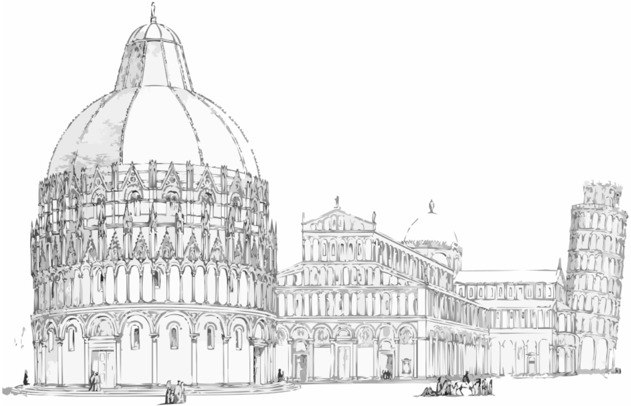
UNIVERSITÀ DI PISA

Bridging the Gap: The Convergence of Cloud-Native Serverless and HPC Workloads

Pesaresi Seminar



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February 11, 2026

Who am I?

Matteo Della Bartola
PhD student at the University of Pisa Department of Computer Science.

Working with the Parallel Programming Models (PPM) Group on *NOUS*, an EU-funded project.

Background:

- B.Sc. in Computer Science 2022, University of Pisa
- M.Sc. in Computer Science 2024, University of Pisa
- Research interests: HPC, serverless computing, parallel programming, and more...

What to expect from this presentation?

Today's Topics:

→ Introduction to Cloud Computing

→ Introduction to Serverless Computing

→ High-Performance Serverless Computing SLR

→ HPSC Future Directions & Open Problems

Cloud Computing - A Definition

Cloud Computing

Cloud computing is a utility-oriented and Internet-centric way of delivering IT services on demand. These services cover the entire computing stack: from the hardware infrastructure packaged as a set of virtual machines to software services such as development platforms and distributed applications.[1]

[1] R. Buyya, C. Vecchiola, and S.T. Selvi. *Mastering Cloud Computing: Foundations and Applications Programming*. ITPro collection. Morgan Kaufmann, 2013. ISBN: 9780124095397. URL: `https://books.google.it/books?id=wqKkqHJhPJQC`

Players in Cloud Computing

Provider: Provides resources, services, and applications (cloud services from now on) to consumers.

- Cloud (infrastructure) provider
- Service / application / software provider
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- a.k.a., cloud **customer**
- Pays the bill

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End User: Uses cloud services.

Deployment Models

Public Cloud:

- Provisioned for open use by the general public.
- Owned by an organization and exists on the provider's premises.

[1] Peter Mell and Timothy Grance. *The NIST definition of cloud computing*. Tech. rep. Special Publication 800-145. National Institute of Standards and Technology, 2011

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Private Cloud:

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Hybrid Cloud:

- Composition of two or more distinct clouds (Private, Community, or Public).
- Bound by technology enabling data and application portability (e.g., cloud bursting).

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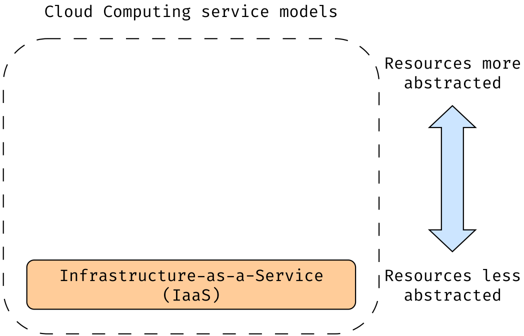
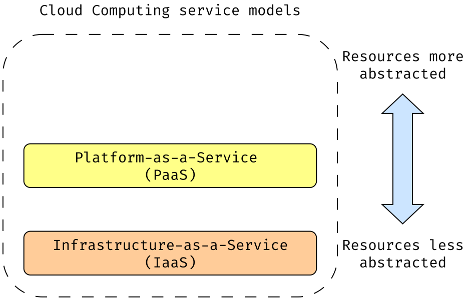
Provisioning Models

- Infrastructure-as-a-Service (IaaS)



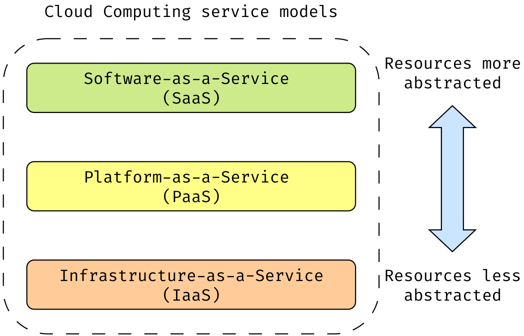
Provisioning Models

- Infrastructure-as-a-Service (IaaS)
- Platform-as-a-Service (PaaS)



Provisioning Models

- Infrastructure-as-a-Service (IaaS)
- Platform-as-a-Service (PaaS)
- Software-as-a-Service (SaaS)



The XaaS Trend

- Infrastructure-as-a-Service (IaaS)
- Platform-as-a-Service (PaaS)
- Software-as-a-Service (SaaS)
- Network-as-a-Service (NaaS)
- Function-as-a-Service (Faas): Serverless Computing
- Security-as-a-Service: Firewall, IDS, authentication,
- DB, storage, caching, queueing, analytics-as-a-Service

Serverless Computing

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Serverless computing is a cloud computing execution model that allows users to deploy and execute fine-grained billed and automatically scaled applications, without having to address the underlying operational logic.[2]

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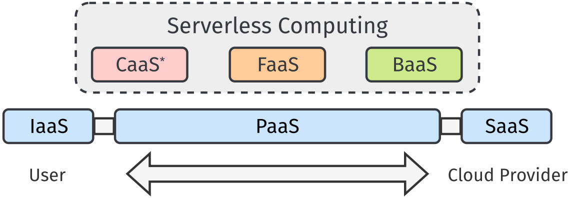


Who is responsible for the operational logic?

**serverless-enabled offerings*

Serverless Service Models

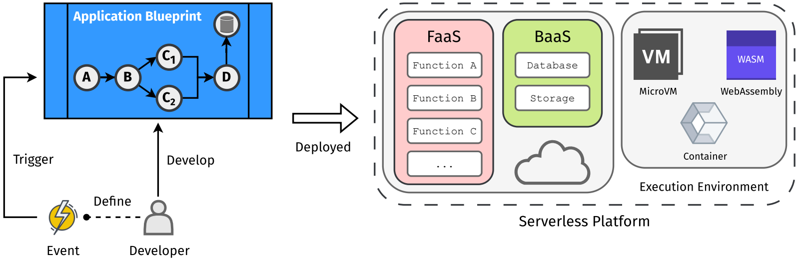
- **FaaS (Function-as-a-Service):** Focuses on managing resource requirements and event-driven triggering of functions.
- **CaaS (Container-as-a-Service):** Allows deployment of containers; considered serverless depending on abstraction levels.
- **BaaS (Backend-as-a-Service):** Provides specialized frameworks for specific needs like storage, databases, or messaging.

Serverless Computing Core Traits

- **No operational logic (NoOps)**
  - Complete abstraction of servers, OS patching, and infrastructure management.
  - Developers focus solely on business logic and code.
- **Utilization-based billing**
  - *Pay-per-use model:* Costs are calculated based on execution time and memory allocated.
  - *Scale-to-zero:* No cost is incurred when functions are idle.
- **Auto-scaling**
  - Rapid, automatic scaling from zero to thousands of instances based on incoming events.
  - Handles ”bursty” traffic without manual intervention or pre-provisioning.

Together, these properties distinguish serverless from PaaS and IaaS, making it ideal for the event-driven workflows shown previously.

Serverless Workflow



Serverless Platforms

Implementing the FaaS and BaaS Layer

The **Serverless Platform** integrates the FaaS (Functions) and BaaS (State) components shown in the previous workflow.

- **Commercial Cloud Providers**
  - **AWS Lambda:** The market leader; deeply integrated with AWS BaaS services (DynamoDB, S3).
  - **Azure Functions:** Focus on enterprise integration and event triggers.
  - **Google Cloud Functions:** Optimized for data processing and Firebase events.
- **Open Source & Kubernetes**
  - **Knative:** Provides the "Serving" and "Eventing" primitives on top of Kubernetes.
  - **Apache OpenWhisk:** A flexible, distributed event-based programming service.
  - **OpenFaaS [6]:** Simplifies deploying functions to Docker Swarm or Kubernetes.

Execution Environments

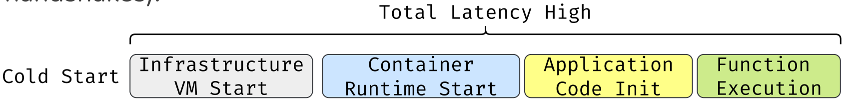
Isolation Technologies

To execute the "Application Blueprint" securely and efficiently, platforms rely on three main isolation technologies:

1. **Containers** (e.g., Docker, OCI)
   - The standard unit of software. Packages code and dependencies.
   - *Trade-off*: High compatibility but slower "cold starts."
2. **MicroVMs** (e.g., Firecracker, gVisor)
   - Lightweight Virtual Machines. They offer the strong security isolation of traditional VMs but with millisecond boot times.
   - Used heavily by AWS Lambda and Fargate.
3. **WebAssembly (Wasm)**
   - A binary instruction format for a stack-based virtual machine.
   - **Key Advantage:** Near-instant startup, platform independence, and extremely high density compared to containers.

The Cold Start Problem in FaaS

- **Definition:** The latency penalty incurred when a FaaS function is invoked after a period of inactivity or for the first time.
- **Why it happens:** The provider must prepare a fresh isolation layer. Before execution, it must:
  - **Infrastructure Provisioning:** Allocate a **MicroVM (e.g., Firecracker [1])** or a **Container**.
  - **Image/Code Loading:** Download and unpack the container image or deployment package.
  - **Environment Setup:** Start the runtime (e.g., JVM, Node.js) and configure system-level resources.
  - **Application Init:** Run initialization logic (e.g., importing heavy libraries, DB handshakes).



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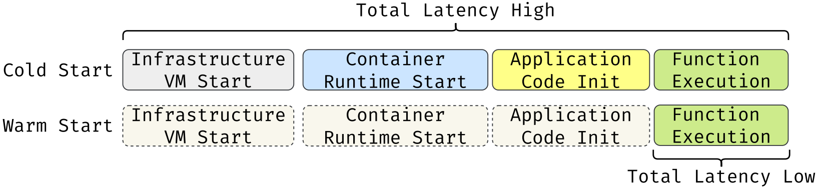

Stateless Computation in Serverless

- **The Core Principle:** FaaS functions are ephemeral (short-lived). They do not retain data between executions.
- **Local Storage is Temporary:**
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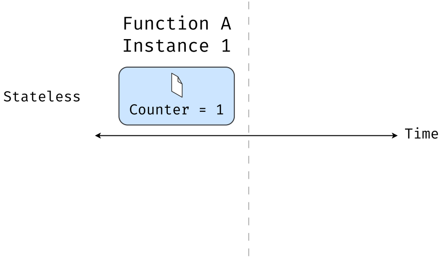

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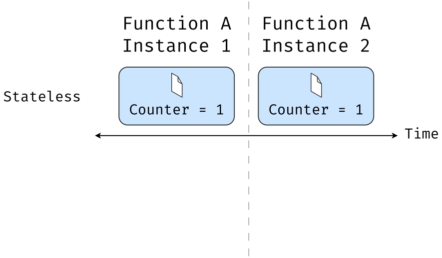

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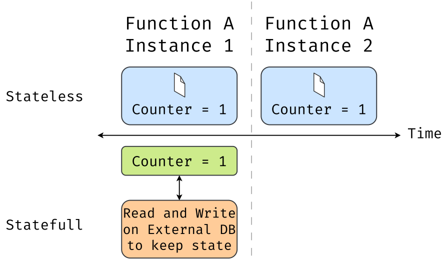
- **How to Persist Data:**
  - State must be externalized.
  - Use managed services (BaaS): S3 (files), DynamoDB/Redis (data), SQS (queues).



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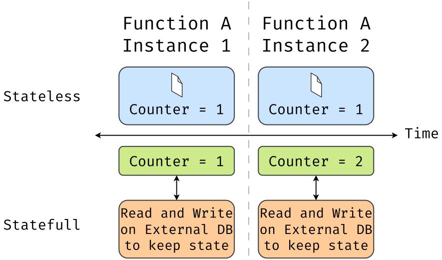


High-Performance Serverless: SLR Overview

Journals & Magazines > IEEE Access > Volume: 13

High-Performance Serverless Computing: A Systematic Literature Review on Serverless for HPC, AI, and Big Data

Datasets Available

Publisher: IEEE Cite This PDF

Valerio Besozzi ; Matteo Della Bartola ; Patrizio Dazzi ; Marco Danelutto **All Authors**

High-Performance Serverless: SLR Overview (Cont.)

Research Goal

To investigate the convergence of **High-Performance Computing (HPC)** and **Cloud-Native** paradigms, analyzing how serverless models support compute-intensive workloads like AI, Big Data, and Scientific Computing.

Scope of Study

- **Timeline:** 2017 – Early 2025
- **Scale:** 122 Primary Studies selected
- **Sources:** ACM, IEEE Xplore, ScienceDirect

Key Contributions

- **Taxonomy:** 8 primary research directions & 9 use case domains.
- **Trends:** Analysis of publication growth and author collaboration.
- **Gaps:** Identification of open problems (e.g., cold starts, heterogeneity).

Research Methodology: Protocol & Strategy

Framework:

- Follows guidelines by Kitchenham et al. [5] for systematic literature reviews in software engineering.
- **Objective:** Analyze the suitability of serverless for HPC, AI, and Big Data workloads.

Research Questions (RQs):

1. **Directions:** Identification of taxonomy and research tracks.
2. **Solutions:** Approaches to specific HPC/Serverless problems.
3. **Use Cases:** Domain-specific applications (e.g., AI inference).
4. **Trends:** Growth, impact, and publication venues.
5. **Community:** Key contributors and collaboration patterns.

Search Strategy:

- **Sources:** ACM Digital Library, Elsevier ScienceDirect, IEEE Xplore.
- **String:** `(Serverless OR FaaS) AND (HPC OR Accelerators)`.
- **Timeframe:** January 2017 – February 2025.

Selection Process & Data Analysis

Inclusion & Exclusion Criteria:

- **Included:** Peer-reviewed papers on Serverless for HPC/AI inference, proposing designs, algorithms, or frameworks.
- **Excluded:** Secondary studies, theses, pre-prints.

The Selection Process:

1. **Initial Search:** 579 papers retrieved.
2. **Screening:** Dual-author review of titles/abstracts.
3. **Manual Additions:** Added 3 seminal works missed by search.
4. **Snowballing:** Followed Wohlin's guidelines (backward/forward), adding 15 relevant studies.
5. **Final Set: 122 primary studies** selected.

Analysis Techniques:

- **Taxonomy:** Constructed via open coding (grouping phrases into categories).
- **Bibliometrics:** Citation analysis and co-authorship networks using VOSviewer.

Current Landscape: Open Problems & Limitations

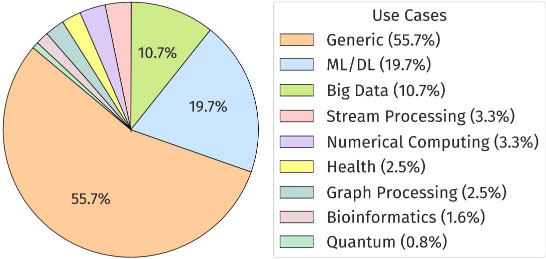
The Challenge: While serverless offers elasticity and scalability, its adoption in HPC is hindered by architectural mismatches between the *stateless*, *ephemeral* nature of FaaS and the *stateful*, *long-running* nature of scientific applications.

Three Fundamental Barriers:

1. **Cold Start Latency:** Unpredictable delays unacceptable for tightly coupled tasks.
2. **Data Communication:** High overhead from mediated storage (e.g., S3) versus direct HPC interconnects.
3. **Hardware Heterogeneity:** Difficulty in efficiently sharing and abstracting accelerators (GPUs, FPGAs, DPUs).

Additionally, critical gaps remain in Sustainability, Security, and Standardization.

Taxonomy of Use Cases: Distribution



Dominance of Generic Research

- **55.7%** of studies focus on general-purpose workloads.
- Indicates a "foundational phase": priority is currently on building robust platforms and frameworks rather than specific applications.

The Leading Specialization

- **ML/DL (19.7%)** has emerged as the primary specialized domain.
- Driven by the natural alignment between stateless, bursty inference tasks and the FaaS model.

Open Problem I: Cold Start Latency

The HPC Context: Unlike web traffic, HPC workloads often lack historical patterns, making standard time-series prediction ineffective.

Current Limitations:

- **Inefficient Mitigation:** Common ”Pre-warming” techniques keep resources idle, contradicting the cost-efficiency of serverless.
- **DAG Complexity:** In workflow-based applications (DAGs), a cold start in one function triggers cascading delays across the entire pipeline.

Future Directions:

- Need for platform-level startup reduction (e.g., snapshotting, lightweight isolation).
- Prediction models tailored specifically for scientific workflow structures rather than historical invocation rates.

Open Problem II: Data Communication

The Bottleneck: Traditional FaaS relies on *mediated communication* (passing data via Object Storage/DBs), introducing latency for parallel HPC tasks.

The ”Serverless Trilemma”: Current systems struggle to achieve three goals simultaneously:

1. Functions as ”Black Boxes” (Composability).
2. Double-billing protection.
3. **High Performance / Low Latency.**

Required Innovation:

- Shift toward **Direct Communication** (e.g., TCP hole punching [3], RDMA support [4]).
- New abstractions that hide communication complexity without sacrificing performance.

Open Problem III: State Management

Stateless vs. Stateful:

- **Paradigm Clash:** FaaS enforces statelessness for elasticity.
- **Reality:** HPC applications (e.g., simulations, training) are inherently stateful and iterative.

Current Inefficiencies:

- Offloading state to external storage (S3/Redis) creates I/O bottlenecks.
- Lack of efficient shared memory models between function instances.

Research Opportunity:

- Development of **Direct Memory Sharing** techniques (e.g., Faasm [8]).
- Efficient, ephemeral storage layers co-located with compute nodes to support "Stateful Serverless."

Open Problem IV: Hardware Heterogeneity

Accelerator Integration (GPUs, FPGAs, NPUs):

- Current platforms often provide coarse-grained ”full device” access, leading to under-utilization.
- Lack of native support for **Resource Disaggregation** (separating compute/memory/accelerators).

Multiplexing Challenges:

- **Techniques:** Using NVIDIA MIG/MPS or Kernel Slicing.
- **Issue:** These introduce significant management complexity and scheduling overheads not handled by standard FaaS providers.

Gap: General-purpose frameworks capable of seamlessly abstracting heterogeneous hardware while maintaining multi-tenant security and isolation.

Open Problem V: Systemic Research Gaps

1. **Sustainability & Energy:**
   - Energy-aware scheduling is largely unexplored.
   - Need to balance ”performance-at-any-cost” with carbon footprint metrics in distributed serverless environments.
2. **Security in HPC FaaS:**
   - Multi-tenant accelerator sharing introduces new attack surfaces (side-channels).
   - Federated workflows require complex authentication/authorization models currently missing.
3. **Benchmarking Standard:**
   - **Current State:** Fragmented, ad-hoc evaluation setups.
   - **Need:** A standardized benchmark suite specifically for *High-Performance* Serverless (beyond simple web microservices).

Conclusions

Summary & Key Findings

The Evolution of Cloud Computing

- We observed a shift from infrastructure-heavy models (IaaS) to pure abstraction (FaaS), where developers focus solely on code.
- **Trade-off:** Serverless offers rapid auto-scaling and pay-per-use but introduces *Cold Starts* and *Statelessness* challenges.

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SLR Insights (2017–2025)

- **Growing Interest:** Analysis of 122 studies confirms a surge in Serverless for HPC, AI, and Big Data.
- **Dominant Workloads:**
  - **Generic (55.7%):** Foundational research on platforms dominates.
  - **ML/DL (19.7%):** The fastest-growing domain due to bursty inference workloads.

Conclusions

Future Research Directions

To make Serverless fully viable for HPC, we must address these open problems:

1. **Latency:** Mitigating cold starts without inefficient pre-warming (e.g., snapshotting).
2. **Communication:** Moving from mediated storage (S3) to direct communication (e.g., RDMA/TCP hole punching).
3. **State Management:** Developing efficient "Stateful Serverless" and shared memory models.
4. **Heterogeneity:** Better abstraction for hardware accelerators (GPUs/FPGAs).
5. **Systemic Maturity:** Establishing standard benchmarks and energy-aware scheduling.

Q&A

Thank you for your attention!
Any Questions?

Slides proudly made in LaTeX

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