Resource Management in Aurora Serverless

Paper by Amazon Web Services

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Background & Motivation

Introduction to Aurora Serverless

- **Definition**: An on-demand, autoscaling relational database service with MySQL and PostgreSQL compatibility.
- **Primary Benefit**: Eliminates the need for customers to manage database capacity, reducing both costs and complexity.
- **Capacity Management**: Utilizes Aurora Capacity Units (ACUs), allowing dynamic scaling between user-defined minimum and maximum limits.

Problem and Motivation

- **Traditional Database Scaling Issues**
  - Users must provision fixed resources, leading to inefficiencies.
  - Over-provisioning during low demand, and performance issues at peak times.

- **User Demand**: Growing need for flexible, cost-efficient, and self-managing databases.

Why Aurora Serverless?

- **Aurora Serverless Solution**
  - Scales resources up and down as needed, reducing costs and ensuring performance stability across workload variations.

- **Scaling Approach**:
  - Granular Scaling: Adjusts in small ACU increments.
  - Usage-Based Charging: Pay only for what is used.
  - Efficiency and Availability: System ensures high host utilization and fast resource adjustments to handle workload surges.

Related Work

Aurora VS other database services

- **Heracles, Sharc, Pythia**
  - Use Approaches like “colocating CPU- vs. memory- vs. network-intensive workloads” to optimize resource allocation; however, they often lack the needed for real-time adaptation.
- **Modellus**
  - Use approaches like queueing theory and control methods to optimize resources. Aurora Serverless uses recent demand data rather than long-term predictions, which achieves better simplicity and accuracy.
- **Remus, Sandpiper**
  - Live migration as a method for resource management has been discussed in these research, but its complexity has limited its practical deployment. Aurora Serverless overcomes these limitations, providing a scalable solution that adjusts resources flexibly based on demand.

Overview

What is Aurora Serverless Accomplishing?

- **Fleet-Wide Management:**
  - Ensures balanced resource utilization with host allocations and migrations
- **Host Level Management:**
  - Manages resources for individual instances on a single host
- **In-Place Scaling:**
  - Dynamically adjusts instance resource allocations (ACUs) to meet changing demands without downtime.
- **Boundary Management:**
  - Ensures efficient resource usage by adjusting reserved ACUs based on observed trends
- **Regulated Scale-Up**:
  - A **token bucket mechanism** controls the rate of instance scaling.
  - Prevents fast-growing instances from saturating hosts, ensuring smooth resource allocation and allowing time for live migrations.

The Aurora Serverless Capacity Bounds

Aurora Serverless Capacity Bounds

- Aurora Serverless dynamically adjusts the necessary resources (such as CPU, memory, and throughput) to match demand
- Resources are measured by Aurora Capacity Units (**ACUs**)
    - Combination of 2GB of memory, corresponding CPU (0.25 vCPU), networking, and storage throughput
- Capacity Bounds (the range)
    - Minimum of 0.5 ACUs
    - Maximum of 128 ACUs
- **Goal**: Ensuring consistent performance, cost-efficiency, and responsiveness

Aurora Serverless Capacity Bounds: ACUs and Scaling

- Given a boundary range, ACUs are scaled up or down based on the demand from the client
- Scaled how?
  - Granularity - Aurora Serverless adjusts the capacity in larger steps instead of tiny increments
    - Helps avoid frequent adjustments that may be costly to the client, optimizing cost and performance stability
- Example:
  - If an increased workload is experienced, then AS will not automatically increase the ACUs until a certain threshold is reached
- Customer charges are calculated at 1-second granularity, offering a pay-as-you-go experience

Aurora Serverless Capacity Bounds: Design Factors

- Main factors that were considered by the authors when designing AS were:
  1. **Pay-as-you-go**
     a. how close to a fully pay-as you-go experience can we offer the customer?
  2. **Quick resume**
     a. how efficiently and quickly can we resume a customer that returns after a period of inactivity?
  3. **Utilization**
     a. at how high a utilization level can we operate our infrastructure?'
- Trade-offs:
  - Fully pausing databases save costs but slows resumption
  - Setting a minimum ACU allows for cost savings while also being able to quickly resume

From ASv1 to ASv2

ASv1 ?

Session Transfer	
Relaunch Needed	
Find Quiet Point	Influence User Experience
Session NOT supported!	Temporary Tables
Features NOT added!	
Only 2x or 0.5x scaling	Cost-Efficient OR Fast Response

ASv2 ?

Scale IN-PLACE	
Relaunch Not Needed	
Scale Simultaneously	Can’t feel it
No Session Transfer	
No Feature Difference	
Scale by ±0.5 ACUs	Cost-Efficient AND Fast Response

ASv2 !

Memory/CPU Hot (un)plug

Live Migration of Instance

Virtual Machine Arch

Scalability

ASv1 really helped!

Fleet Wide Resource Management

Live Migration-Based Dynamic Instance Re-Packing

- **Heat Metrics**:
  - Hosts are monitored for resource usage along multiple dimensions: **CPU, memory, network bandwidth, and I/O**.
  - A host is flagged as hot if its aggregate reserved ACUs exceed a predefined threshold
- **3-Stage Heuristics for Instance Selection**:
  - **Stage 1: Filtering**:
    - Exclude instances unsuitable for migration (e.g., those recently migrated)
  - **Stage 2: Ranking**
    - Score instances based on resource usage and migration cost, prioritizing high-impact migrations.
  - **Stage 3: Selection**
    - Choose the instance that balances heat reduction and migration efficiency.
    - Uses two scores: one relative to the ACUs and one that linearly aggregates the resource metrics

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Live Migration-Based Dynamic Instance Re-Packing

- **Destination Host Selection**:
  - **Filters**:
    - Ensure the host has sufficient capacity and supports migration.
  - **Ranking**:
    - Prioritize hosts with minimal failures and better resource balance.
  - **Scoring**:
    - Optimize load balancing across resources in host (CPU, memory, etc.).
      - First score determines the heat on the host after adding the instance
      - Second score determines the overall balance of resources on the host
- **Unbalanced Load Strategy**:
  - The protocol intentionally aims for unevenly distribution among the hosts such so some hosts have enough headroom for serving as live migration destinations

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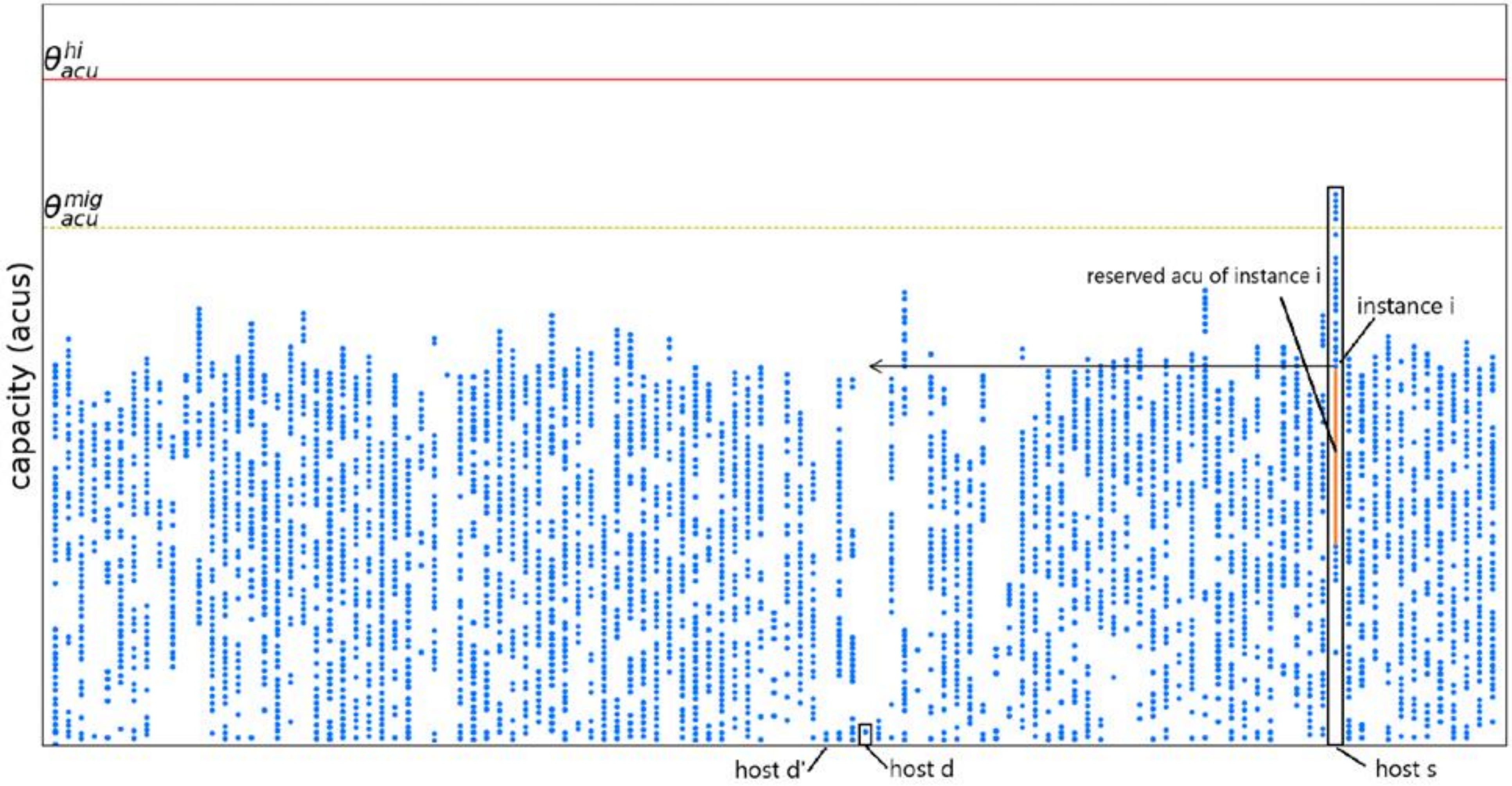
Example



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New Instance Placement

- Follows same three step process to choose the host for the new instance
- Problem the team faced was determining the resource needs of the new instance without having much knowledge on the instance itself
    - Aurora automatically chooses the minimum amount of resources as specified by the customer's min and max thresholds
    - The system will automatically scale from the minimum if the instance requires additional resources
    - Underestimating was seen to be better than overestimating since Aurora scales up faster than it scales down preventing wasted resources

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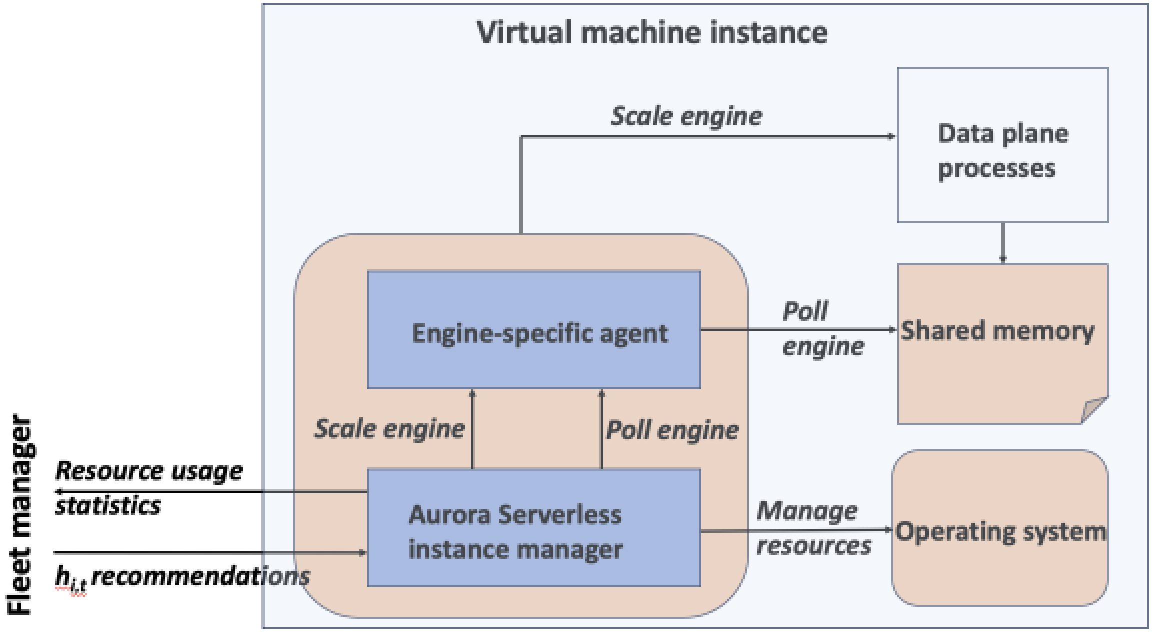
Fleet Size Adjustment

- **Demand Prediction and Threshold-Based Scaling**:
  - The fleet manager employs fleet-level demand prediction to trigger additional hosts
- **Threshold Levels:**
  - The system triggers additional procurement upon a fleet utilization exceeding a predetermined threshold.
- **Fleet Size Limitations**
  - Larger fleets lead to **higher overhead** for data collection, processing, and decision-making, which can affect system performance and scalability.
  - Fleet size is deliberately kept below a threshold that allows the entire fleet's health to be monitored and computed using a **single heat management server**.

Resource Management within Host

Instance Manager

- A library encapsulating serverless resource management functionality.
- One per instance
- Manages:
  - **Data collection**: Monitors engine-specific resource usage (e.g., buffer pool size, memory, CPU).
  - **Scaling policies**: Dynamic in-place scaling and boundary management.
  - **Resource limits**: Enforces scaling boundaries using mechanisms like cgroups and resource on/offlining.



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Enabling Mechanisms

- **Data Collection**
  - Collects engine and OS metrics every second for fine-grained responsiveness.
  - Buffer pool size estimate - Estimated by engine
  - Other usage statistics - Guest OS

- **Virtualization**
  - Instances run in secure VMs using the Nitro system for low IO latency and scalable CPU/memory provisioning.
  - Provides strong isolation between instances for security.

Enabling Mechanisms - continued

- **Efficient Memory Scale-Up**
  - Collects engine and OS metrics every second for fine-grained responsiveness.
  - Key Mechanisms
    - Memory Offlining: Dynamically releases memory back to the host.
    - Cold Page Identification: Frees or swaps out infrequently used pages.
    - Free Page Reporting: Reports 2MB free blocks for hypervisor reclamation.
    - Compaction: Coalesces 4KB free pages into 2MB blocks for efficiency.

- **Boundary enforcement**
  - Ensures instance is allocated resource based on “boundary” established by scaling policies.
  - 2 mechanisms to manage instance CPU/memory allocations
    - Cgroups: Enforces precise CPU and memory quotas.
    - CPU/Memory On-Offlining:
      - Adds/removes vCPUs or memory to handle spikes.
      - Reclaims unused memory efficiently (2MB blocks).

Policies

- **Boundary Management**
  - Dynamically adjusts the resource allocation boundary based on its **recent** usage patterns
  - Ensures reserved ACU stays slightly above current usage for quick scaling.
  - Key Considerations
    - Agile Growth Detection
      - Monitors memory, CPU, network, and IO every second.
      - Allocates more resources if current usage exceeds limits, up to the customer-defined maximum.
    - Regulated Growth
      - Controlled scale-up rate to avoid overwhelming hosts and enable live migration.
      - Scale-down is cautious to prepare for potential workload spikes.
      - Token Bucket system employed

Policies - continued

- **In-place scaling**
  - Provides rapid scale-up without disruption, ensuring sufficient resources are allocated for growing demands.
  - Employs conservative scaling down to avoid premature resource release.
  - Process
    - **Deciders**: Assess resource-specific needs (e.g., memory, CPU, network, storage).
    - **Combining Deciders**: Single projection derived by taking the **maximum** need across all deciders.

Empirical Observations and Evaluation

Datasets and metrics of interest

- Authors analyzed data from two fleets over different time periods:
  - Fleet 1 in us-east-1 and Fleet 2 in us-west-2
  - Both fleets used real-world observations and simulations
- Wanted to measure two key metrics:
  - **Operational efficiency**: focuses on how well servers are utilized
  - **Customer experience**: measures how elastic and responsive the system is when scaling
- Specific metrics given:
  - Scale up events satisfied in-place vs. via live migration
    - Fewer migrations is indicative of better placement strategies
  - Hosts that are deemed “hot” during scale-ups
    - For hot hosts, their max ACU is temporarily limited to avoid overloading
  - Impact on workload due to remedial actions

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Customer experience observations

- Fleet 1
  - 16,440,024 scale-up events across 33,792 total instances
  - Live migrations: only 2,923 scale-up events needed one or more live migrations
  - Single migrations: 52% of those needing migrations only required one
  - 198 cases of hot hosts breaches
- Fleet 2
  - 8,151,229 scale-up events across 12,467 total instances
  - Live migrations: only 1,214 scale-up events needed one or more live migrations
  - Single migrations: 55% of those needing migrations only required one
  - 48 cases of hot hosts breaches
- Observations between the two fleets show that Aurora Serverless repacking and placement strategies are effective

Comparison against an alternative re-packing strategy

- Baseline Method:
  - Concentrate instances on fewer hosts.
  - Increases host utilization but limits spare capacity for migration.
  - Requires more migrations to address heat.

- Aurora Serverless Strategy
  - Deliberately leaves some hosts lightly loaded.
  - Reduces migration frequency.

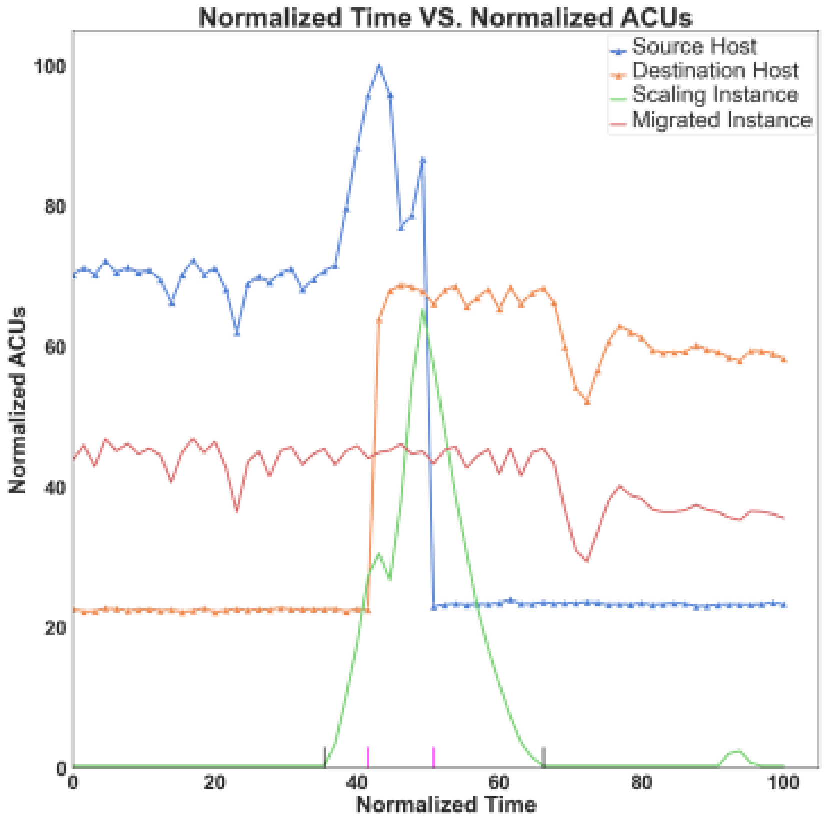
- Comparison
  - Aurora Serverless requires 82% fewer migrations in Fleet 1 and 57% fewer migrations in Fleet 2 compared to the baseline.
  - Aurora Serverless requires 10% fewer utilization of hosts in Fleet 1 and 12% in Fleet 2, increasing system flexibility.

A close look at a migration-assisted scale up

- An instance that scaling up was satisfied in-place

- Timeline
  - Heat scaling up at around 35 time units
  - Reach the threshold at around 41 time units, the migration starts.
  - Migration ends around 50 time units

- Observation
  - The live migration is efficient and ensures resource availability without significant performance drops.



Lessons & Takeaways

Lessons and Takeaways

Start Simplest

ONLY add based on needs

Reactive ✅ Predictive ❎

Fleet-wide + Host-level

Specialized OS kernels

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Conclusions

Conclusions

Token Buckets: Controllable!

Reactive!

Fleet-wide + Host-level

Live Migration

About future…

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About future…

Predictive!

+ Reactive!

Resource Combination

Machine Learning…

Study Questions

How does Aurora Serverless dynamically manage resource allocation within a host while ensuring predictable elasticity and minimal resource contention?

What trade-offs are involved in balancing high host utilization with seamless scale-up in Aurora Serverless, and how are these trade-offs addressed by mechanisms like live migration and regulated growth?

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