



Fast and Effortless  
FPGA-accelerated  
Hardware Simulation with  
On-Prem and Cloud Flexibility

<https://fires.im>

 @firesimproject

**Speaker: Sagar Karandikar**



Berkeley Architecture Research



# The architect/chip-developer's design flow

1. High-level Simulation
2. Write RTL + Software, plug into your favorite ecosystem (e.g. Chipyard)
3. Co-design in software RTL sim (e.g. Verilator, VCS, etc.)
  - Run microbenchmarks
4. Co-design in FPGA-accelerated simulation
  - Boot an OS and run the complete software stack, obtain realistic performance measurements
5. Tapeout → Chip
  - Boot OS and run applications, but no more opportunity for co-design





# The architect/chip-developer's design flow

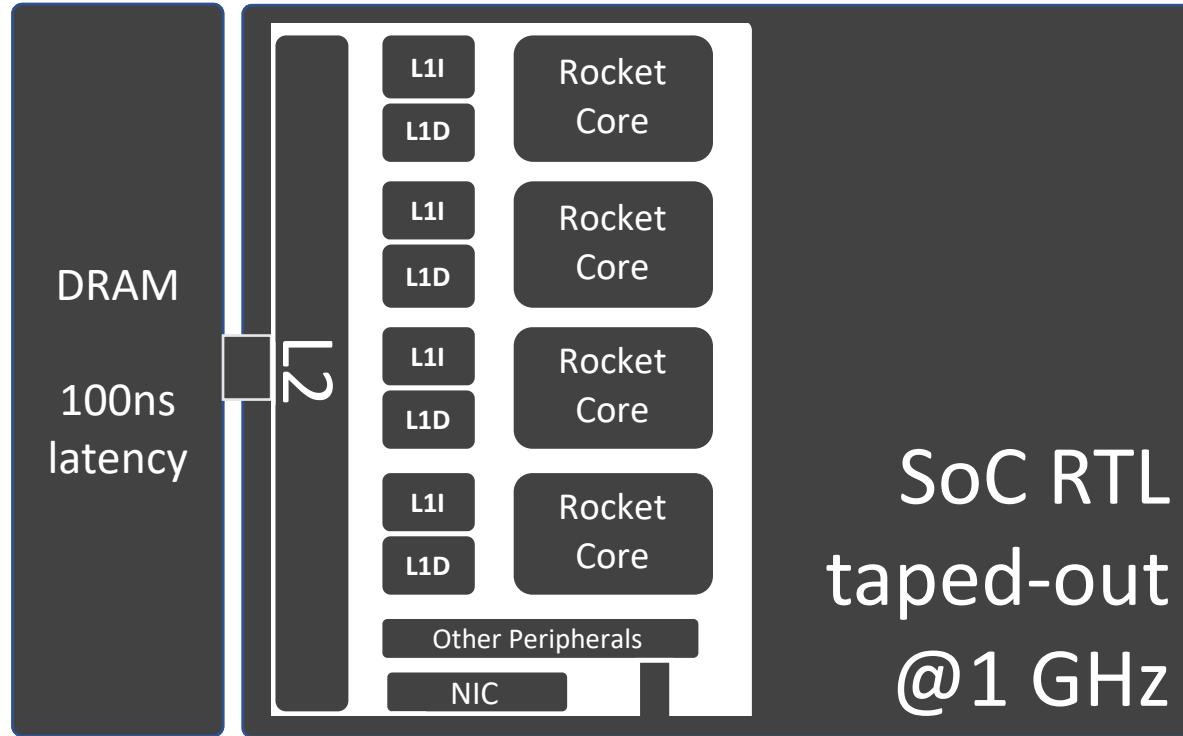
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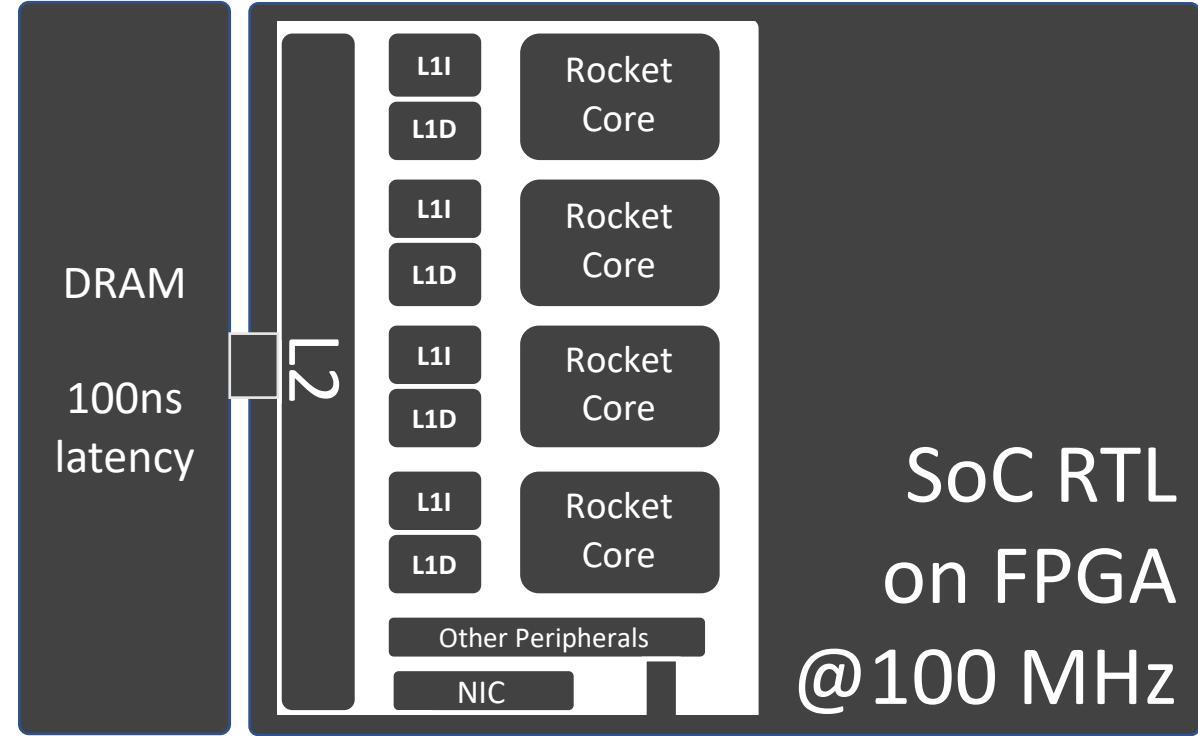
# What about FPGA prototyping?

Taped-out SoC



SoC sees 100 cycle DRAM latency

FPGA Prototype of SoC



SoC sees 10 cycle DRAM latency  
***Incorrect by a factor of 10!***





# Difficulties with FPGA Prototypes

## In an FPGA prototype:

- Every FPGA clock executes one cycle of the simulated target
- Performance of FPGA-attached resources is exposed to the simulated world, e.g. DRAM, SD Card, UART, Ethernet, etc.

## This leads to three problems:

- 1) Incorrect performance modeling: FPGA resources probably not an accurate representation of target system
  - a) E.g., DRAM performance off by **10x** on previous slide
- 2) Simulations are non-deterministic
- 3) Different host FPGAs produce different simulation results





# Want HW simulators that:

- Are as fast as silicon
- Are as detailed as silicon
- Have all the benefits of SW-based simulators
- Are low-cost

## Our Thesis:

- FPGAs are the only viable basis technology  
→ Build *FPGA-accelerated* simulators with  
SW-like flexibility using an *open-source* tool





# How? Useful Trends Throughout the Stack

Open ISA



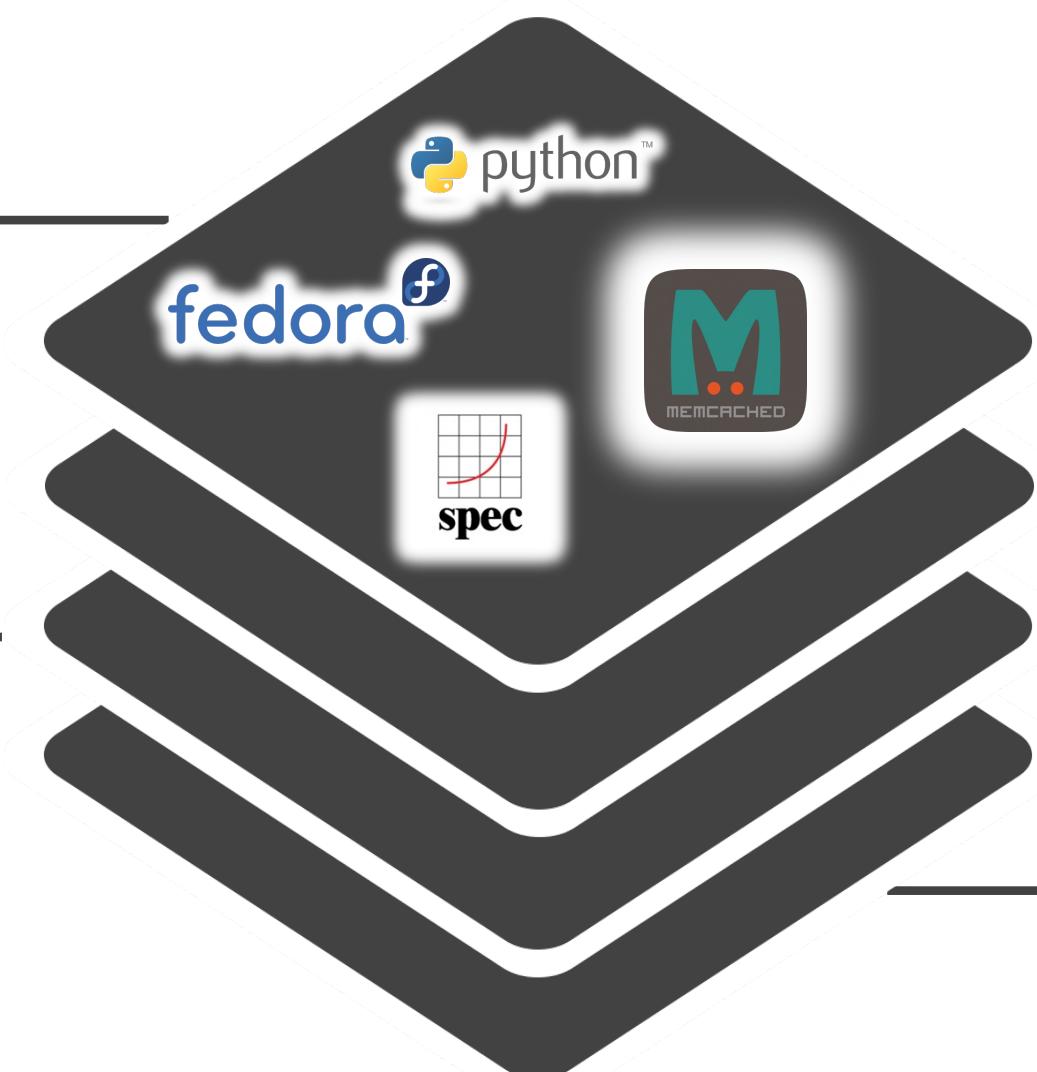
CHISEL

High-Productivity  
Hardware Design

Language & IR



Berkeley Architecture Research



Open, Silicon-Proven  
SoC Implementations



FPGAs in the Cloud





# FireSim at 35,000 feet

- Open-source, fast, automatic, deterministic FPGA-accelerated hardware simulation for pre-silicon verification and performance validation
- Ingests:
  - Your RTL design: FIRRTL (Chisel), blackbox Verilog
    - Or Chipyard-generated designs with Rocket Chip, BOOM, NVDLA, PicoRV32, and more
  - HW and/or SW IO models (e.g. UART, Ethernet, DRAM, etc.)
  - Workload descriptions
- Produces: Fast, cycle-exact simulation of your design + models around it
- Automatically deployed to on-prem or cloud FPGAs
  - E.g., Xilinx Alveo or AWS EC2 F1





# Three Distinguishing Features of FireSim

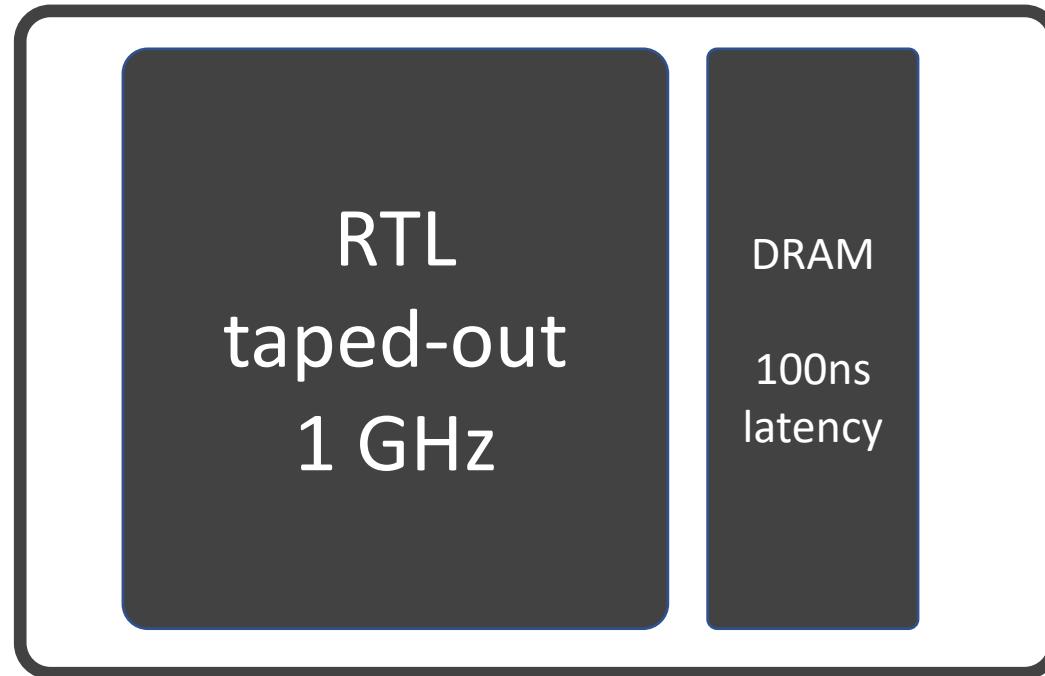
- 1) Not FPGA prototypes, rather FPGA-accelerated simulators
  - Automatic transformation of RTL designs into FPGA-accelerated simulators
  - Enables new debugging, resource optimization, and profiling capabilities
- 2) Flexible scaling from on-prem to cloud FPGAs
  - Scale easily from one or more on-prem FPGAs to massively parallel simulations on elastic supply of cloud FPGAs
  - Standardized host platforms = easy to collaborate with other researchers and perform artifact evaluation
  - Heavy automation to hide FPGA complexity, regardless of on-prem or cloud platform
- 3) Open-source (<https://fires.im>)





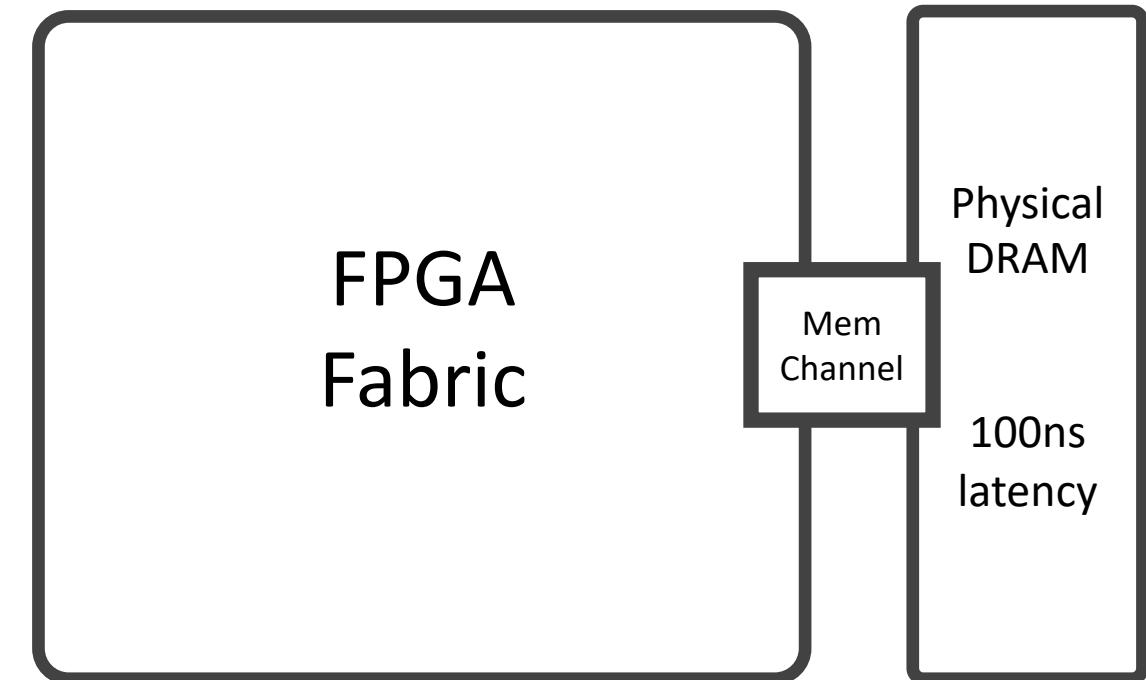
# Separating Target and Host

Target: the machine under simulation



*Closed simulation world.*

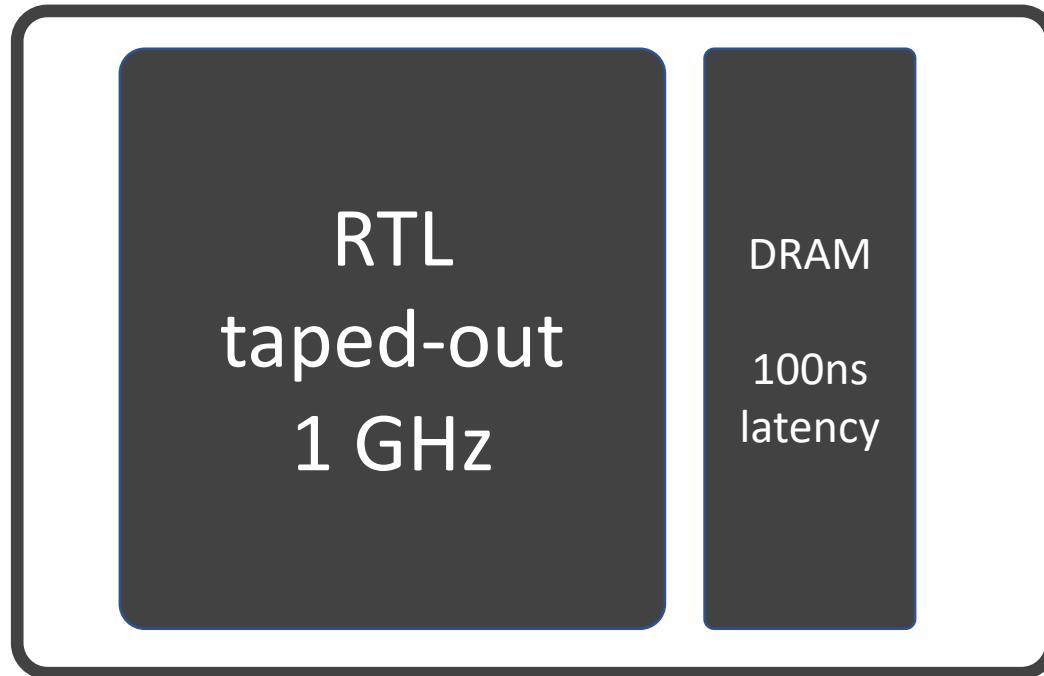
Host: the machine executing (*hosting*) the simulation





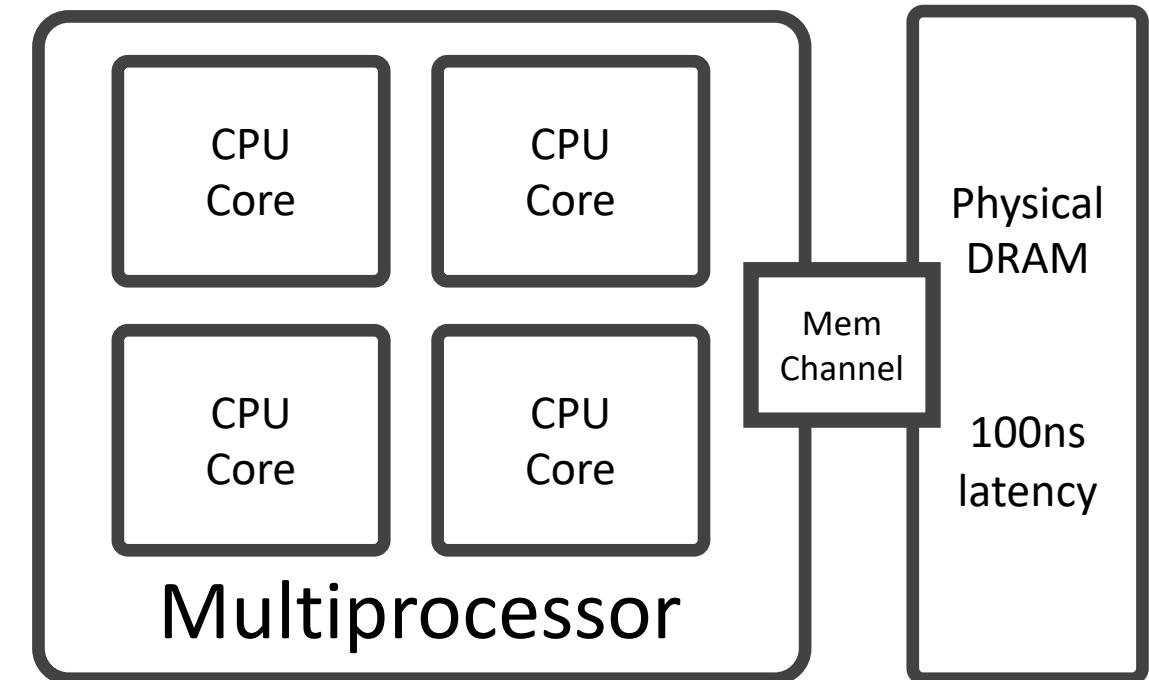
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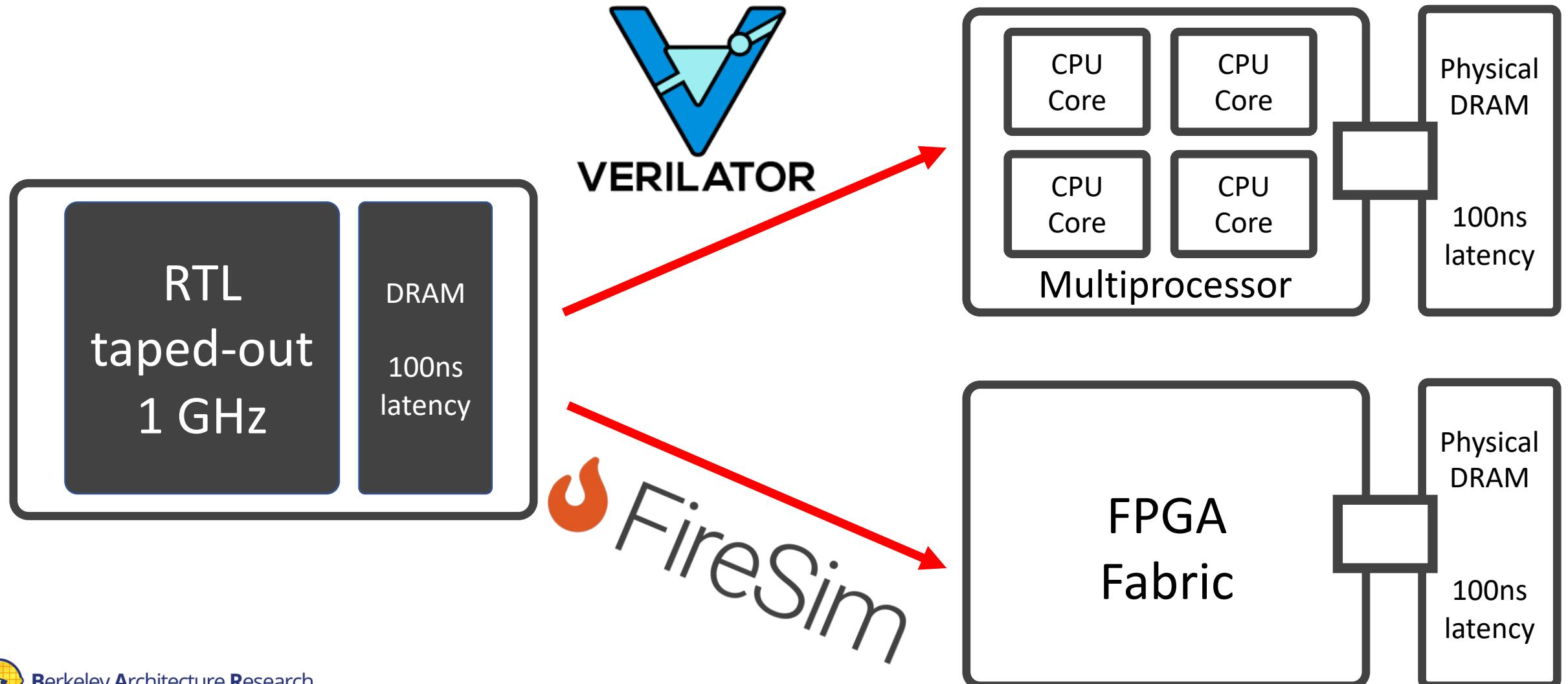
*Closed simulation world.*

Host: the machine executing (*hosting*) the simulation





# FireSim Generates FPGA-Hosted Simulators





# Host Decoupling in FireSim: Transforming the Target

- 1) Convert RTL into a latency-insensitive [1] model using FIRRTL transform



- 2) Generate FPGA-hosted model for DRAM [2] (think DRAMSim on an FPGA)
- 3) Generate queues (token channels) to connect the target models

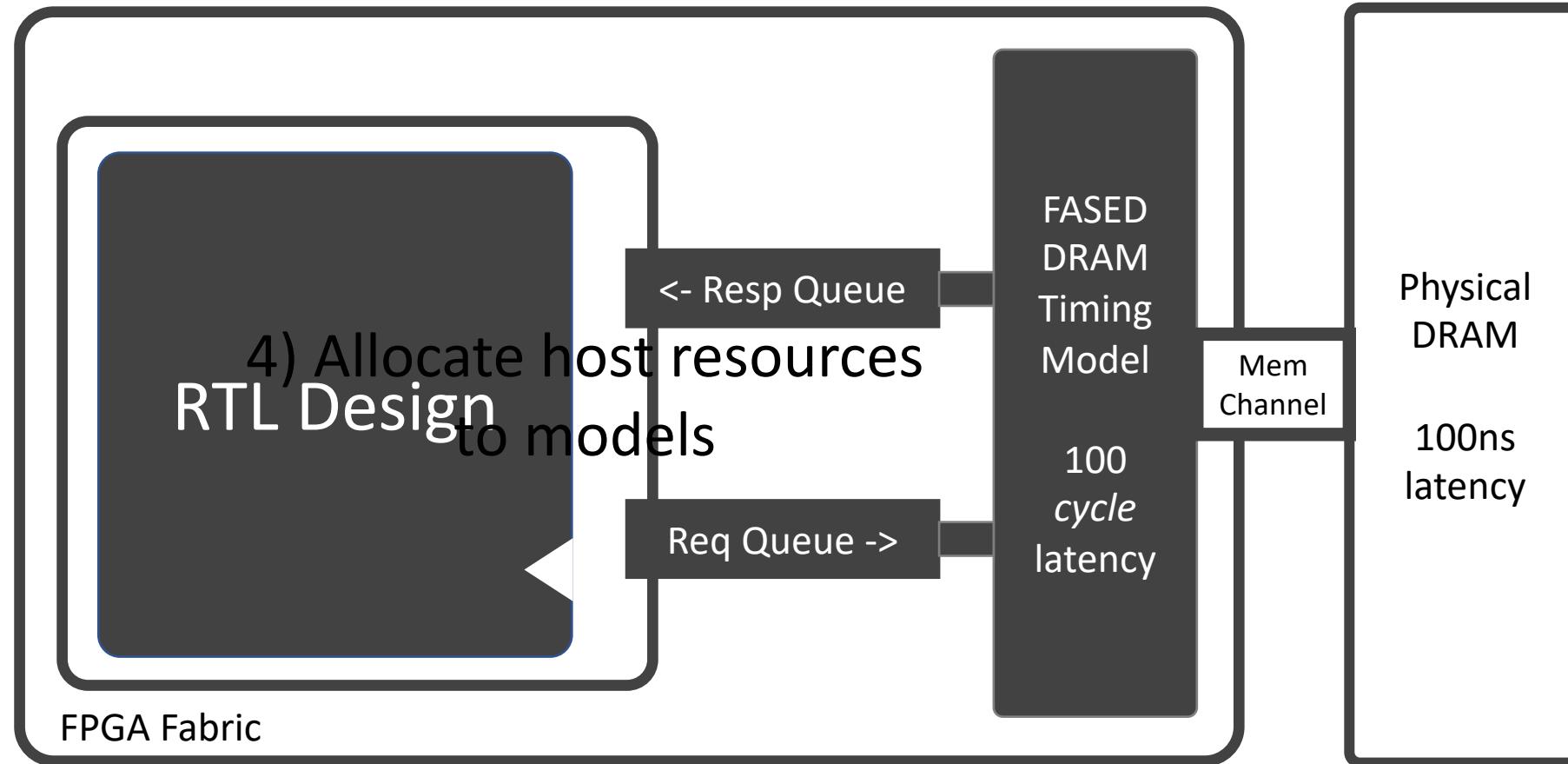
[1] *Theory of Latency Insensitive Design*, Carloni et al, also see: RAMP

[2] FASED: FPGA-accelerated Simulation and Evaluation of DRAM, Biancolin et al





# Host Decoupling in FireSim: Mapping to the FPGA



SoC sees realistic DRAM latency





# Benefits of Host Decoupling on FPGAs

Simulations will now:

- Execute deterministically
- Produce identical results on different hosts (FPGAs & CPUs)

Decoupling enables support for:

1. SW co-simulation (e.g. block device, network models)
2. Simulating large targets over distributed hosts (ISCA '18, Top Picks '18)
3. Non-invasive debugging and instrumentation (FPL '18, ASPLOS '20, ASPLOS '23)
4. Multi-cycle resource optimizations (ICCAD '19)





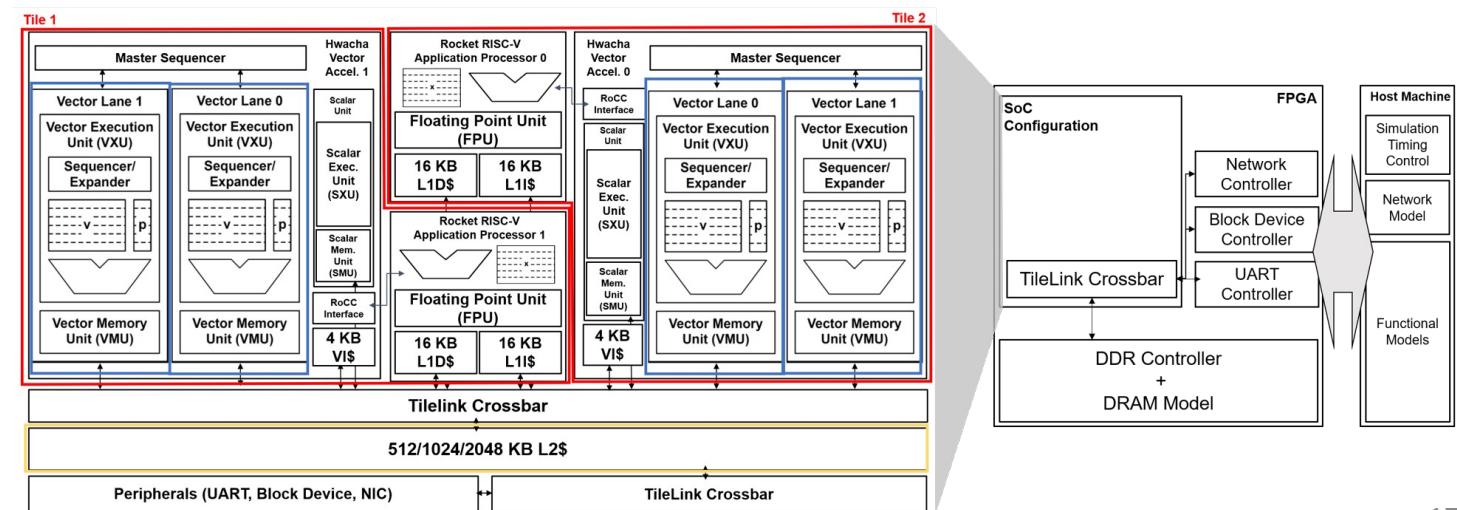
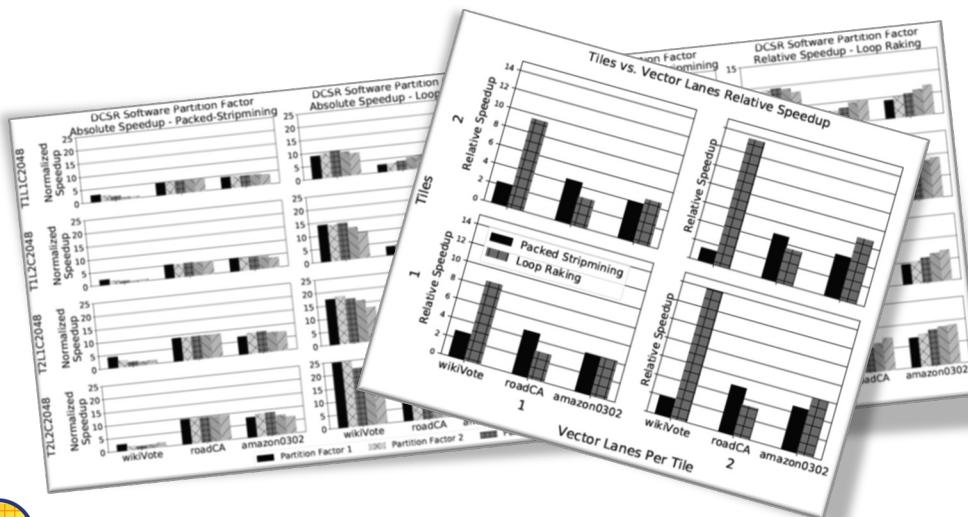
# What Can You Do With FireSim?





# Example use cases: Evaluating SoC Designs

- “Classical” Performance Measurement
  - Run SPECint 2017 with full reference inputs on Rocket Chip in parallel on ~10 FPGAs within a day (e.g., in D. Biancolin, et. al., *FASED*, FPGA ’19)
- Rapid Full-System Design Space Exploration
  - Can rapidly sweep parameter space of a design with FireSim automation
  - Data-parallel accelerators (Hwacha) and multi-core processors
  - Complex software stacks (Linux, OpenMP, GraphMat, Caffe)





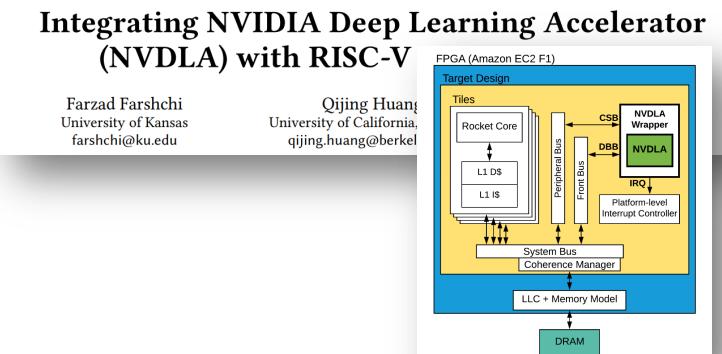
# Example use cases: Evaluating SoC Designs

- Security:
  - BOOM Spectre replication
    - A. Gonzalez, et. al., *Replicating and Mitigating Spectre Attacks on an Open Source RISC-V Microarchitecture*, CARRV '19
  - Keystone Enclave performance evaluation
    - D. Lee, et. al., *Keystone*, EuroSys '20
- Accelerator evaluation
  - Chisel-based accelerators:
    - Machine learning (H. Genc, et. al., *Gemmini*, DAC 2021)
    - Garbage collection (M. Maas, et. al., *A Hardware Accelerator for Tracing Garbage Collection*, ISCA '18)
  - Integrating Verilog-based accelerators:
    - NVDLA (F. Farshchi, et. al. *Integrating NVIDIA Deep Learning Accelerator (NVDLA) with RISC-V SoC on FireSim*. EMC2 '19)
    - HLS-based rapid prototyping (Q. Huang, et. al., *Centrifuge*, ICCAD '19)
  - Scale-out accelerators
    - nanoPU NIC-CPU co-design (S. Ibanez, et. al., *nanoPU*, OSDI '21)
    - Protobuf Accelerator (S. Karandikar, et. al., *A Hardware Accelerator for Protocol Buffers*, MICRO '21. MICRO-54 Distinguished Artifact Winner.)

### Replicating Spectre-v1/2

BOOM Hardware Security Research

This screenshot shows a terminal window titled "Replicating Spectre-v1/2" from the "BOOM Hardware Security Research" project. The terminal displays memory dump data from a simulation, showing various memory addresses and their corresponding values. It also shows the simulation status, which includes the current log file path, the number of cycles simulated, and the current instance status (terminated). The background of the slide features a diagram of a complex SoC architecture with various components like the Rocket Core, L1 DS, L1 IS, NVDLA Wrapper, and DRAM.



# Example use cases: Debugging and Profiling SoC Designs



- Debugging a Chisel design at FPGA-speeds
  - Many FireSim debugging features: Assertion synthesis, printf synthesis, ILA insertion, etc.
  - e.g. FireSim Debugging Docs

The screenshot shows the FireSim documentation website with a blue header featuring the FireSim logo and the word "stable". A search bar is present. The main content area has a dark sidebar with navigation links: "GETTING STARTED:", "AWS EC2 F1 TUTORIAL:", and "ADVANCED DOCS:". The main content area is titled "Debugging and Profiling on the FPGA" and contains several sections with sub-links, such as "Capturing RISC-V Instruction Traces with TracerV", "Assertion Synthesis: Catching RTL Assertions on the FPGA", "Printf Synthesis: Capturing RTL printf Calls when Running on the FPGA", and "AutoILA: Simple Integrated Logic Analyzer (ILA) Insertion".

» Debugging and Profiling on the FPGA

Edit on GitHub

## Debugging and Profiling on the FPGA

A common issue with FPGA-prototyping is the difficulty involved in trying to debug and profile systems once they are running on the FPGA. FireSim addresses these issues with a variety of tools for introspecting on designs once you have a *FireSim* simulation running on an FPGA. This section describes these features.

### Debugging and Profiling on the FPGA:

- Capturing RISC-V Instruction Traces with TracerV
  - Building a Design with TracerV
  - Enabling Tracing at Runtime
  - Selecting a Trace Output Format
  - Setting a TracerV Trigger
  - Interpreting the Trace Result
  - Caveats
- Assertion Synthesis: Catching RTL Assertions on the FPGA
  - Enabling Assertion Synthesis
  - Runtime Behavior
  - Related Publications
- Printf Synthesis: Capturing RTL printf Calls when Running on the FPGA
  - Enabling Printf Synthesis
  - Runtime Arguments
  - Related Publications
- AutoILA: Simple Integrated Logic Analyzer (ILA) Insertion
  - Enabling AutoILA
  - Annotating Signals
  - Setting a ILA Depth
  - Using the ILA at Runtime
- AutoCounter: Profiling with Out-of-Band Performance Counter Collection
  - Chisel Interface
  - Enabling AutoCounter in Golden Gate
  - Rocket Chip Cover Functions
  - AutoCounter Runtime Parameters
  - AutoCounter CSV Output Format
  - Using TracerV Trigger with AutoCounter



# Example use cases: Debugging and Profiling SoC Designs



- Debugging a Chisel design at FPGA-speeds
  - Many FireSim debugging features: Assertion synthesis, printf synthesis, ILA insertion, etc.
  - e.g. FireSim Debugging Docs

The screenshot shows a dark-themed sidebar of a documentation site. At the top, there's a navigation bar with links like "Assertion Synthesis", "Printf Synthesis", "AutoILA", "AutoCounter", "TracerV + Flame Graphs", "Dromajo Co-simulation", "Debugging a Hanging Simulator", "Non-Source Dependency Management", "Supernode", "Miscellaneous Tips", "FireSim Asked Questions", and "(Experimental) Using On Premise FPGAs". Below this, there's a section titled "COMPILER (GOLDEN GATE) DOCS:" with links to "Overview & Philosophy" and "Read the Docs". A dropdown menu indicates the version is "v: stable".

- Assertion Synthesis: Catching RTL Assertions on the FPGA
- Printf Synthesis: Capturing RTL printf Calls when Running on the FPGA
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  - AutoCounter Runtime Parameters
  - AutoCounter CSV Output Format
  - Using TracerV Trigger with AutoCounter
  - AutoCounter using Synthesizable Printfs
  - Reset & Timing Considerations
- TracerV + Flame Graphs: Profiling Software with Out-of-Band Flame Graph Generation
  - What are Flame Graphs?
  - Prerequisites
  - Enabling Flame Graph generation in `config_runtime.yaml`
  - Producing DWARF information to supply to the TracerV driver
  - Modifying your workload description
  - Running a simulation
  - Caveats
- Dromajo Co-simulation with BOOM designs
  - Building a Design with Dromajo
  - Running a FireSim Simulation
  - Troubleshooting Dromajo Simulations with Meta-Simulations
- Debugging a Hanging Simulator
  - Case 1: Target hang.
  - Case 2: Simulator hang due to FPGA-side token starvation.
  - Case 3: Simulator hang due to driver-side deadlock.
  - Simulator Heartbeat PlusArgs

Previous

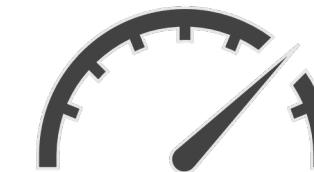
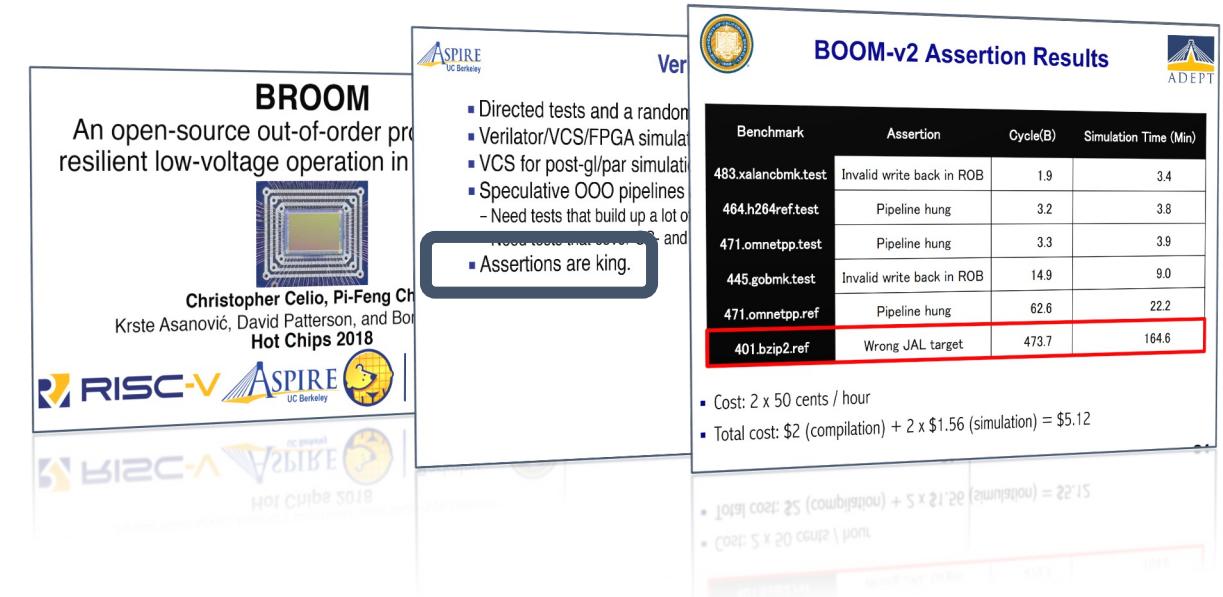
Next





# Example use cases: Debugging and Profiling SoC Designs

- Debugging a Chisel design at FPGA-speeds
  - Many FireSim debugging features: Assertion synthesis, printf synthesis, ILA insertion, etc.
  - e.g. FireSim Debugging Docs
  - e.g. Fixing BOOM Bugs (D. Kim, et. al., *DESSERT*, FPL '18)
- Profiling a custom RISC-V SoC at FPGA-speeds
  - e.g. HW/SW Co-design of a networked RISC-V system (S. Karandikar, et. al., *FirePerf*, ASPLOS 2020)



## FirePerf





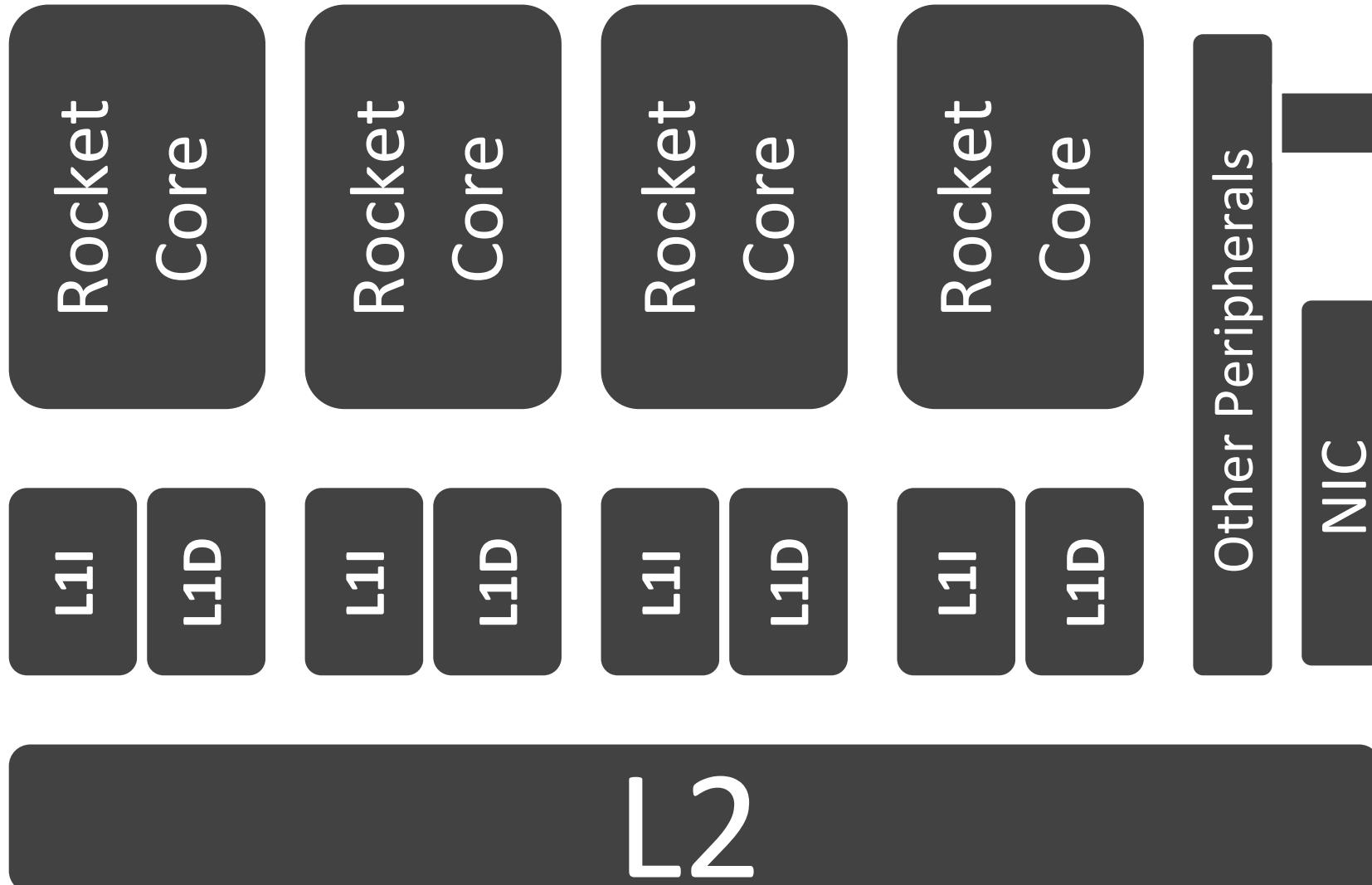
# How-to-build a *datacenter-scale* FireSim simulation

- [1] S. Karandikar et. al., "FireSim: FPGA-Accelerated Cycle-Exact Scale-Out System Simulation in the Public Cloud." *ISCA 2018*
- [2] S. Karandikar et. al., "FireSim: FPGA-Accelerated Cycle-Exact Scale-Out System Simulation in the Public Cloud." *IEEE Micro Top Picks 2018*





# Step 1: Server SoC in RTL



## Modeled System

- 4x RISC-V Rocket Cores @ 3.2 GHz
- 16K I/D L1\$
- 256K Shared L2\$
- 200 Gb/s Eth. NIC

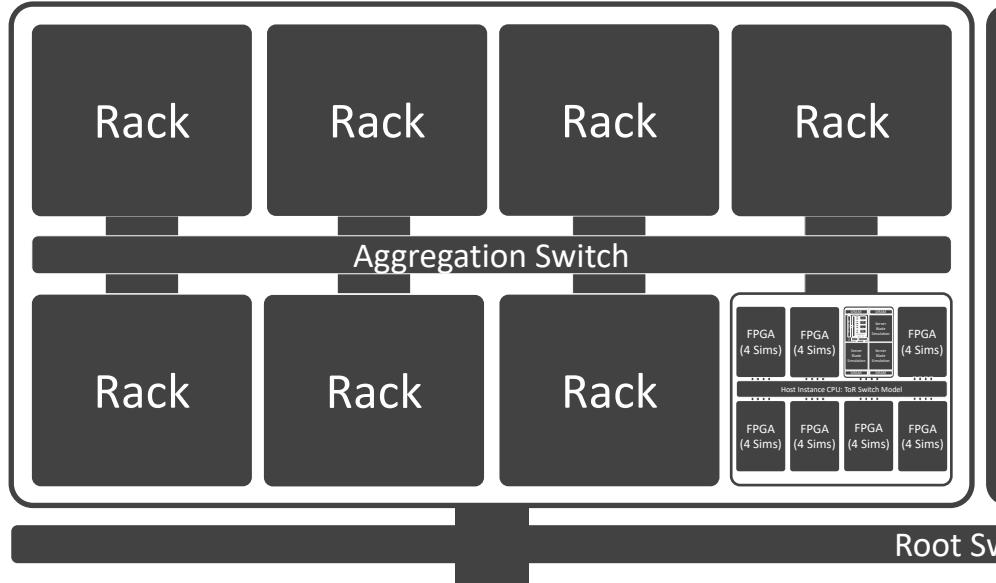
## Resource Util.

- < ¼ of an FPGA

## Sim Rate

- N/A

# Step 6: Simulating a 1024 node datacenter



## Modeled System

- 1024 Servers
- 4096 Cores
- 16 TB DDR3
- 32 ToRs, 4 Aggr, 1 Root
- 200 Gb/s, 2us links

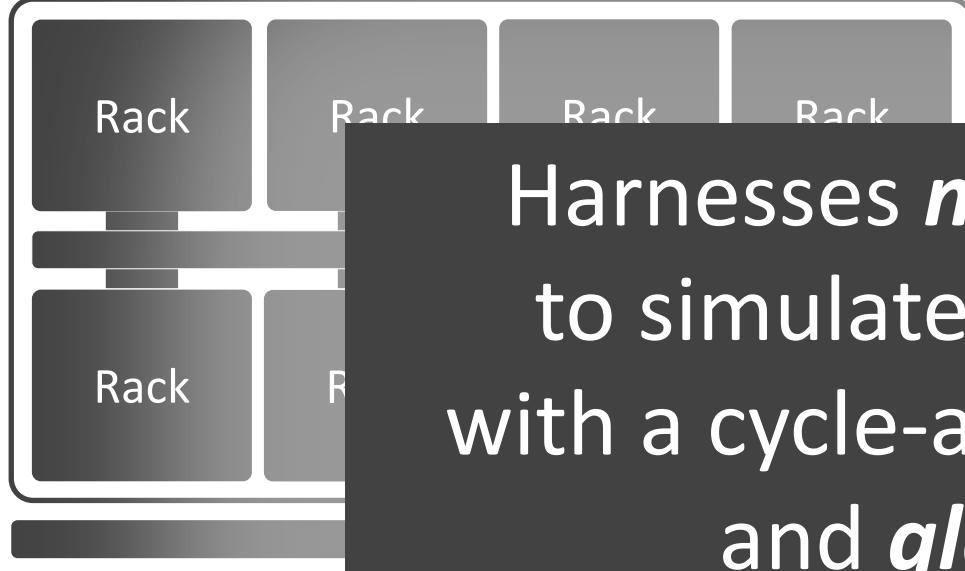
## Resource Util.

- 256 FPGAs =
- 32x f1.16xlarge
- 5x m4.16xlarge

## Sim Rate

- ~6.6 MHz (netw)

# Step 6: Simulating a 1024 node datacenter



Harnesses *millions of dollars* of FPGAs  
to simulate *1024 nodes cycle-exactly*  
with a cycle-accurate *network simulation*  
and *global synchronization*  
at a cost-to-user of only *100s of dollars/hour*

Aggregation Pod

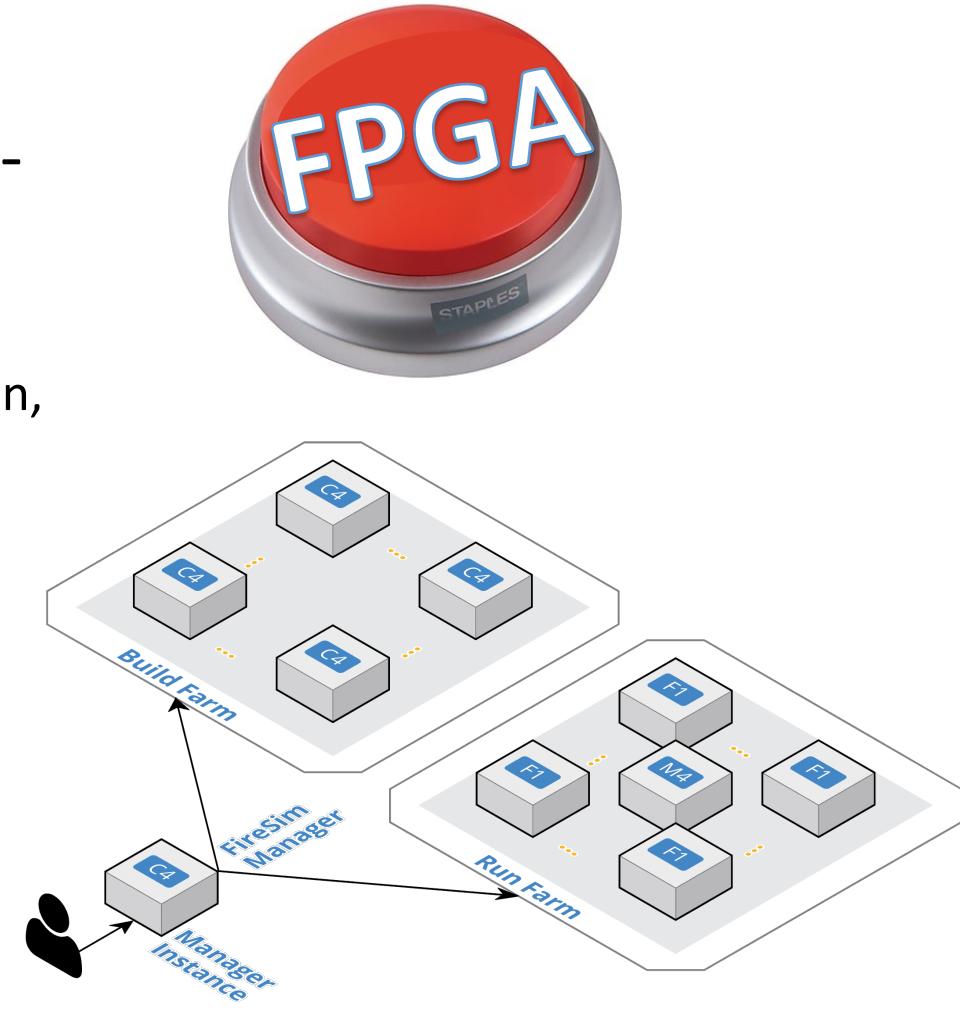
Aggregation Pod

Modeled System  
- 1024 Servers  
6 Cores  
1TB DDR3  
ToRs, 4 Aggr, 1  
Gb/s, 2us  
source Util.  
250 FPGAs =  
- 32x f1.16xlarge  
- 5x m4.16xlarge  
Sim Rate  
- ~6.6 MHz (netw)



# Productive Open-Source FPGA Simulation

- [github.com/firesim/firesim](https://github.com/firesim/firesim), BSD Licensed
- An “easy” button for fast, FPGA-accelerated full-system simulation
  - Plug in your own RTL designs, your own HW/SW models
  - One-click: Parallel FPGA builds, Simulation run/result collection, building target software
  - Scales to a variety of use cases:
    - Networked (performance depends on scale)
    - Non-networked (150+ MHz), limited by your budget
- **firesim command line program**
  - Like docker or vagrant, but for FPGA sims
  - User doesn’t need to care about distributed magic happening behind the scenes

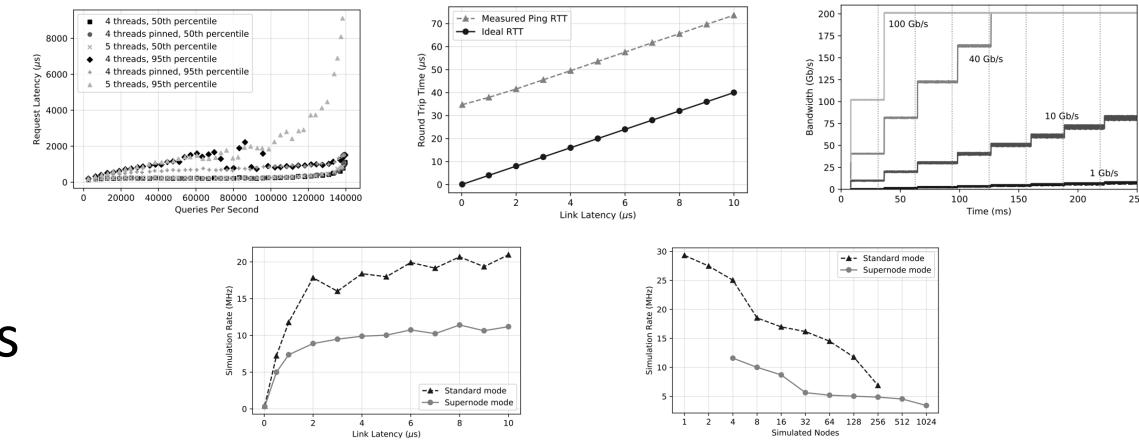
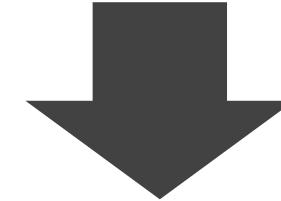




# Productive Open-Source FPGA Simulation

- Scripts can call `firesim` to fully automate distributed FPGA sim
  - **Reproducibility:** included scripts to reproduce ISCA 2018 results
  - e.g. scripts to automatically run SPECInt2017 with full **reference inputs** in  $\approx 1$  day
  - Many others included
  - Several user papers have gone through artifact evaluation using FireSim (*nanoPU*, *FirePerf*, *Protobuf accel.*, *MoCA*, *Simulator Independent Coverage*, etc.)
- 200+ pages of documentation: <https://docs.firesim.org>
- AWS provides grants for researchers:  
<https://aws.amazon.com/grants/>
- Xilinx University Program provides FPGA donations for university researchers:  
<https://www.xilinx.com/support/university.html>

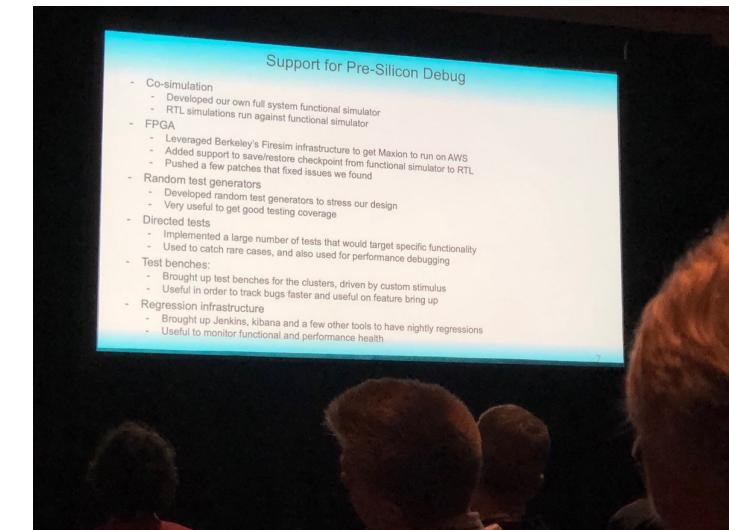
```
$ cd fsim/deploy/workloads  
$ ./run-all.sh
```





# Join the FireSim Community!: Open-source users and industrial users

- More than 200 mailing list members and 850 unique cloners per-week
- Projects with public FireSim support
  - Chipyard
  - Rocket Chip
  - BOOM
  - Hwacha Vector Accelerator
  - Keystone Secure Enclave
  - Gemmini
  - NVIDIA Deep Learning Accelerator (NVDLA)
    - NVIDIA Blog post:  
<https://devblogs.nvidia.com/nvdl/>
  - BOOM Spectre replication/mitigation
  - Protobuf Accelerator
  - Too many to list here!
- Companies publicly announced using FireSim
  - Esperanto Maxion ET
  - Intensivate IntenCore
  - SiFive validation paper @ VLSI'20
  - Galois and Lockheed Martin (DARPA SSITH/FETT)



Esperanto announcement at RISC-V Summit 2018





# FireSim in DARPA FETT

- DARPA SSITH: Building hardware defenses to address common software vulnerabilities
- DARPA FETT: How good are the defenses built in SSITH?
  - Multiple designs hosted for attack in FireSim [1]
- “Morpheus II: A RISC-V Security Extension for Protecting Vulnerable Software and Hardware”
  - Developed by UT Austin, U Mich., Agita Labs
  - Hosted on FireSim for FETT [2]
  - Over 500 attackers tried to break Morpheus II defenses, working for large bug bounties. None succeeded [3]



[1] K. Hopfer. Leveraging Amazon EC2 F1 Instances for Development and Red Teaming in DARPA’s First-Ever Bug Bounty Program. AWS APN Blog. May 2021.

[2] A. Harris, et. al., “Morpheus II: A RISC-V Security Extension for Protecting Vulnerable Software and Hardware”. In proceedings of the 2021 IEEE International Symposium on Hardware Oriented Security and Trust (HOST), December 2021.

[3] T. Austin., et. al., “Morpheus II: A RISC-V Security Extension for Protecting Vulnerable Software and Hardware”. In HotChips 33, August 2021.



# Join the FireSim Community!:

## Academic Users and Awards



- **ISCA '18:** Maas et. al. HW-GC Accelerator (**Berkeley**)
- **MICRO '18:** Zhang et. al. “Composable Building Blocks to Open up Processor Design” (**MIT**)
- **RTAS '20:** Farshchi et. al. BRU (**Kansas**)
- **EuroSys '20:** Lee et. al. Keystone (**Berkeley**)
- **OSDI '21:** Ibanez et. al. nanoPU (**Stanford**)
- **CCS '21:** Ding et. al. “Hardware Support to Improve Fuzzing Performance and Precision” (**Georgia Tech**)
- Too many to list here: see FireSim website for more!
  - <https://fires.im/publications/#userpapers>
- Awards: FireSim ISCA '18 paper:
  - IEEE Micro Top Pick
  - CACM Research Highlights Nominee from ISCA '18
- Awards: FireSim users:
  - ISCA '18 Maas et. al.:
    - IEEE Micro Top Pick
  - MICRO '18 Zhang et. al.:
    - IEEE Micro Top Pick
  - MICRO '21 Gottschall et. al.:
    - MICRO-54 Best paper runner-up
  - MICRO '21 Karandikar et. al.:
    - MICRO-54 Distinguished Artifact winner
    - IEEE Micro Top Pick Honorable Mention
  - DAC '21 Genc et. al.:
    - DAC 2021 Best Paper winner



# Join the FireSim Community!:

## Academic Users and Awards



- ISCA '18: Maas et. al. HW-GC Accelerator (Berkeley)
- MICRO '18: Blocks to...
- RTAS '20
- EuroSys '20
- OSDI '21
- CCS '21: Improve (Georgia)
- Too many to list here. See FireSim website for more!
  - <https://firesim.org/publications/#userpapers>

- Awards: FireSim ISCA '18 paper:
  - IFFF Micro Top Pick

*FireSim has been used\* in published work from authors at over 20 academic and industrial institutions*

*\*actually used, not only cited*

- IEEE Micro Top Pick Honorable Mention
- DAC '21 Genc et. al.:
  - DAC 2021 Best Paper winner





# Questions?



Berkeley Architecture Research

## Learn More:

Web: <https://fires.im>

Docs: <https://docs.fires.im>

GitHub: <https://github.com/firesim/firesim>

Mailing List:

<https://groups.google.com/forum/#!forum/firesim>

 [@firesimproject](https://twitter.com/firesimproject)

Email: [sagark@eecs.berkeley.edu](mailto:sagark@eecs.berkeley.edu)

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000849, by DARPA, Award Number HR0011-12-2-0016, and by NSF CCRI ENS Chipyard Award #2016662. Research was also partially funded by SLICE/ADEPT Lab industrial sponsors and affiliates Amazon, Apple, Google, Intel, Qualcomm, and Western Digital, and RISE Lab sponsor Amazon Web Services. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.