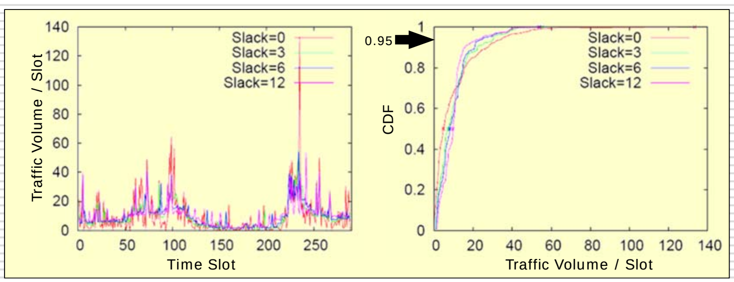


Theoretical PoA is n but not in practice

Trading Phase: Smoothing effect

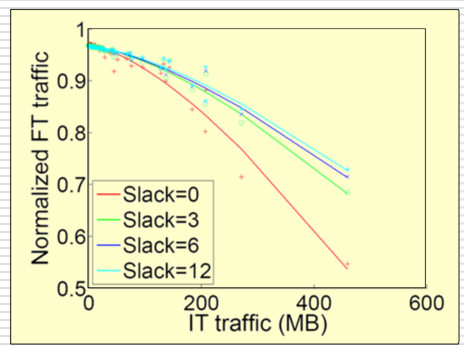
Value proposition to ISPs

Max Slack	Reduction in 95%
3	15%
6	24%
12	31%



Trade & Cap: Flexibility pays off!

Value proposition to customers



Trade & Cap: Beyond DSLAMs

- Trade & Cap is a *general* mechanism

  It can be used to coordinate how a shared resource is used by selfish parties who are not subject to the "pay as you go" model – e.g., "fixed pricing"

- Examples
  - Coordinating consumption of "reserved" versus "fluid" (CPU/network) capacities of VMs sharing a single host
  - Coordinating "reserved" versus "fluid" bandwidth utilization by multiple ISP customers (e.g., enterprises)

Fixed Pricing: Alternatives?

- Vickrey-style auctions work†
  - Assumes supply < demand
  - Takes a social perspective
  - Offers a strategy-proof solution
  - Requires central authority
  - Susceptible to collusion

† A. Young, B. Chun, A. Snoeren, and A. Vahdat. *Resource allocation in federated distributed computing infrastructures*. In OS/architectural support for on-demand IT infrastructure, 2004.

Dynamic pricing: Better mechanism?

- Customer cost should be a function of supply and demand
  - Supply may vary over time
  - Supplier's cost may vary over time
  - Demand may vary over time
  - Demand may exhibit structure, and may be subject to malleable constraints
- Need language to specify supply and demand (and act as basis for SLAs)

Resource Supply/Demand Model

- Supply/demand SLA types: (C, T, D, W)
  - C ~ amount available or consumed
  - T ~ allocation period
  - D ~ tolerable number of missed allocations in W
  - W ~ window of >= 1 allocation intervals
- Examples
  - SLA type $(2,5,0,1)$

    2 resource units supplied/consumed every 5 seconds with no missed allocations allowed
  - SLA type $(3,30,2,5)$

    3 resource units supplied/consumed every 30 seconds with no more than 2 out of 5 missed allocations

SLA Calculus

- ☐ Models various patterns of allocation and consumption (e.g., RR, GPS, LB, …)
- ☐ SLA types define type hierarchies
  - $(1, N, 0,1) < (k, k * N, 0,1)$
  - $(C, T, D, W) < (C, T, D', W)$, if $D < D'$
  - …
- ☐ Possible to transform SLAs from one form to another (safer) form

Using SLA Calculus for Colocation

- ☐ Not possible to colocate

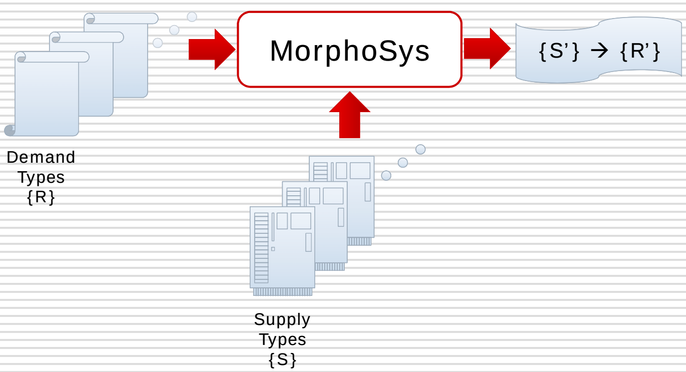
	Job 1	Job 2	Job 3	Job 4	Job 5
C	1	2	3	4	5
T	4	9	17	34	67

- ☐ Possible to colocate

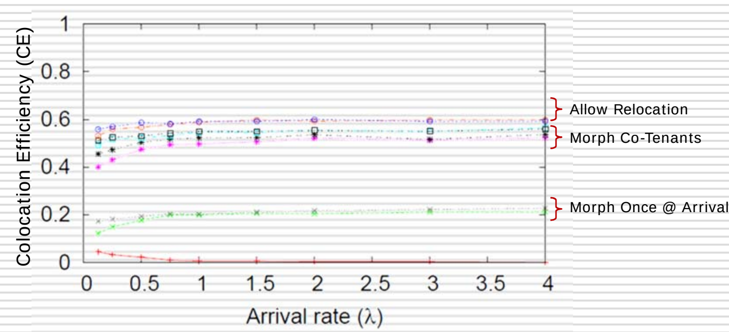
	Job 1	Job 2	Job 3	Job 4	Job 5
C	1	2	3	4	5
T	4	8	16	32	64

- ☐ SLA types and calculus provide a notion of supply & demand elasticity

Morphing SLAs for Efficiency



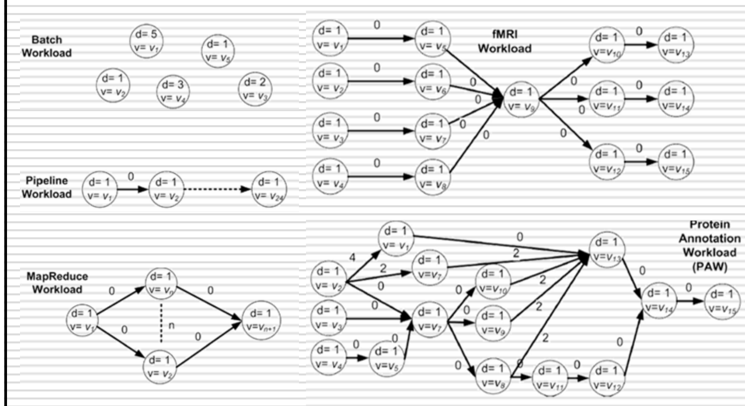
MorphoSys: Performance



Beyond Simple Types

- A workload is a set of requests (tasks), each with its SLA, subject to constraints:
  - Temporal dependencies between tasks
  - Start and end times
- Flexibilities might exist; another source of elasticity:
  - Min and max delays between tasks
  - Deadline slacks

Workload = DAG of SLA types



The Customer's Perspective

- Why should customers expose the elasticity of their workloads?
- Current IaaS (fixed) pricing mechanisms do not provide proper incentives
- Implications:
  - Less efficient workload management
  - Customers (should) game the marketplace

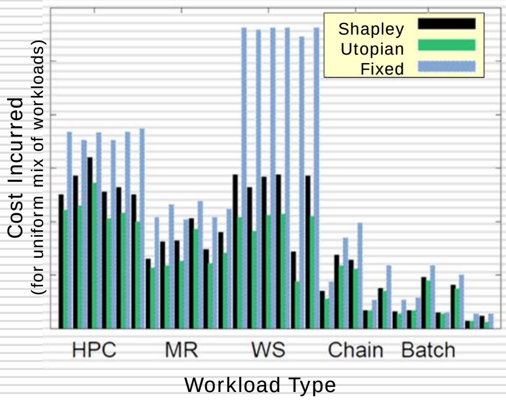
Dynamic Pricing: Shapley Value

- Well defined concept for fair cost sharing from coalitional game theory
  - Marginal contribution to the total cost, averaged over every permutation, e.g., for 3 workloads

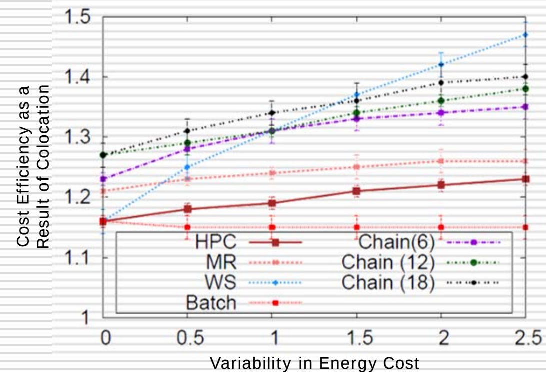
$$s(w_1) = \frac{1}{6}\begin{pmatrix} 2\,c(\mathrm{w}_1) + [c(\mathrm{w}_2\mathrm{w}_1) - c(\mathrm{w}_2)] + [c(\mathrm{w}_3\mathrm{w}_1) - c(\mathrm{w}_3)] + \\ [c(\mathrm{w}_2\mathrm{w}_3\mathrm{w}_1) - c(\mathrm{w}_2\mathrm{w}_3)] + [c(\mathrm{w}_3\mathrm{w}_2\mathrm{w}_1) - c(\mathrm{w}_3\mathrm{w}_2)] \end{pmatrix}$$

  - Impractical to calculate
  - Estimate by sampling random permutations

Workload Elasticity = Savings



Workload Elasticity = Savings



CloudCommons: http://csr.bu.edu/cc

Supported by a NSF Large CyberTrust Award (in collaboration with Brown and UCI)

Problem with today's cloud solutions

Public clouds are "closed" & prescriptive

- Stock hardware (hard to justify GPUs or a BlueGene)
- Special computational models (MapReduce, or?)
- Operational data is not visible (limits innovation)
- Irrational economic models (why fixed pricing?)
- Designed to lock in customers
- Perform poorly on HPC and big data
- Not conducive to federation of data assets
- Security by obscurity

Not conducive to experimentation/innovation

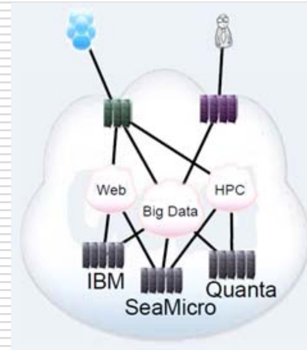
Can we change this status quo?

Need an ecosystem for

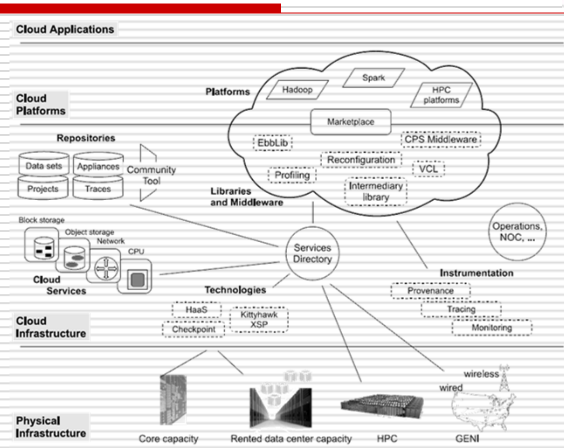
- Infrastructure Providers
  EMC, IBM, Dell, NTAP, Cisco, Intel, AMD, …
- Software Platforms
  VMware, RedHat, Hadoop, Azure, MapReduce…
- Aggregators and Resellers
  XCS, Morphosys, CloudPack, …
- Customers
  HPC apps, Web apps, Enterprise, Gov, …

Open Cloud: A Paradigm Shift

- Multiple implementation and operational models
  - Competing platforms suited to HPC, big data, …
  - Open economic model to create an efficient market
  - Operational data visible to various stakeholders
- Ecosystem needs a facility for "mashups"



Open Cloud eXchange: Architecture



Massachusetts Green HPC Facility

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The Massachusetts Open Cloud

- An initiative of The BU Hariri Institute for Computing in collaboration with MGHPCC
  - Project is spearheaded by Center for Cloud Innovations (Orran Krieger, Director)
  - Project leverages three Institute research priorities: Cybersecurity, Big Data, and Cloud Computing
- A great vehicle for inter/national collaboration
  - Federation interest from Oakridge, Brazil, …

Conclusion

- Resource management must be seen in an economics context
- By setting up the right mechanisms, one can engender trust in the cloud marketplace
- Supply elasticity meets demand elasticity for an efficient marketplace
- New services needed to support strategic and operational aspects of new mechanisms
- Need to experiment at scale!

Partial Paper Trail…

- V. Ishakian, R. Sweha, A. Bestavros, and J. Appavoo. CloudPack: Exploiting Workload Flexibility Through Rational Pricing. In ACM/IFIP/USENIX Middleware Conference, Montreal, Canada, December 2012. (Best Paper Award)
- V. Ishakian and A. Bestavros. MorphoSys: Efficient Colocation of QoS-Constrained Workloads in the Cloud. In CCGrid'12: IEEE/ACM Symposium on Cluster, Cloud and Grid Computing, Ottawa, Canada, May 2012.
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- J. Londono, A. Bestavros, and N. Laoutaris. Trade and Cap: A Customer-Managed, Market-Based System for Trading Bandwidth Allowances at a Shared Link. In NetEcon'10: USENIX/ACM OSDI Workshop on the Economics of Networks, Systems, and Computation, Vancouver, Canada, October 2010.
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