## Energy Management and Adaptive Behavior

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## Energy in Data Centers

- Data centers account for 1.5% of total energy consumption in the US
  (Equivalent to 5% of all US housing)
  According to the U.S. EPA Report, 2007:
- The cost of energy already accounts for at least 30% of the total operation cost in most data centers.
  According to BroadGroup (independent market research firm)



## The Energy Optimization Problem

- Requires a holistic approach
- Local optimization of individual knobs is not equivalent to global optimization

## Problem: Composability of Adaptive Behavior

- Modern time-sensitive and performance-sensitive systems are getting more complex
  - → Manual tuning becomes more difficult, hence: automation
  - → Automation calls for adaptive capabilities (e.g., IBM's autonomic computing initiatives) hence: adaptive components
  - → Emerging challenge
    Composition of adaptive components
    (Locally stable but globally unstable systems?)



## Locally Stable – Globally Unstable Preliminary Insights

- Positive feedback versus negative feedback



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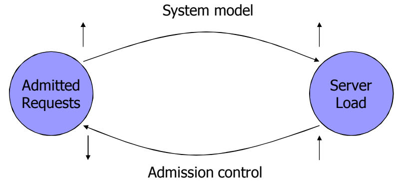

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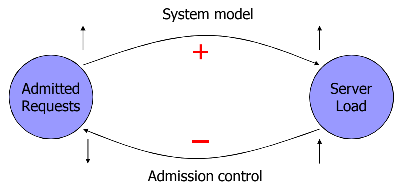
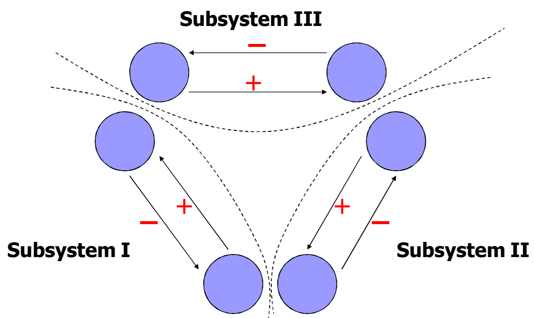
- Positive feedback versus negative feedback




All stable feedback is negative



## Composition of Adaptive Systems



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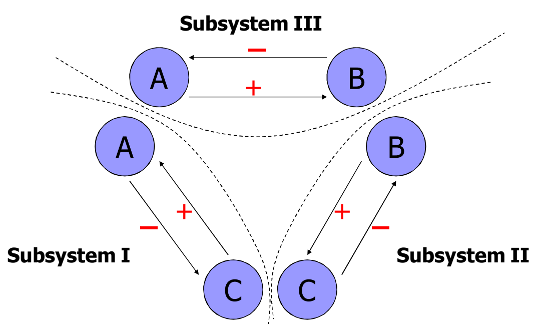
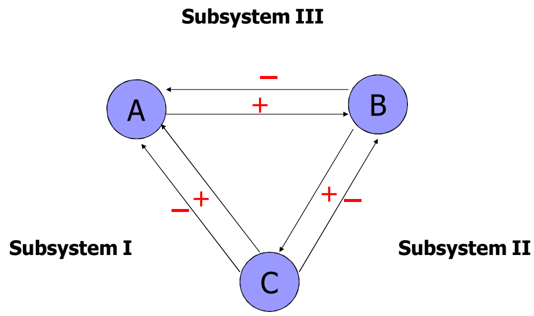
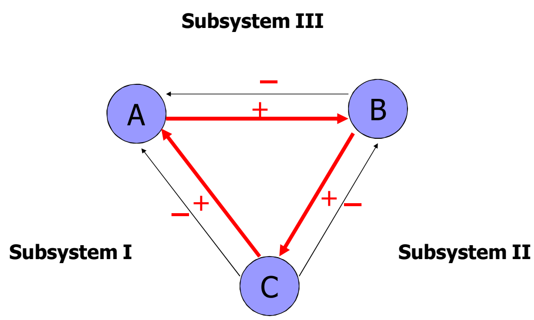


## Composition of Adaptive Systems






## Composition of Adaptive Systems



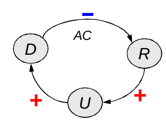



## Composability of Adaptive Behavior

- Many adaptive policies may perform well in isolation, but conflict when combined
- Example: DVS enabled QoS-aware Web server
  - DVS policy and admission control policy (AC) +
  - In an underutilized server, DVS decreases frequency, hence increasing delay
  - AC responds to increased delay by admitting fewer requests
  - Unstable cycle - throughput diminishes

## Detection of Potential Conflicts:
### Introduction to Adaptation Graphs

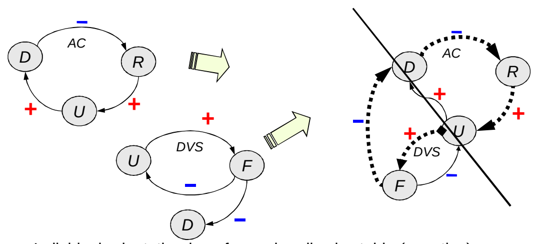
- Adaptation graphs determine which adaptive policies conflict (if they do)
- Adaptation graphs
  - Graphical representation of causal effects among performance control knobs and system performance metrics
- A affects B: *A* → *B*
  - Changes in A cause changes in B
  - Direction of change (+, -)
  - Natural consequences or programmed behavior
  - The sign of a cycle: multiplication of the signs of all edges




Adaptation graph for QoS-aware Web Server



## Example: DVS-enabled QoS-aware Web Server

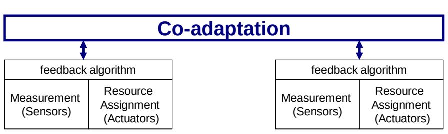



Individual adaptation loop for each policy is stable (negative)

**Combined together, unstable positive loop across policy boundaries → Use co-adaptation!!**



## Co-adaptation Design Methodology




Adaptive policy (software component) 1 Adaptive policy (software component) 2

**Co-adaptation guides you to design a shared co-adapt module - Outputs knob settings that increases utility**

**Constrained optimization (Necessary condition) + Feedback control**

## Co-adaptation Cont.

- Step1: Casting the objective
  - Find a common objective function – minimize cost or maximize utility
- Step2: Formulating optimization problems
  - Decision variables: settings of adaptation "knobs"
  - Subject to two types of constraints
    - resource constraints
    - performance specifications

$$\min_{x_1,\ldots,x_n} \quad f(x_1,\ldots,x_n)$$
$$\text{subject to} \quad g_j(x_1,\ldots,x_n) \le 0, \quad j = 1,\ldots,m$$

*$X_1,\ldots X_n$*: adaptation knob settings for policy *I*

*j = 1, …, m:* resource and performance constraints



## Co-adaptation Cont.

- Step3: Derivation of necessary conditions
  - Lack of accurate model for computing systems
  - Augmented by feedback to move closer to the point that increases utility
  - Use the Karush-Kuhn-Tucker (KKT) optimality condition

$$\frac{\partial f(x_1,\ldots,x_n)}{\partial x_i} + \sum_{j=1}^{m} \nu_j \frac{\partial g_j(x_1,\ldots,x_n)}{\partial x_i} = 0$$

$\Gamma x_i$ ←

  - Necessary condition $\partial x_1 = \ldots = \partial x_n$
    - Define $\partial x = (\partial x_1 + \ldots + \partial x_n)/n$

*$X_1,\ldots X_n$*: a set of adaptation knob for policy *i*

*j = 1, …, m:* resource and performance constraints



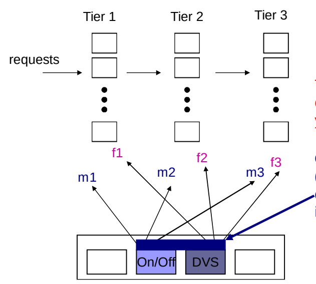
## Co-adaptation Cont.

- Step4: feedback control
  - Measurement based – periodic measurement to estimate $\Gamma x_i$
  - Try to meet the necessary condition $\Gamma x_1 = \ldots = \Gamma x_n$ by Hill climbing
    - Pick one with the largest or smallest value of $\Gamma x_i$
    - Search through the neighboring knob settings (values of Xi)
      - Reduce the error ($\Gamma x - \Gamma x_i$ )
      - Maximum increase in utility subject to constraints

*X1,…Xn*: a set of adaptation knobs for policy *i*

# A Server Farm Case study

## Energy Minimization in Server Farms



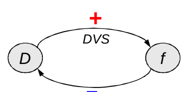

Two policies were shown to be in conflict by adaptation graph analysis: yielding more energy consumption

**Co-adaptation finds knob settings, (m1, m2, m3, f1, f2, f3) in the direction where energy consumption is reduced**

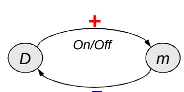


# 1. Incompatibility Detection:

- Two adaptive policies
  - DVS policy
  - On/Off policy




DVS policy

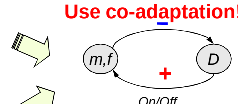



On/Off policy

**Combined together, it is still negative.**

**But potentially unstable. →**

**Use co-adaptation!!**




(c) Adaptation graph for combined DVS and On/Off policies: possible interference in the control of *D*



# 2. Design of a Co-adaptive Energy Minimization Policy

**Formulate constrained optimization**

$P_i(f_i) = A_i \cdot f_i^p + B_i$ Power estimation of a machine at tier i

$U_i = \frac{\lambda}{\mu} = \frac{\lambda_i / m_i}{f_i} = \frac{\lambda_i}{m_i f_i}$ Queuing equation using number of machines and arrival rate

$P_i(U_i, m_i) = A_i \cdot \left(\frac{\lambda_i}{U_i m_i}\right)^p + B_i = \frac{A_i \lambda_i^p}{U_i^p m_i^p} + B_i$ Power estimation function of a machine at tier i

$$\min_{U_i \geq 0,\ m_i \geq 0} P_{tot}(U_i, m_i) = \sum_{i=1}^{3} m_i \left(\frac{A_i \lambda_i^3}{U_i^3 m_i^3} + B_i\right)$$

$$\text{subject to} \quad \sum_{i=1}^{3} \frac{m_i}{\lambda_i} \cdot \frac{U_i}{1 - U_i} \leq K, \qquad \sum_{i=1}^{3} m_i \leq M$$

Find best composition of ($m_1$, $m_2$, $m_3$, $U_1$, $U_2$, $U_3$)

## Design of a Co-adaptive Energy Minimization Policy

- Derive necessary condition for optimality
  - Karush-Kuhn-Tucker (KKT) condition

$$\frac{\lambda_1^4(1-U_1)^2}{m_1^3U_1^4} = \frac{\lambda_2^4(1-U_2)^2}{m_2^3U_2^4} = \frac{\lambda_3^4(1-U_3)^2}{m_3^3U_3^4}$$
$$\Gamma(m_1, U_1) = \Gamma(m_2, U_2) = \Gamma(m_3, U_3)$$

**Try to find ($m_1$, $m_2$, $m_3$, $U_1$, $U_2$, $U_3$) tuple that balance the condition.**



## Design of a Co-adaptive Energy Minimization Policy

$$\frac{\lambda_1^4(1-U_1)^2}{m_1^3U_1^4} = \frac{\lambda_2^4(1-U_2)^2}{m_2^3U_2^4} = \frac{\lambda_3^4(1-U_3)^2}{m_3^3U_3^4}$$
$$\Gamma(m_1, U_1) = \Gamma(m_2, U_2) = \Gamma(m_3, U_3)$$

- Feedback Control
  - Goal: balance the necessary condition in the direction to reduce energy consumption
  - *When delay constraint violated*: Pick the tier with the most overloaded tier (the lowest $\Gamma(m_i, U_i)$)
  - *Else*: Pick the most underloaded tier (highest $\Gamma(m_i, U_i)$)
  - Choose ($m_i$, $U_i$) pair that makes the error within a bound and yields the lowest total energy
    - Error = $\Gamma_x - \Gamma(m_i, U_i)$ , where $\Gamma_x$ is average of $\Gamma(m_i, U_i)$



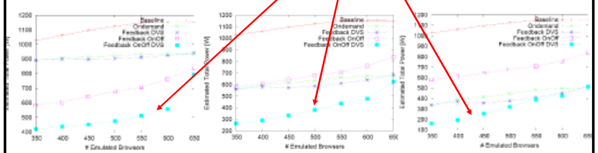
## Evaluation on a Server Farm Testbed

- Energy minimization framework in 3-Tier Web server farms
  - Web tier (Web servers), application server tier (business logic), and database tier
  - Total 17 machines
  - Industry standard Web benchmark TPC-W

## Evaluation

- Comparison with other mechanisms on different DVS settings
  - Baseline
  - Linux Ondemand
  - Feedback DVS
  - Feedback OnOff
  - Feedback OnOff DVS

DVS + On/Off with co-adaptation: gives the best performance



**δ=0.8, saving from DVS is small** **δ=0.5** **δ=0.3, saving from DVS is big**

SIGMETRICS 2008: Introduction to Control Theory. Abdelzaher, Diao, Hellerstein, Lu, and Zhu

## Conclusion

- Presented methods for composition of adaptive components
- Adaptation graph analysis to identify incompatibilities
- Co-adaptation design methodology for composition
- Web server farm case-study in the testbed with 17 machines

SIGMETRICS 2008: Introduction to Control Theory. Abdelzaher, Diao, Hellerstein, Lu, and Zhu

## Questions?

SIGMETRICS 2008: Introduction to Control Theory. Abdelzaher, Diao, Hellerstein, Lu, and Zhu