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Challenges in Data Stream Processing

Corso di Sistemi e Architetture per Big Data

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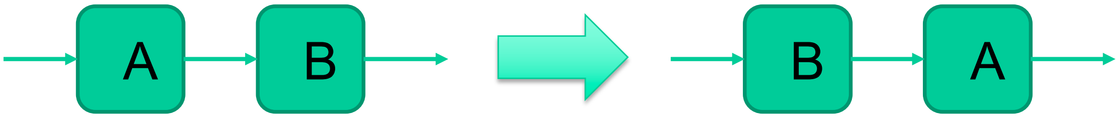
Challenges

- Let's consider how to tackle some challenges in DSP systems

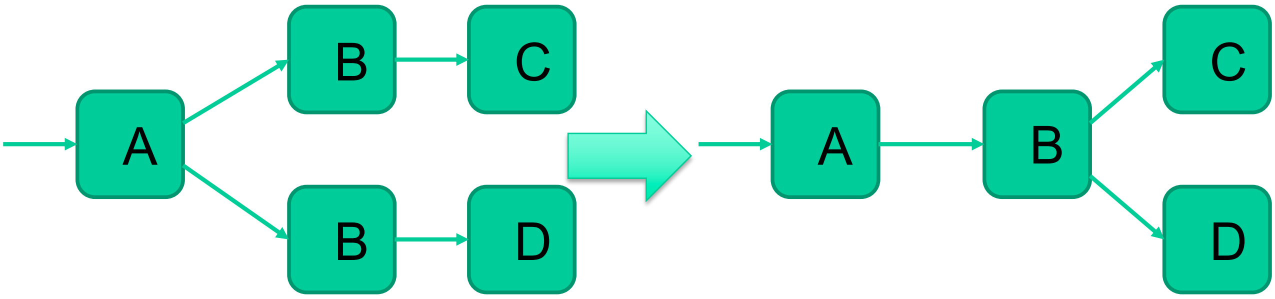
1. Optimize DSP application
2. Place DSP operators on computing infrastructure
3. Manage load variations
4. Self-adapt at run-time
5. Manage stateful operators
6. Fault tolerance

Challenge 1: Optimize the DSP application

- Apply some transformation to streaming graph
  - At design time or run-time
- Operator reordering
  - To avoid unnecessary data transfers

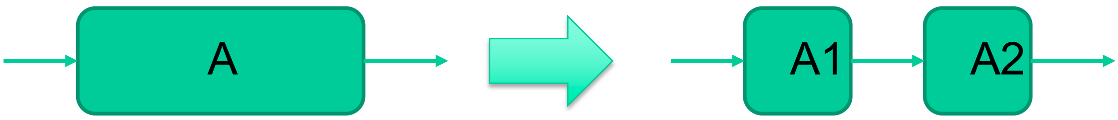


- Redundancy elimination

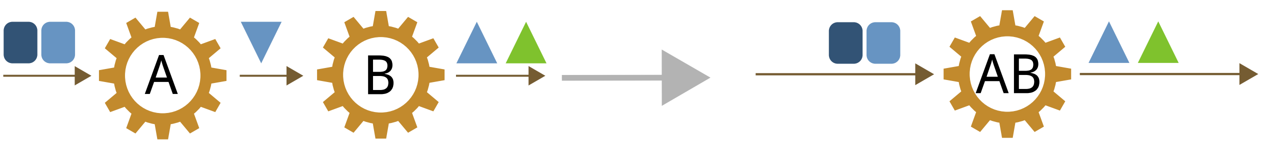


Challenge 1: Optimize the DSP application

- Operator separation

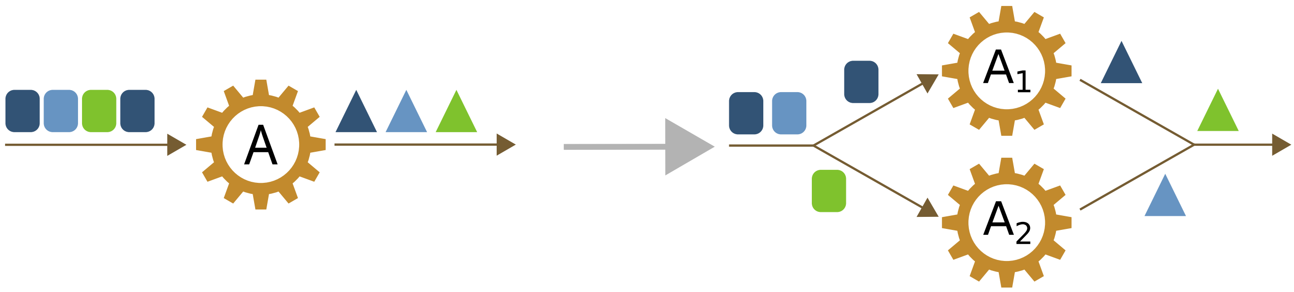


- Operator fusion



Challenge 1: Optimize the DSP application

- Operator scaling (aka *operator fission*)

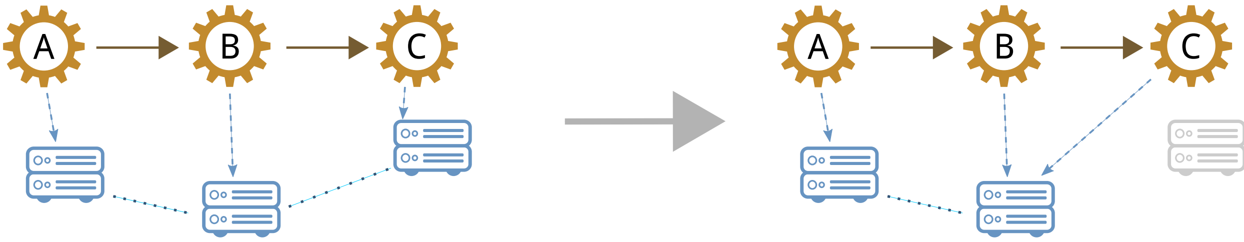


At the streaming system layer

- The previous challenge is addressed at the *DSP application layer* and usually offline
- What about the *streaming system layer*?
- What about *run-time adaptation*?
- Let's first consider two solutions to improve performance (e.g., to control application latency) at the streaming system layer
  - **Place DSP operators**
  - **Manage load variations**

Challenge 2: Place DSP operators

- Determine, within a set of available distributed computing nodes, those nodes that should host and execute each operator instance of a DSP application

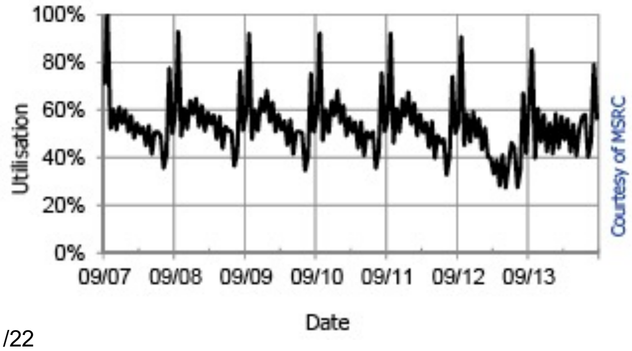


Challenge 2: Place DSP operators

- Operator placement decision: complex problem
  - Trade communication cost against resource utilization
- When
  - Initial (static) operator placement
    - Can be more expensive and comprehensive
  - Can also be at run-time
    - Place again all the operators or only a subset
    - Require **self-adaptation**
- We will focus on this issue later

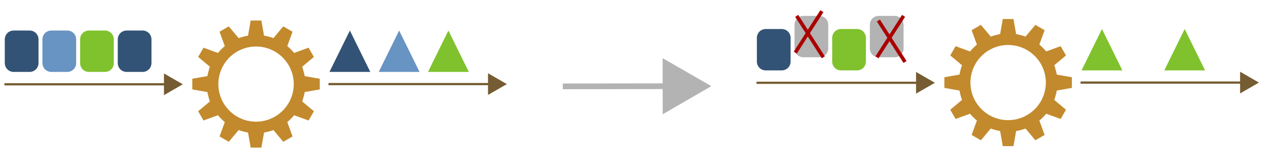
Challenge 3: Manage load variations

- Typical stream processing workloads are:
  – with high volume and high rates
  – bursty and with workload spikes not known in advance
    - Twitter in 2013: rate of tweets per second = 5700
    - … but significant peak of 144,000 tweets per second



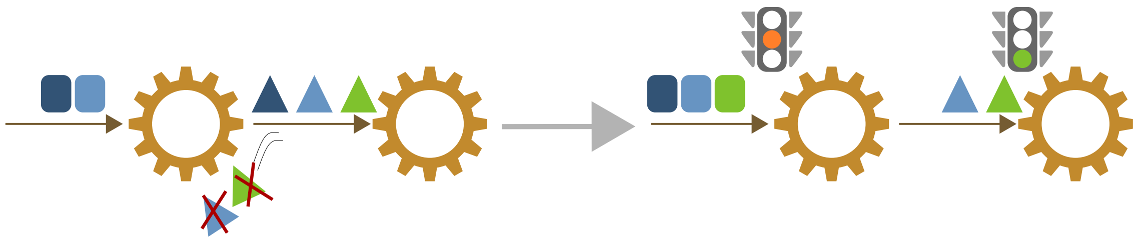
Challenge 3: Manage load variations

- Some solutions:
  – Admission control
  – Static reservation
    - Reserve specific resources in advance
    - *Cons*: over-provisioning and cost increase
  – Apply dynamic techniques such as load shedding
    - Selectively drop tuples at strategic points (e.g., when CPU usage exceeds a specific limit)
    - *Cons*: sacrifice accuracy and completeness



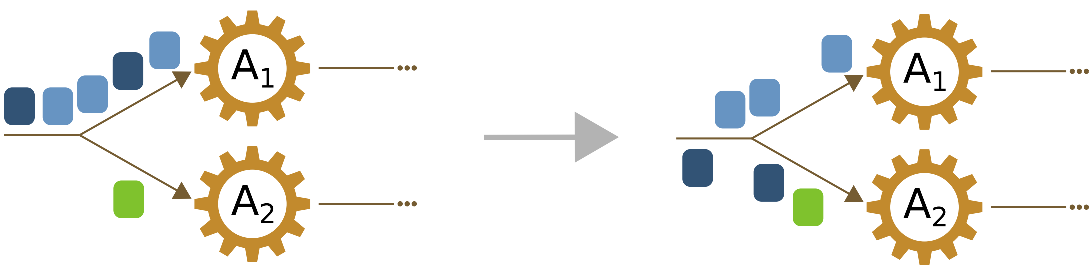
Challenge 3: Manage load variations

- Some solutions (*continued*):
  - Use adaptive rate allocation
    - E.g., backpressure: the upstream operator that precedes the bottleneck operator stores data in an internal buffer to reduce the pressure; backpressure recursively propagates up to the source operators



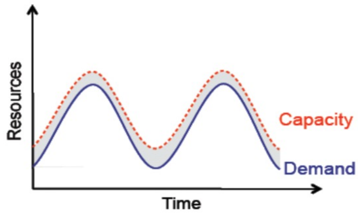
Challenge 3: Manage load variations

- Some solutions (*continued*):
  - Redistribute load, e.g., changing the partitioning or determining a new operator placement and relocating operators on computing nodes
    - *Cons*: available resources could be insufficient



Exploit elasticity

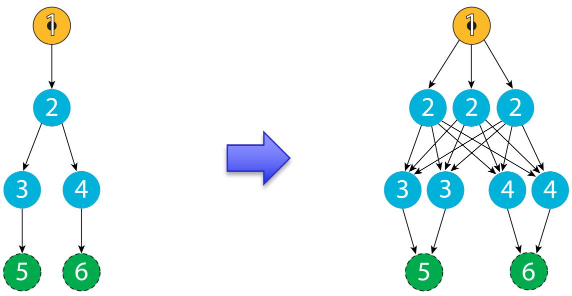
- Another solution:
  - Detect bottleneck and solve it by exploiting **elasticity**: acquire and release resources when needed



  - *How?*
    - By hand: possible, but cumbersome
    - So what? Self-adapt and organize the architecture using MAPE!

Elastic data stream processing

- *Where?*
  - At application layer (i.e., operator scaling)
    - i.e., apply **SPMD** paradigm: concurrent execution of multiple replicas of the same operator on different data portions
    - Scale-out (in) operators by adding (removing) operator replicas



Elastic data stream processing

- *Where*?
  - At infrastructure layer
    - Scale horizontally computing resources (containers, virtual machines, physical machines)
    - Also scale vertically computing resources (containers, virtual machines)

Elastic stream processing

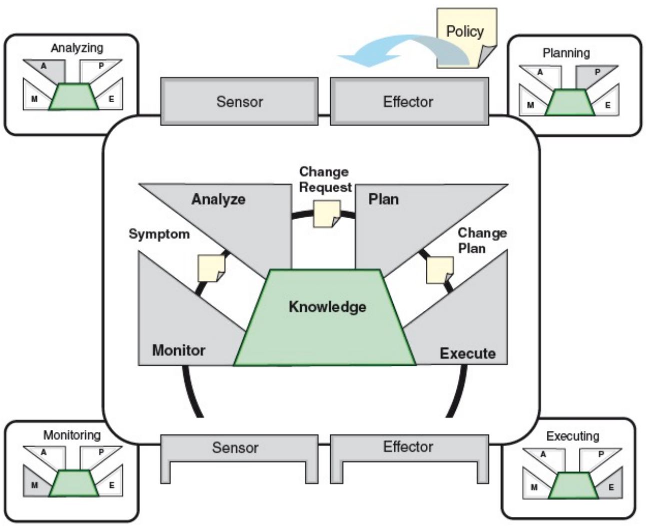
- *When* and *how* to scale?
  - Open issues
  - Some simple example:
    - When: threshold-based (like AWS Auto Scaling)
    - How: add/remove one operator replica at time
    - Where: determine randomly (or in a round-robin fashion) location of new replica
- Be careful: elasticity overhead is not zero!
  - In most streaming systems: required to run new placement decision to take new replicas into account
  - Dynamic scaling impacts stateful operators

Challenge 4: Self-adapt at run-time

- Many factors may change at runtime, e.g.,
  - Load variations, QoS of computing resources, cost of computing resources (e.g., due to dynamic pricing schemes), network characteristics, node mobility, …
- How to adapt the DSP application when changes occur?
  - Enrich DSP systems with run-time adaptation capabilities
- Which **adaptation actions**?
  - Scale-out/in number of operator replicas
  - Migrate operators on different computing nodes
  - …

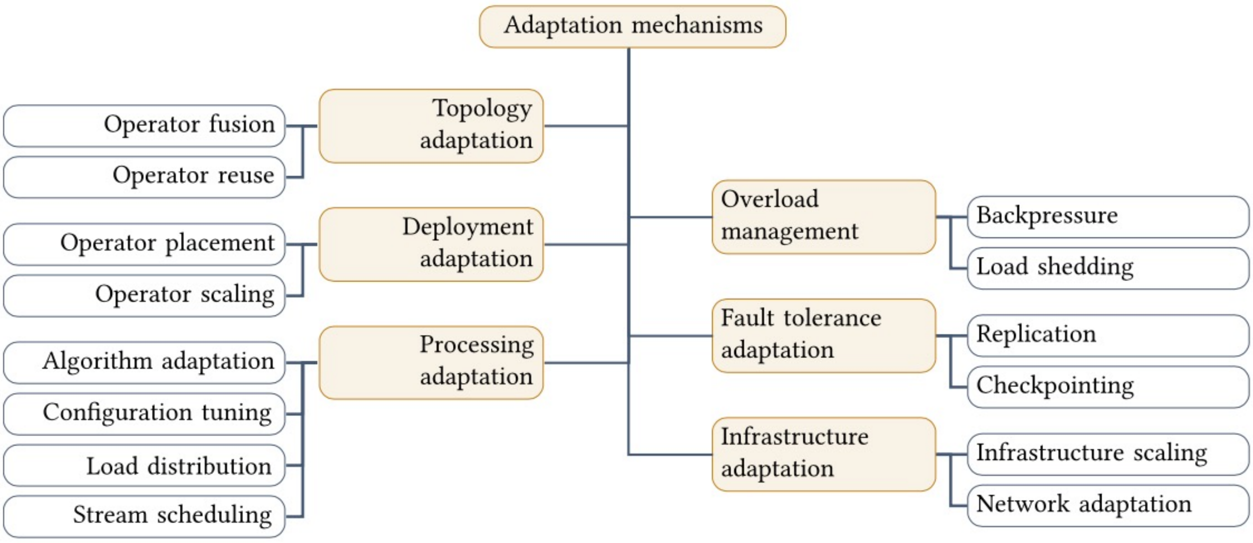
Self-adaptive deployment

- **MAPE** (**M**onitor, **A**nalyze, **P**lan and **E**xecute)

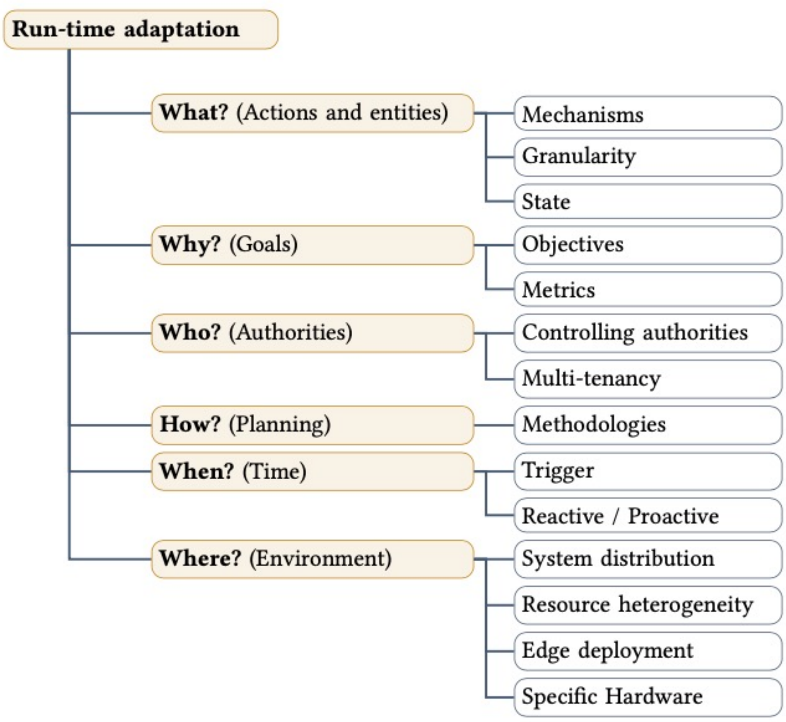


- **Plan** phase: how to **adapt** DSP application deployment

Main adaptation mechanisms



Dimensions used to classify adaptation solutions



Reconfiguration challenges

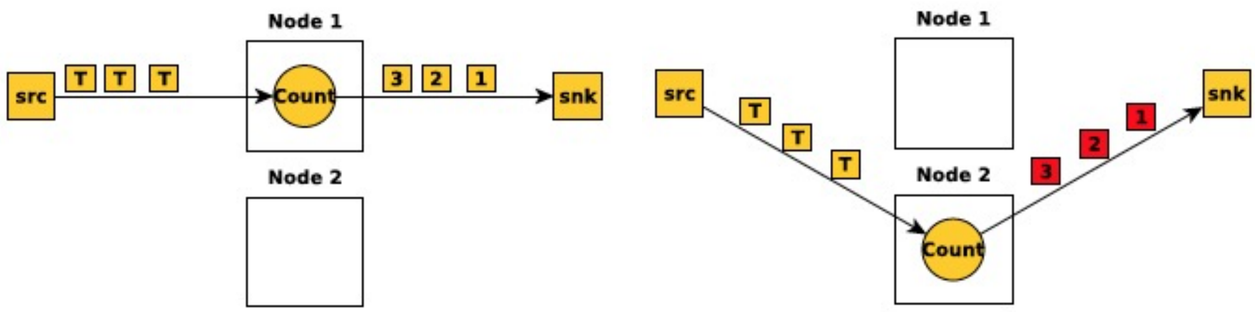
- Reconfiguring the deployment has a non negligible cost
- Can affect negatively application performance in the short term
  – Application freezing times caused by operator migration and scaling, especially for stateful operators
- Solution:
  – Perform reconfiguration only when needed
  – Take into account the overhead for migrating and scaling the operators

Challenge 5: Stateful operators

- State complicates things…

1. Dynamic scaling
2. Operator re-placement
3. Recovery from failure

impact state



Loss of state!

Approaches for stateful migration

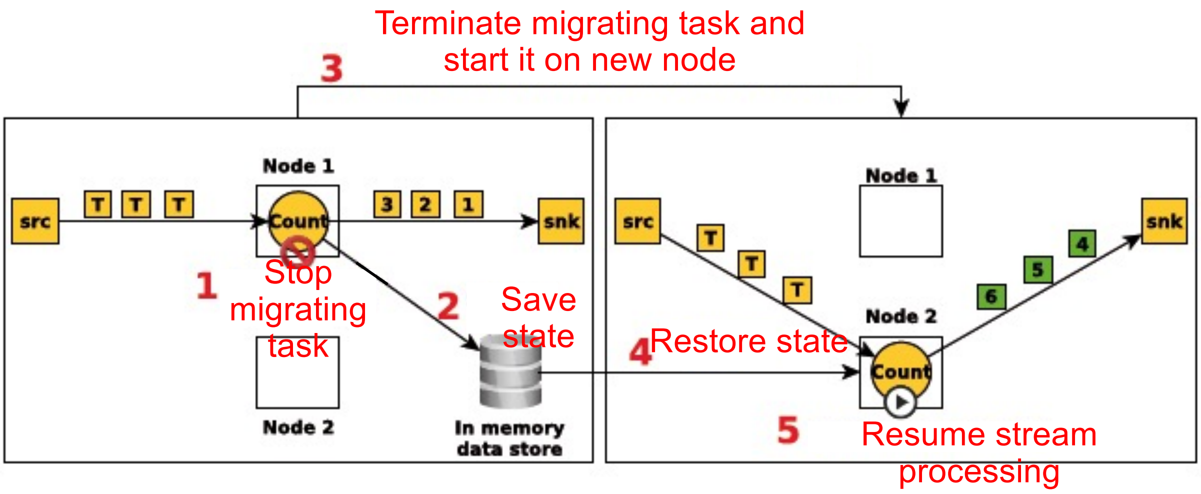
- Most streaming systems do not support migration of stateful operators
- Recent interest in research prototypes and production-ready streaming systems
  – E.g., Heron, Spark Streaming
- Requirements for stateful operatior migration
  – Safety (i.e., to preserve operation consistency)
  – Application transparency
  – Minimal footprint

Issues with stateful operators

- Require mechanisms to:
  – Migrate stateful operators
    - Pause-and-resume approach
    - Parallel track approach
  – Partition streams and load balance among operator replicas

Stateful operator migration

- Pause-and-resume approach
  - Application latency peak during migration



Stateful operator migration

- Parallel track approach
  - Old and new operator instances run concurrently until their state is synchronized
  - No latency peak
  - Enhanced mechanisms for synchronization

Issues for stateful migration: stream partitioning

- How to identify the portion of state to migrate? Possible approaches:
  - Expose an API to let the user manually manage the state
  - Support only partitioned stateful operators
    - Partitioned stateful operators store independent state for each sub-stream identified by a partitioning key
    - Automatically determine, on the basis of a partitioning key, the optimal number of state partitions to be used and migrate

Issues for stateful migration: load balancing

- How to balance the load among multiple stateful replicas?
- Can use consistent hashing
- Can use partial key grouping
  - Uses two hash functions where a key can be sent to two different replicas instead of one
- Only available in research prototypes

Challenge 6: Guarantee fault tolerance

- DSP applications run for long time

  ➡ failures are unavoidable
- Possible solutions:
  - Active replication
  - Check-pointing
  - Replay logs
- Having different trade-offs between runtime cost in absence of failures and recovery cost
- Large-scale complicates things…
  - Network partitions and CAP theorem

References

- M. Hirzel, R. Soulé, S. Schneider, B. Gedik, R. Grimm, A catalog of stream processing optimizations, *ACM Comput. Surv.*, 2014.

- V. Cardellini, F. Lo Presti, M. Nardelli, G. Russo Russo, Run-time adaptation of data stream processing systems: The state of the art, *ACM Computing Surveys*, 2022.