TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA
Macroarea di Ingegneria
Dipartimento di Ingegneria Civile e Ingegneria Informatica

Self-adaptive Distributed Systems

Corso di Sistemi Distribuiti e Cloud Computing
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Valeria Cardellini

Laurea Magistrale in Ingegneria Informatica

Self-adaptive software systems

"Intelligence is the ability to adapt to changes"
S. Hawking

- We aim to a software system capable of adapting its operations at run-time with respect to itself and the environment: a self-adaptive (or autonomic) software system
  - Applications of self-adaptive systems in many computing environments
    - Cloud computing
    - Edge/fog computing
    - Compute continuum
    - HPC
    - Cyber-physical systems

Self-adaptive software systems

- **Autonomic computing**: computing paradigm able of responding to the need of managing IT systems complexity and heterogeneity through automatic adaptations
  - Inspired by human autonomic nervous system, able to control some vital functions (heart rate, digestion, temperature, ...) masking their complexity to humans

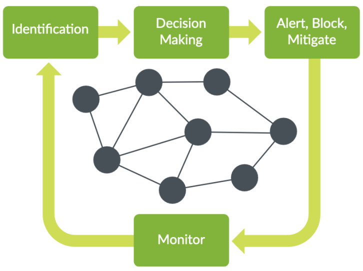
- A self-adaptive (or autonomic) software system can:
  - Manage its functionalities and goals autonomously (i.e., without or with minimal human intervention)
  - Handle changes and uncertainty in its environment and system itself

Kephart and Chess, The vision of Autonomic Computing, *IEEE Computer*, 2003

Self-adaptation is everywhere

kubernetes

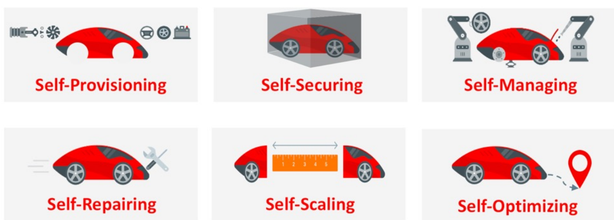
kubernetes.io



Self-healing networks, www.juniper.net

aws.amazon.com/ec2

Autonomous Vision: Effortless, Limitless, Unbreakable Data Cloud



Autonomous database, www.oracle.com/autonomous-database/what-is-autonomous-database/

Goals of self-adaptive systems

- A self-adaptive (***self-****) software system is able to self-manage, pursuing the following goals:
- Self-optimize
  - Capability of system to optimize its resource usage or performance while providing its required quality goals
  - E.g., change placement of application components onto system nodes to satisfy application response time
- Self-heal
  - Capability of system to discover, diagnose and recover from faults to provide its required quality goals or degrade gracefully otherwise
  - E.g., detect crashed nodes and exclude them from serving requests

Goals of self-adaptive systems

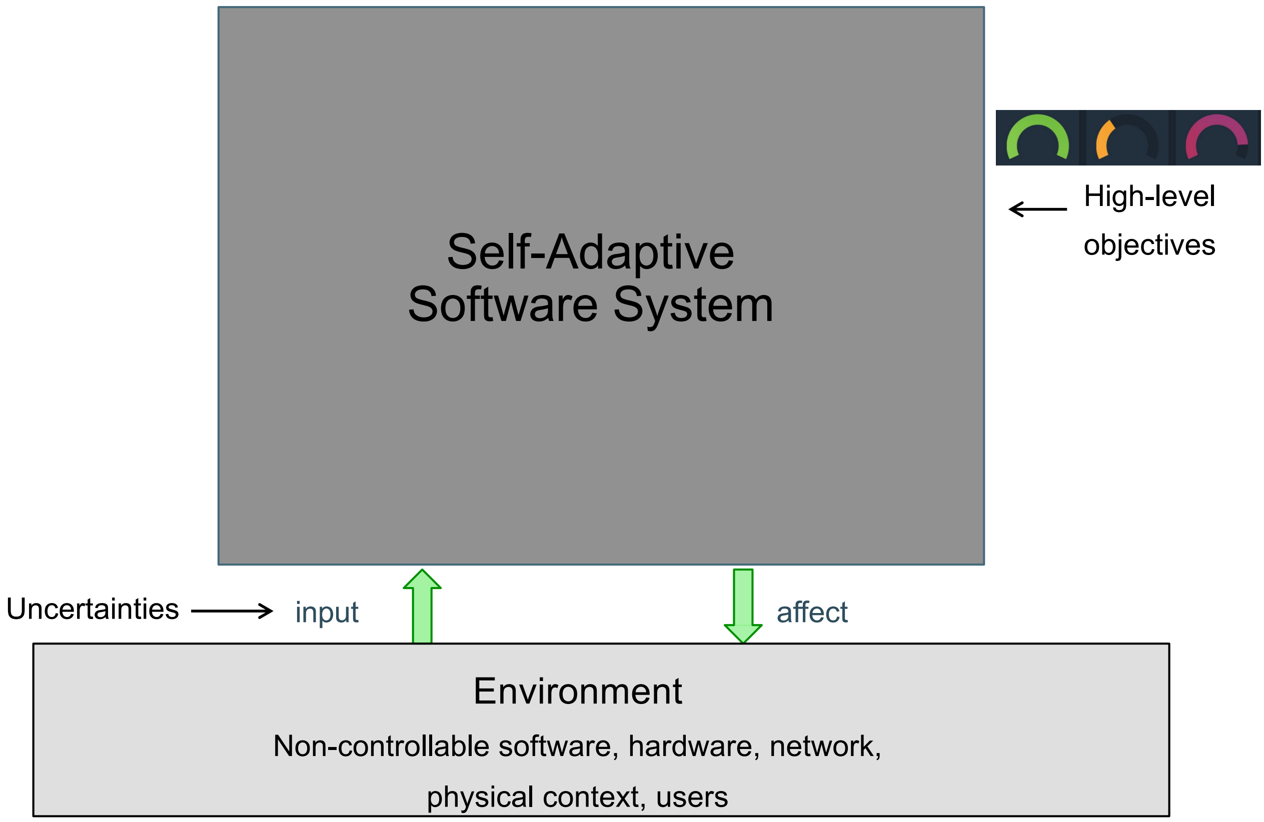
- Self-configure
  - Capability of system to automatically integrate new elements, without interrupting the system's normal operation, or tune some configuration parameters
  - E.g., discover new nodes and add them to serve requests
- Self-protect
  - Capability of system to detect anomalies (i.e., intrusion detection) and react to intrusion and attack actions and its consequences (i.e., intrusion response) so to protect from security threats
  - E.g., in a network of IoT devices detect a jamming attack that corrupts network traffic and adapt packets schedule

How to achieve the goals of a self-* system?

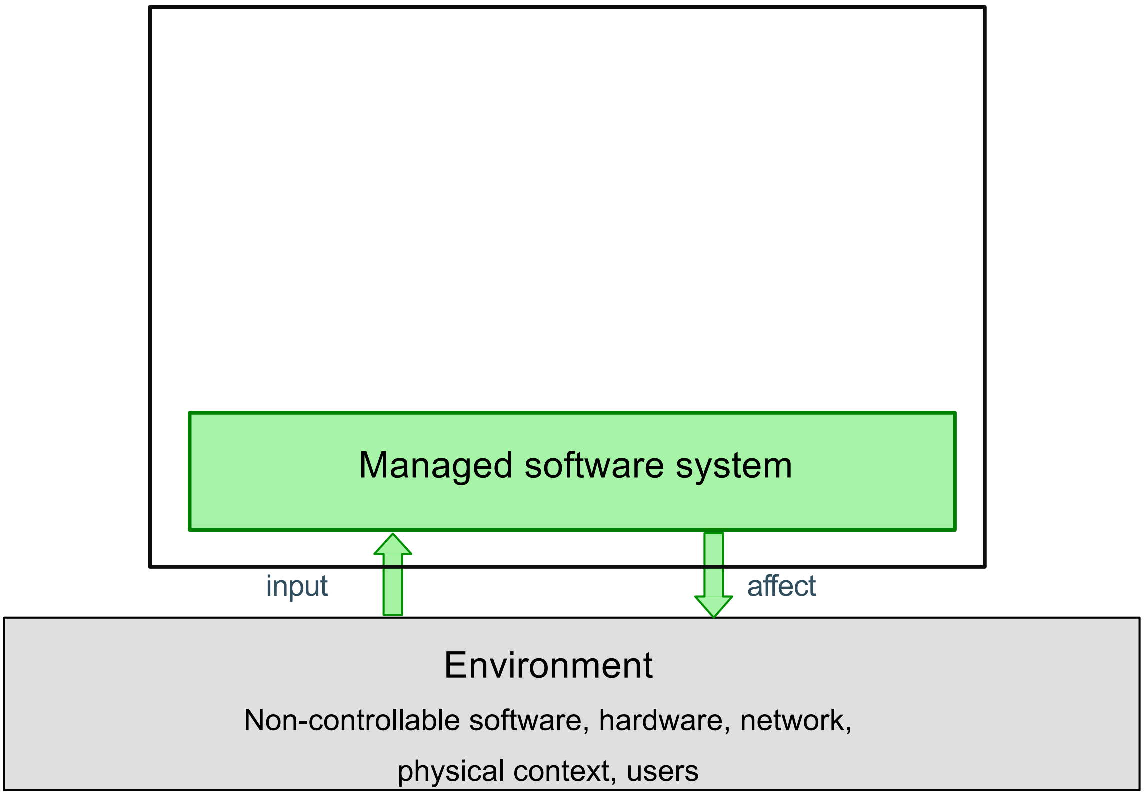
- The system should know its internal state (self-awareness) and the current external operating conditions (self-situation)
- Should identify changes regarding its state and the surrounding environment (self-monitoring)
- And should adapt consequently (self-adjustment)

- These attributes are the implementation mechanisms

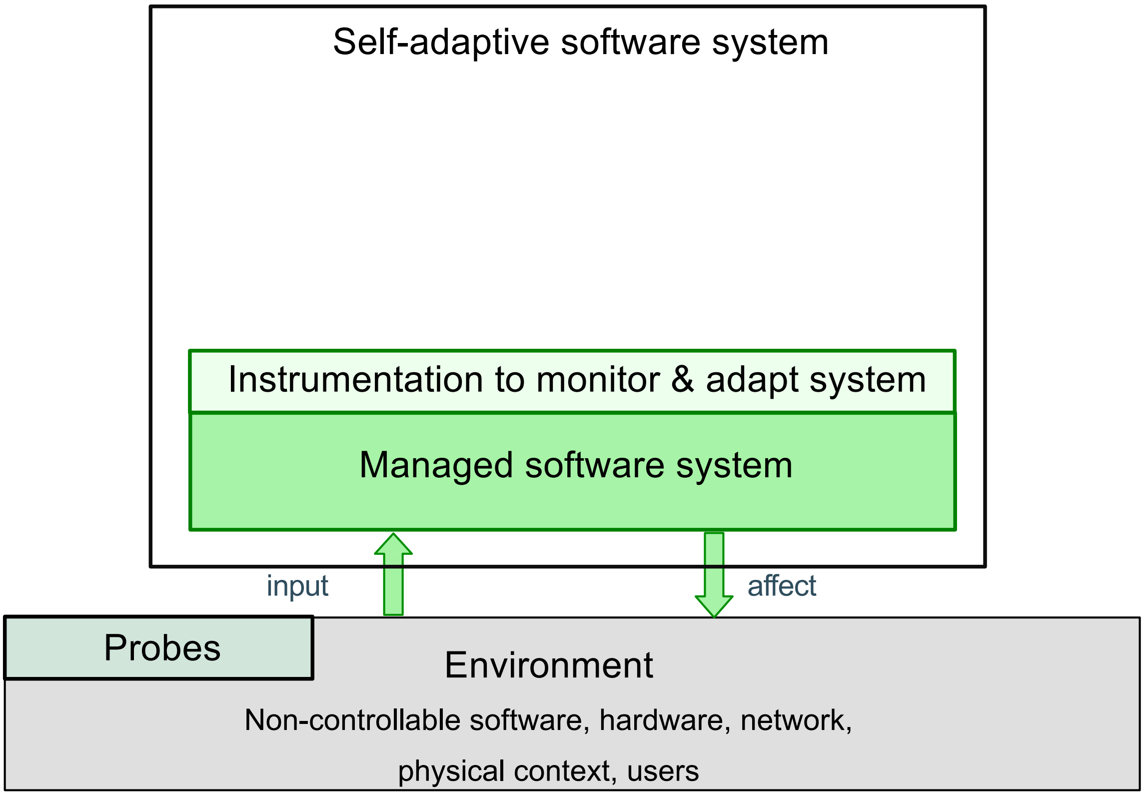
Conceptual model of self-adaptive system



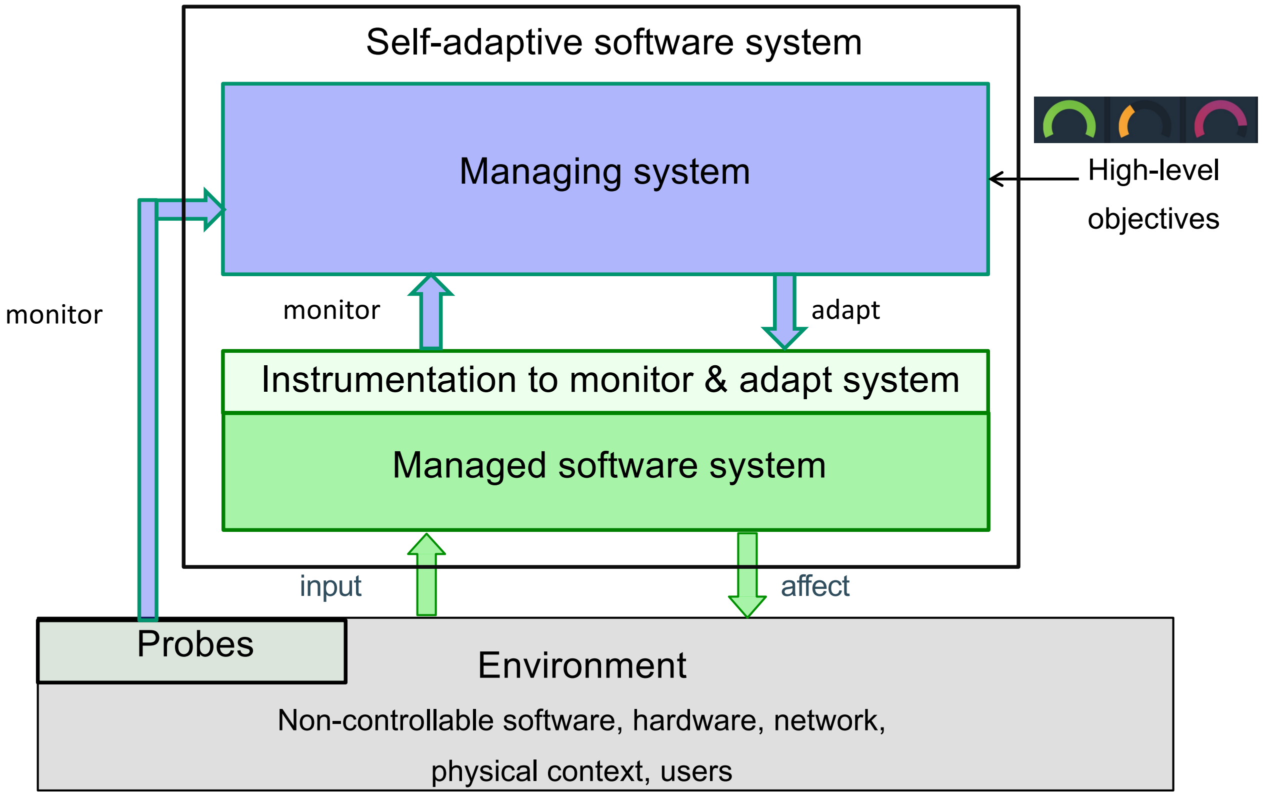
Conceptual model of self-adaptive system



Conceptual model of self-adaptive system

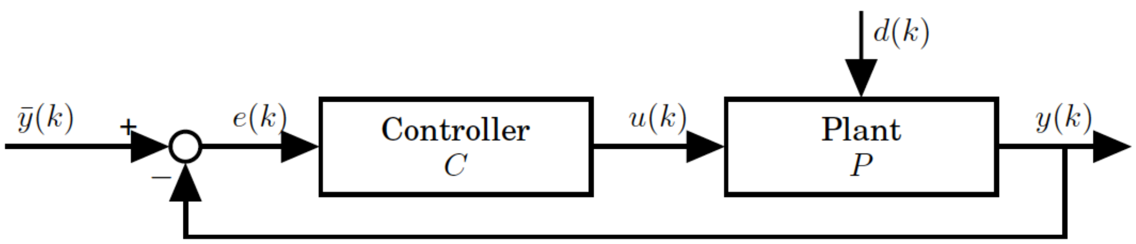


Conceptual model of self-adaptive system



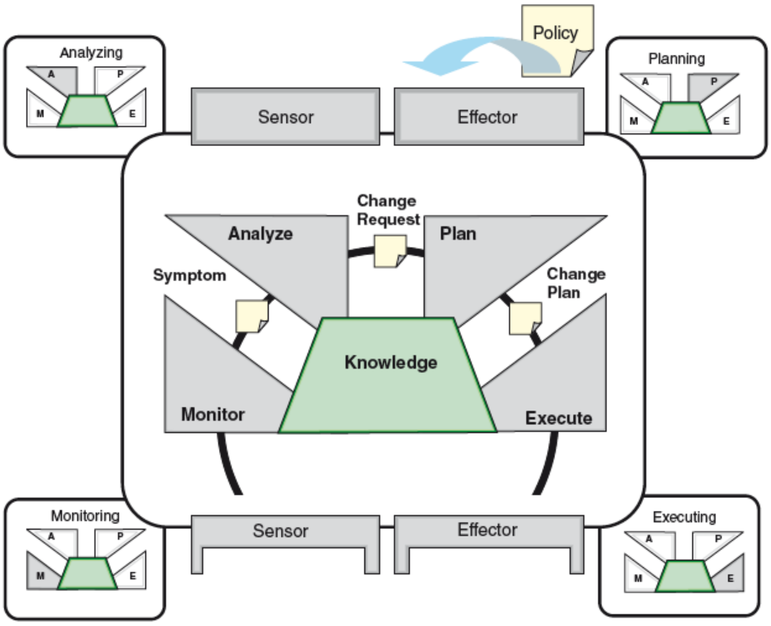
You are already familiar with this model

- The control-theory perspective of a self-adaptive system



MAPE: reference architecture for self-adaptive system

- **MAPE** (Monitor, Analyze, Plan, Execute) loop



MAPE: building blocks (or phases)

- **Monitor**
  - Collects data from the managed system and execution environment through sensors; aggregates, filters and correlates these data into symptoms that can be analyzed
- **Analyze**
  - Observes and analyzes situations to determine need for adaptation
  - If adaptation is required, it triggers Plan
- **Plan**
  - Determines which mitigation actions need to be performed so to enact a desired alteration in the managed system
- **Execute**
  - Enacts the change plan by carrying out the actions determined by Plan through effectors so to adapt the managed system
- Plus **Knowledge (MAPE-K)**
  - Stores shared knowledge regarding relevant aspects of the managed system, environment, and the administrator's goals

MAPE: Monitor

- Main design options for Monitor:
  - *When* to monitor: continuously, on demand
  - *What* to monitor: resources, workload, performance, …
  - *How* to monitor: architecture (centralized vs. decentralized), methodology (active vs. passive)
  - *Where to store* monitored data (e.g., time-series database) and *how* (e.g., some pre-processing)

MAPE: Analyze

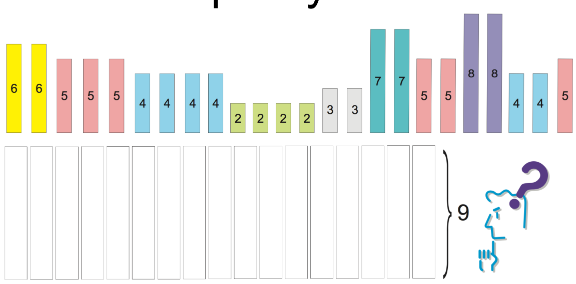
- Main design options for Analyze:
  - *When* to analyze: event- or time-triggered
  - Reactive vs. proactive adaptation
    - *Reactive*: *in reaction to* events that have already occurred (e.g., increase number of resources *after* workload increase)
    - *Proactive*: based on *prediction* so to plan adaptation actions in advance (e.g., increase number of resources *before* workload increase occurs)

MAPE: Plan

- The most challenging and studied MAPE phase
- A variety of methodologies and techniques can be used to plan adaptation, including
  - Optimization theory
    - ✓ Optimal adaptation actions
    - ✗ Con: formulation can be NP-hard, too expensive to solve at runtime
  - Heuristics
    - ✓ Faster
    - ✗ Sub-optimal adaptation actions
  - Machine learning, including reinforcement learning
  - Control theory
  - Queueing theory
- Example: optimal bin packing and heuristic policies to dynamically place virtual machines or containers on servers

Example: VM/container placement

- VM/container placement problem can be modeled as bin packing optimization problem
- Bin packing: pack items of different sizes (VMs/containers) into a minimum number of bins (server nodes), each of a given capacity (amount of resources), such that total size of items in each bin does not exceed bin capacity



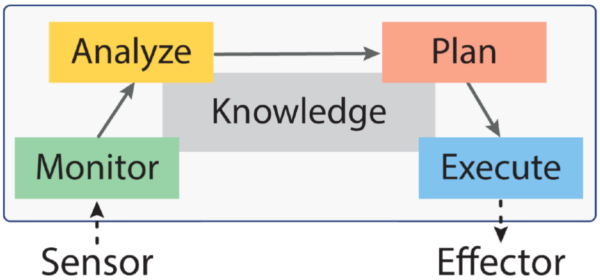
- Integer optimization problem ⇒ NP-hard ⇒ we need efficient heuristics to find a new placement when some change occurs

Example: VM/container placement

- Some examples of baseline heuristic policies
- *Round robin:* organize bins in a *circular* list, saving the latest bin used for placement; allocate each item on next bin with enough capacity, starting from current position on list
  - Does not minimize number of used bins
- *First fit:* organize bins in a list and place each item into *the first bin* in which it fits, restarting for each item at the beginning of list
  - First fit decreasing: variant in which items are sorted in decreasing order
- Many other heuristics, e.g.,
  - *Best fit*: place item into the bin with the *minimum amount* of capacity into which the item can fit
  - *Worst fit*: similar to best fit, but *maximum*

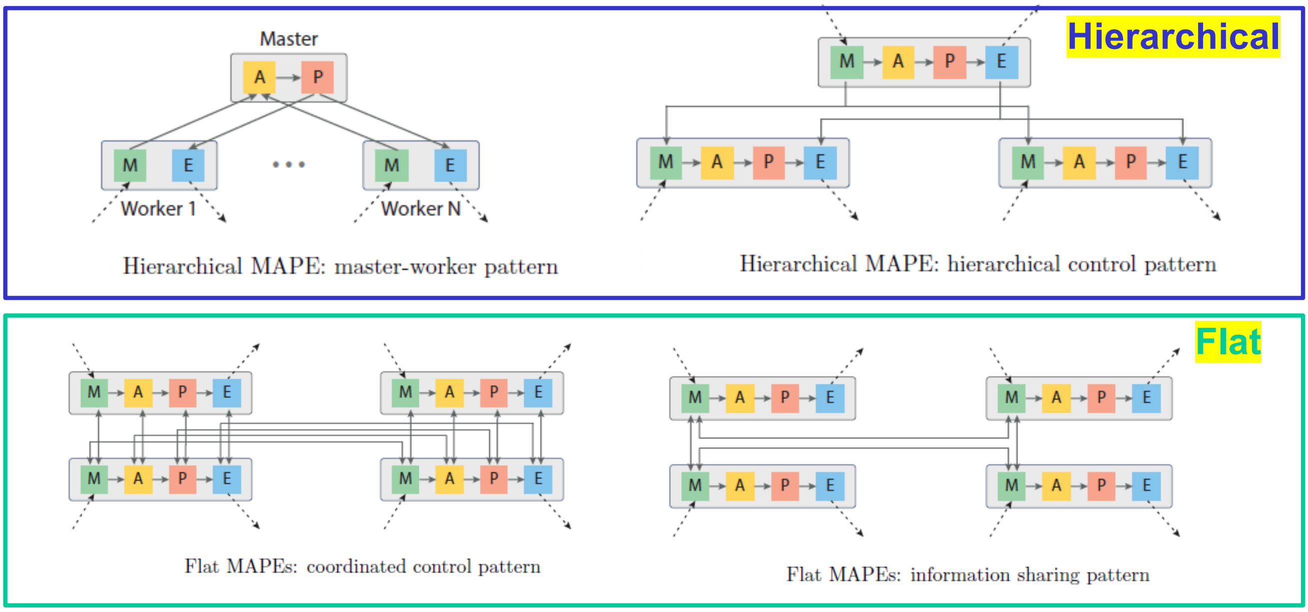
Alternative architectures for MAPE

- How to design the managing system?
  - Centralized MAPE: all MAPE components on same node, simpler but lack of scalability in geo-distributed environments
  - **Decentralized MAPE**: MAPE components are distributed; many architectural patterns, each one with pros and cons
    - No clear winner, it depends on system and application features and requirements



How to decentralize the adaptation control

- Main architectural patterns for decentralized MAPE



Hierarchical MAPE: master-worker pattern

Hierarchical MAPE: hierarchical control pattern

Flat MAPEs: coordinated control pattern

Flat MAPEs: information sharing pattern

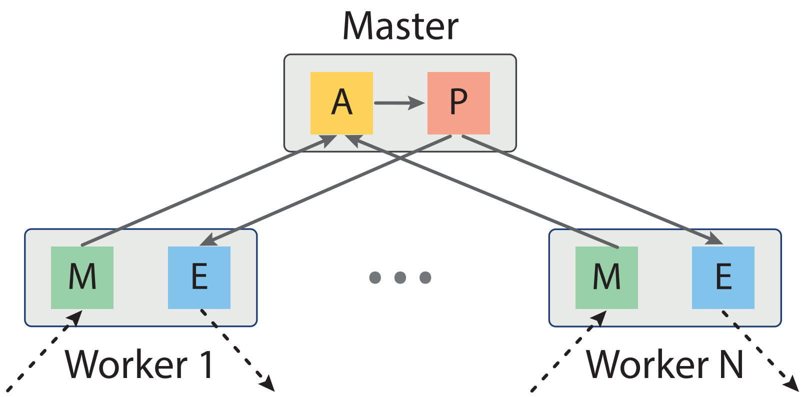
Weyns et al., On patterns for decentralized control in self-adaptive systems. In *Software Engineering for Self-Adaptive Systems II*, 2013

How to decentralize the adaptation control

- First design choice: ***hierarchical*** vs. ***flat***
  - Hierarchical: easier to design, but risk of bottleneck in top level of hierarchy
  - Flat: more difficult to coordinate, but can scale better
- Hierarchical MAPE patterns: multiple MAPE loops organized in a hierarchy, where a higher-level control loop manages subordinated control loops
  - Master-worker
  - Hierarchical control
- Flat MAPE patterns: multiple MAPE loops cooperate as peers
  - Coordinated control
  - Information sharing

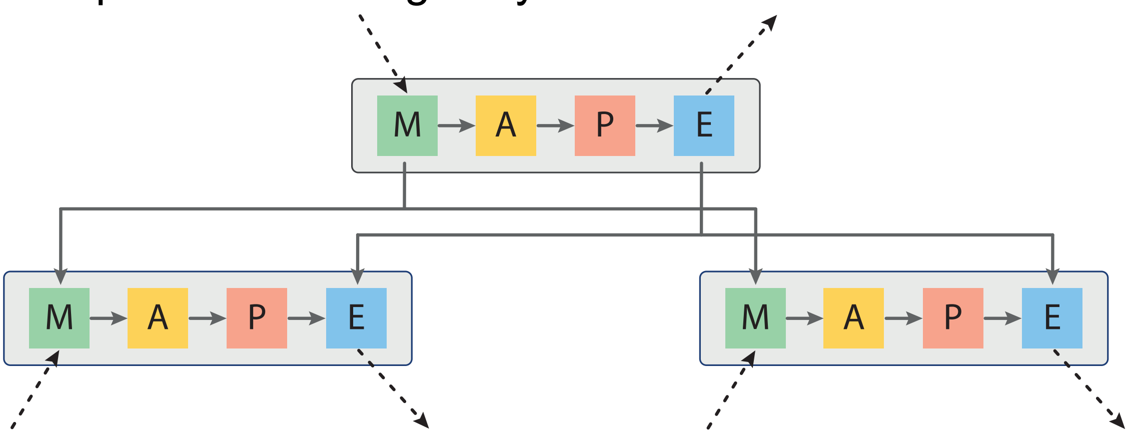
Hierarchical MAPE: master-worker pattern

- Decentralize M and E on workers, keep A and P centralized on master
- ✓ Global view on master who can achieve global adaptation goals
- ✗ Communication overhead and risk of performance bottleneck and SPOF on master



Hierarchical MAPE: hierarchical control pattern

- Multiple MAPE loops, which can operate at different time scales and with separation of concerns
- ✓ Top-level MAPE can achieve global goals, increased flexibility
- ✗ Can be non-trivial to identify different levels of control, depends on managed system characteristics

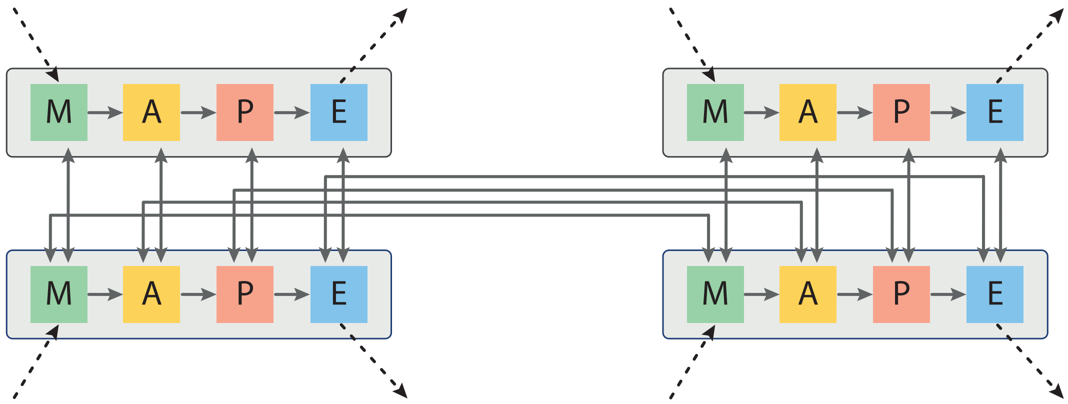


Flat MAPE: coordinated control pattern

- Multiple control loops, each one in charge of some part of the managed system but coordinated through interaction

✓ Better scalability

✗ More difficult to take joint adaptation decisions

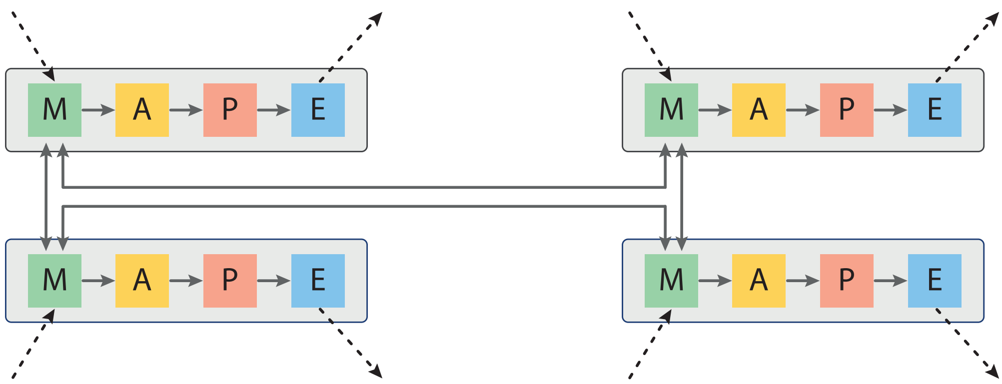


Flat MAPE: information sharing pattern

- Special case of coordinated control pattern: interaction only among M components

✓ Better scalability

✗ Lack of coordination on planning, conflicting or sub-optimal adaptation actions can be enacted

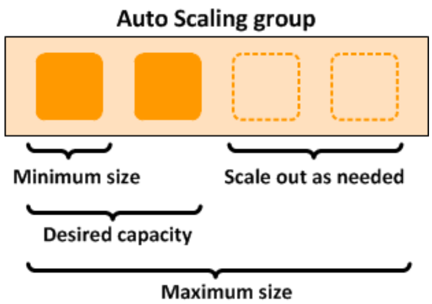


Examples of self-adaptive systems

- Let's analyze 3 examples of self-adaptive systems for resource management
  1. Auto-scaling EC2 instances
  2. Selecting services of composite applications
  3. Auto-scaling microservice-based applications
- Common ground
  – Applications face unexpected events (e.g., workload surge and spikes, node crashes)
  – Adaptation goal: satisfy some SLO (e.g., based on application response time, application availability)
  – Examples differ in planning methodologies and control architectures

Example 1: Amazon EC2 Auto Scaling

- AWS service to automatically add or remove EC2 instances according to user-defined conditions and health checks aws.amazon.com/ec2/autoscaling



- **M**APE Monitor: monitor scaling metrics on EC2 instances using CloudWatch
- Which scaling metrics?
  – CPU utilization, network I/O, Application Load Balancer request count, …

Example 1: Amazon EC2 Auto Scaling

- MAPE Plan: we study 2 policies implemented in Auto Scaling for determining scale-out/in decisions
  - Dynamic simple scaling
  - Predictive scaling
- In addition to auto-scaling, Auto Scaling is a self-healing system
  - Can detect when an EC2 instance is unhealthy, terminate it, and launch a new instance to replace it

Example 1: Amazon EC2 Auto Scaling

- **Dynamic simple scaling**: user-defined scaling plan to decide when and how to scale (*reactive*)
- Based on a threshold-based heuristic policy
  - Set upper and lower thresholds on some scaling metric(s)

```
if (metric > upper_thr) scale-out
else if (metric < lower_thr) scale-in
```

    - Example of *scale-out* rule: if average CPU utilization of all instances > 70% in last 1 minute, then add 1 new instance
    - Example of *scale-in* rule: if average CPU utilization of all instances is <35% in last 5 min, then remove 1 instance
  - CloudWatch monitors and sends alarms, one for scaling out (upper_thr) and the other for scaling in (lower_thr)
  - *Cooldown* period between each scaling activity

Threshold-based policy: pros & cons

✓ Simple and easy-to-understand: select scaling metric(s), period and thresholds for alarms

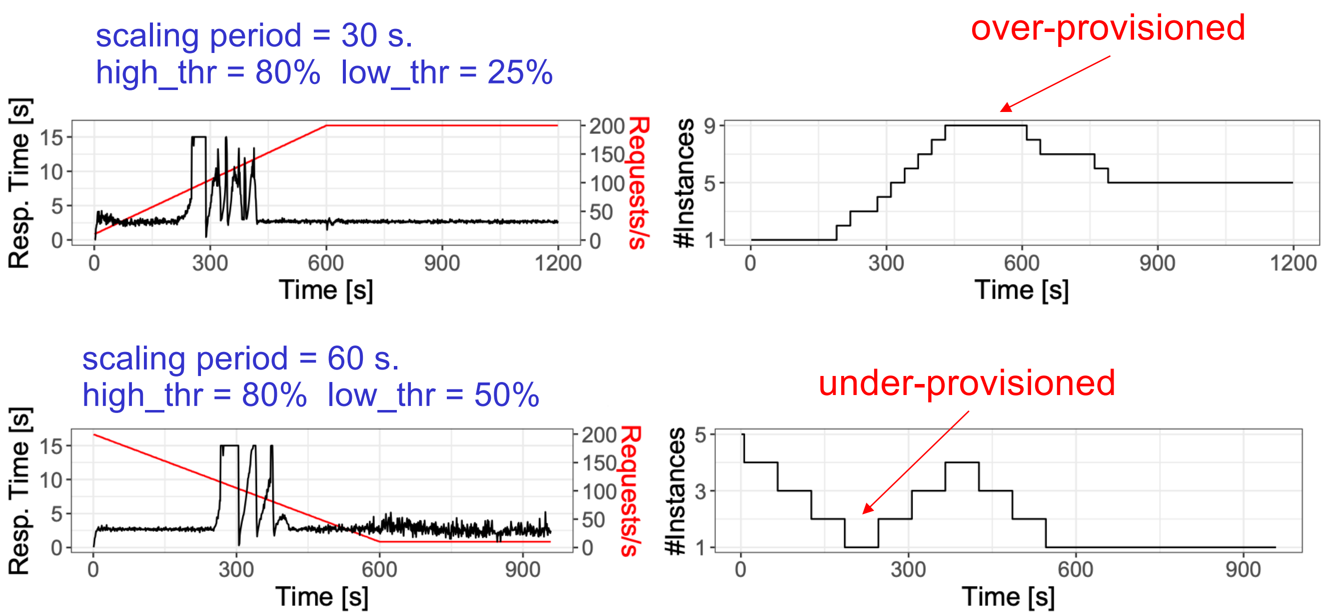
✗ Not easy to choose metrics and thresholds

- Metric can be application-dependent: application components can be CPU/memory/IO-intensive or a mix
- Thresholds value can be either too aggressive or conservative, some example
  - ➢ Slow scale-out, e.g., not enough instances added because upper_thr is high ⇒ SLO violations occur
  - ➢ Rapid scale-out, e.g., too many instances added because upper_thr is low ⇒ large underutilization and high cost
  - ➢ Slow scale-in, e.g., not enough instances removed because scaling period is long ⇒ large underutilization and high cost
  - ➢ Rapid scale-in, e.g., too many instances removed because lower_thr is high ⇒ SLO violations occur
- No application-specific metric (e.g., response time)

✗ Not robust against varying load patterns

Threshold-based policy: cons

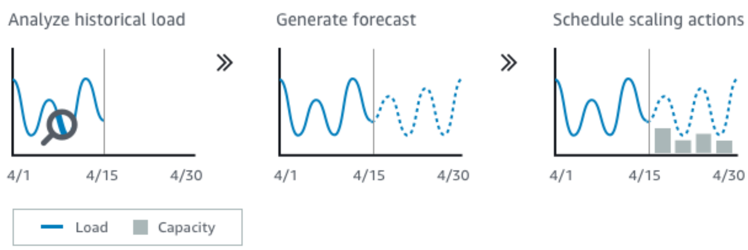
- Example of wrong choices



Strasser et al., Autoscaler Evaluation and Configuration: A Practitioner's Guideline, ICPE 2023

Example 1: Amazon EC2 Auto Scaling

- **Predictive scaling**: based on ML (*proactive*)
  - Trained ML model to predict application expected traffic and EC2 usage, including daily and weekly patterns
  - Requires historical data collected from CloudWatch
    - Model needs at least one day's of historical data to start making predictions
    - Re-evaluated every 24 hours to forecast for the next 48 hours



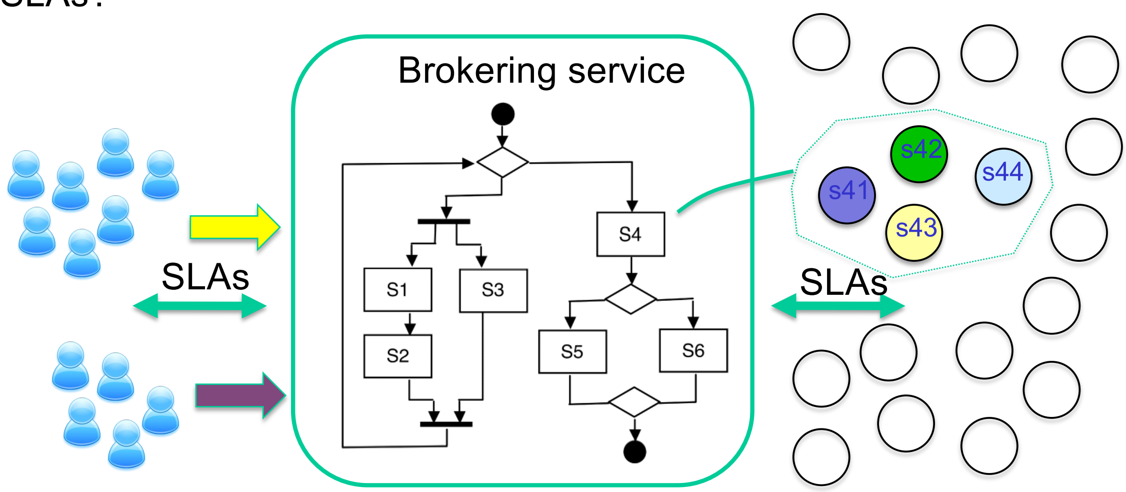
✓ Proactive

✗ Requires training: the more the historical data, the more accurate the forecast

✗ Choice of scaling metric is core

Example 2: Service selection

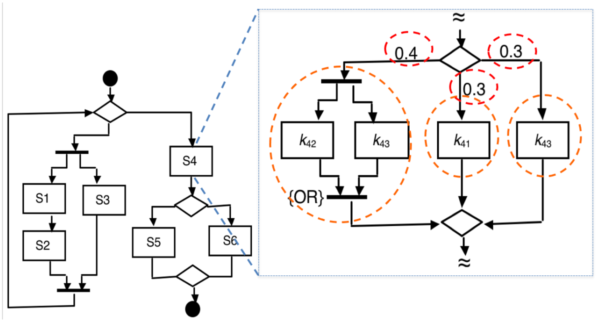
- QoS-driven self-adaptation of SOA applications
  - Multiple concrete services for each abstract service: how to select which concrete services to use so to satisfy application SLAs?

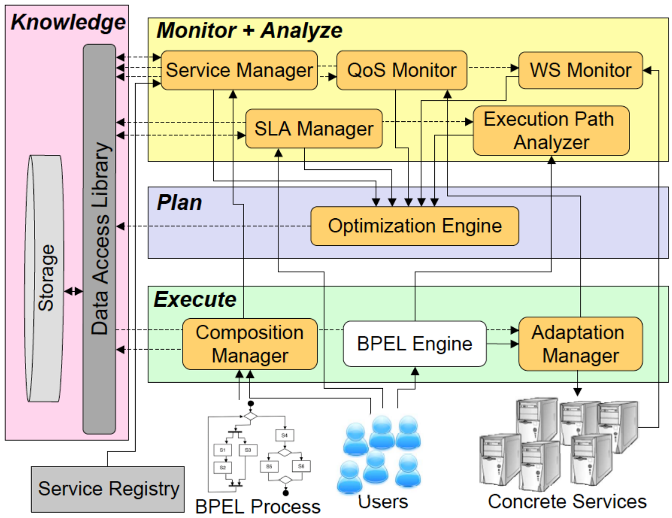


Cardellini et al., MOSES: a framework for QoS driven runtime adaptation of service-oriented systems, *IEEE Trans. Soft. Eng.*, 2012

Example 2: Service selection

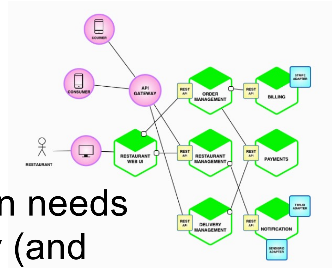
- QoS-driven self-adaptation of SOA applications
  - Centralized Plan: select *optimal set of concrete services* (and their coordination) by means of linear programming optimization

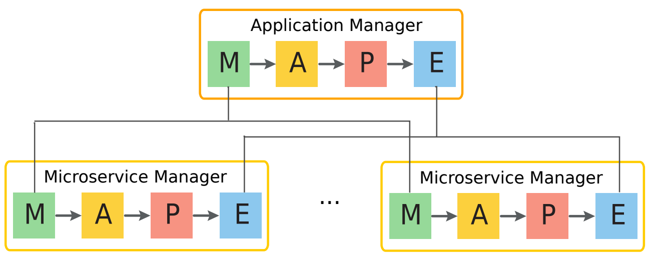


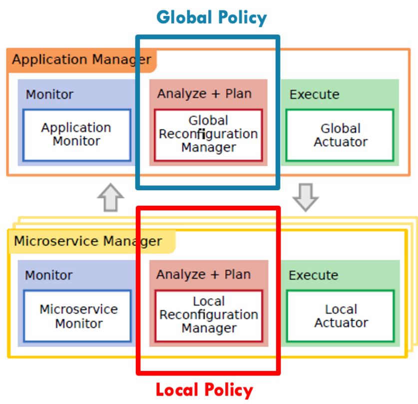


Example 3: Hierarchical scaling of microservices

- Hierarchical control pattern to elastically scale a microservices-based application
  - Goal: keep response time below maximum
  - Each Microservice Mngr. determines scale-out/in needs through a local policy based on queueing theory (and workload prediction) and sends proposal to Application Mngr.
  - Application Mngr. coordinates scaling proposals by accepting or not them and sends decision to local Execute components
  - Implemented in Kubernetes







Rossi et al., Hierarchical scaling of microservices in Kubernetes, *Proc. IEEE ACSOS 2020*

References

- The vision of Autonomic Computing
- An Introduction to Self-Adaptive Systems: A Contemporary Software Engineering Perspective, chapter 1
- On patterns for decentralized control in self-adaptive systems