

Computer Architecture Simulation



Outline

What is gem5 and a bit of history

My perspective on architecture simulation

gem5's software architecture

First there was M5



Created at Michigan by students of Steve Reinhardt,
principally Nate Binkert .

“A tool for simulating systems”

Two Views of M5

1. A framework for event-driven simulation
 - Events, objects, statistics, configuration
 2. A collection of predefined object models
 - CPUs, caches, busses, devices, etc.
-
- This tutorial focuses on #2
 - You may find #1 useful even if #2 is not



Then there was GEMS



Created at Michigan by students of Steve Reinhardt,
principally Nate Binkert .

“A tool for simulating systems”



Multifacet GEMS

General Execution-driven Multiprocessor Simulator

Created at Wisconsin by students of Mark Hill and David Wood
Detailed memory system

GEMS at ISCA 2005



Now, we have two simulators...



Created at Michigan by students of Steve Reinhardt,
principally Nate Binkert .

“A tool for simulating systems”



Multifacet GEMS

General Execution-driven Multiprocessor Simulator

Created at Wisconsin by students of Mark Hill and David Wood
Detailed memory system

What is gem5?

Michigan m5 + Wisconsin GEMS = gem5

"The gem5 simulator is a modular platform for computer-system architecture research, encompassing system-level architecture as well as processor microarchitecture."

Citations for gem5

Lowe-Power et al. The gem5 Simulator: Version 20.0+. ArXiv Preprint ArXiv:2007.03152, 2021.
<https://doi.org/10.48550/arXiv.2007.03152>

Nathan Binkert, Bradford Beckmann, Gabriel Black, Steven K. Reinhardt, Ali Saidi, Arkaprava Basu, Joel Hestness, Derek R. Hower, Tushar Krishna, Somayeh Sardashti, Rathijit Sen, Korey Sewell, Muhammad Shoaib, Nilay Vaish, Mark D. Hill, and David A. Wood. 2011. The gem5 simulator. SIGARCH Comput. Archit. News 39, 2 (August 2011), 1-7.
DOI=<http://dx.doi.org/10.1145/2024716.2024718>

gem5-20+: A new era in computer architecture simulation

| | | | | | | | | | | |
|---------------------------------|-----------------|------------------|-----------------|-------------------|------------------|-------------------|------------------|------------------|------------------|------------------|
| Abdul Mutaal | Bagus | Curtis Dunham | Gabe Black | Jakub Jermar | Krishnendra | Maximilien | Nils Asmussen | Robert Kovacsics | Stan Czerniawski | Vilas Sridharan |
| Ahmad | Hanindhito | Dam Sunwoo | Gabe Loh | James Clarkson | Nathella | Breughe | Nuwan Jayasena | Robert Scheffel | Stanislaw | Vince Weaver |
| Adrian Herrera | Benjamin Nash | Dan Gibson | Gabor Dozsa | Jan-Peter Larsson | Lena Olson | Michael Adler | Ola Jeppsson | Rohit Kurup | Czerniawski | Vincentius Robby |
| Adrien Pesle | Bertrand | Daniel Carvalho | Gedare Bloom | Jason Lowe- | Lisa Hsu | Michael LeBeane | Omar Naji | Ron Dreslinski | Stephan | Wade Walker |
| Adrià Armejach | Marquis | Daniel Johnson | Gene WU | Power | Lluc Alvarez | Michael | Pablo Prieto | Ruben | Diestelhorst | Weiping Liao |
| Akash Bagdia | Binh Pham | Daniel Sanchez | Gene Wu | Javier Bueno | Lluís Vilanova | Levenhagen | Palle Lyckegaard | Ayrapetyan | Stephen Hines | Wendy Elsasser |
| Alec Roelke | Bjoern A. Zeeb | David Guillen- | Geoffrey Blake | Hedo | Mahyar Samani | Michiel Van Tol | Pau Cabre | Rune Holm | Steve Raasch | William Wang |
| Alexandru Dutu | Blake Hechtman | Fandos | Georg Kotheimer | Javier Cano-Cano | Malek Musleh | Miguel Serrano | Paul Rosenfeld | Ruslan Bukin | Steve Reinhardt | Willy Wolff |
| Ali Jafri | Bobby R. Bruce | David Hashe | Giacomo | Javier Setoain | Marc Mari | Mike Upton | Peter Enns | Rutuja Oza | Stian Hvatum | Xiangyu Dong |
| Ali Saidi | Boris Shisharov | David Oehmke | Gabrielli | Jayneel Gandhi | Barcelo | Miles Kaufmann | Pin-Yen Lin | Ryan Gershord | Sudhanshu Jha | Xianwei Zhang |
| Amin Farmahini | Brian Klemm | Derek Horner | Giacomo | Jeffrey Goldblum | Marcos | Pi-Jia Yu | Rui Xiao | Samuel | Sandip | Xiaoyu Ma |
| Anders Handler | Brian Knofe | Dylan G | Travaglini | Jinglong Guo | Marko | Ping Li | Rinaldo | Sebastien | Santi G | Ouyang |
| Andrea Mondelli | Brad W | Fabio | Glenn Berg | Lin Qu | Matthew Elgar | Pratik Dayal | Perry | Shihab | Thomas | Eckert |
| Andrea Pellegrini | Brandon Potter | Djordje | Hamid Reza | Jiuyue Ma | Marjan Fariborz | Mohammad | Petrakis | Sascha Bischoff | Tao Zhang | |
| Andreas Hansson | Brian Grayson | Kovacevic | Khaleghzadeh | Joe Gross | Matt DeVuyst | Alian | Pouya Fotouhi | Sean McGoogan | Thomas Grass | |
| Andreas Cagdas Dirik | Dongxue Zhang | Hanhwi Jang | Joel Hestness | Matt Evans | Monir | Prakash | Sean Wilson | Tiago Mück | | |
| Sandberg Chander | Doğukan | Hoa Nguyen | John Alsop | Matt Horsnell | Mozumder | Ramrakhiani | Sergei Trofimov | Tim Harris | | |
| Andrew Bardsley Sudanthi | Korkmaztürk | Hongil Yoon | John | Matt Poremba | Moyang Wang | Pritha Ghoshal | Severin | Timothy Hayes | | |
| Andrew Lukefahr Chen Zou | Dylan Johnson | Hsuan Hsu | Kalamatianos | Matt Sinclair | Mrinmoy Ghosh | Radhika Jagtap | Wischmann | Timothy M. | | |
| Andrew Schultz Chris Adeniyi- | Earl Ou | Hussein | Jordi Vaquero | Matteo | Nathan Binkert | Rahul Thakur | Shawn Rosti | Jones | | |
| Andriani Jones | Edmund Grimley | Elnawawy | Jose Marinho | Andreozzi | Nathanael | Reiley Jeapaul | Sherif Elhabbal | Tom Jablin | | |
| Mappoura Chris Emmons | Evans | Ian Jiang | Jui-min Lee | Matteo M. Fusi | Premillieu | Rekai Gonzalez- | Siddhesh | Tommaso | | |
| Ani Udupi Christian Menard | Emilio Castillo | IanJiangICT | Kanishk Sugand | Matthew | Nayan | Alberquilla | Poyarekar | Marinelli | | |
| Anis Peysieux Christoph Pfister | Erfan Azarkhish | Ilias Vougioukas | Karthik Sangiah | Poremba | Deshmukh | Rene de Jong | Somayeh | Tony Gutierrez | | |
| Anouk Van Laer Christopher | Eric Van | Isaac Richter | Ke Meng | Matthias Hille | Neha Agarwal | Ricardo Alves | Sardashti | Trivikram Reddy | | |
| Arthur Perais Torng | Hensbergen | Isaac Sánchez | Kevin Brodsky | Matthias Jung | Nicholas Lindsay | Richard D. Strong | Sooraj Puthoor | Tuan Ta | | |
| Ashkan Tousi Chuan Zhu | Erik Hallnor | Barrera | Kevin Lim | Maurice Becker | Nicolas | Richard Strong | Sophiane Senni | Tushar Krishna | | |
| Austin Harris Chun-Chen Hsu | Erik Tomusk | Ivan Pizarro | Khalique | Maxime | Derumigny | Rico Amslinger | Soumyaroop Roy | Umesh Bhaskar | | |
| Avishai Tsvila Ciro Santilli | Faissal Sleiman | Jack Whitham | Koan-Sin Tan | Martinasso | Nicolas Zea | Riken Gohil | Srikant | Uri Wiener | | |
| Ayaz Akram Clint Smullen | Fernando Endo | Jairo Balart | Korey Sewell | Maximilian Stein | Nikos Nikoleris | Rizwana Begum | Bharadwaj | Victor Garcia | | |

Your name here!

gem5's goals



Agile Hardware Dev. Methodology



From Hennessey and Patterson
Turing Lecture

gem5's goals

Anyone (including non-architects) can download and use gem5

Used for cross-stack research:

- Change kernel, change runtime, change hardware, all in concert
- Run full ML stacks, full AR/VR stacks... other emerging apps

We're close... just a lot of rough edges! You can help!

The gem5 community

100s of contributors & 1000s(?) of users

Aim to meet the needs of

- Academic research
- Industry research and development
- Classroom use

Code of conduct (see repo)

We want to see the community grow!



My views on simulation

(a) Scientific research



(b) Systems research



From [Computer Architecture Performance Evaluation Methods](#) by Lieven Eeckhout

Highlighted block is where computer architecture simulation fits in

Why simulation?

Why simulation? (Answer)

- Need a tool to evaluate systems that don't exist (yet)
 - Performance, power, energy, etc.
- Very costly to actually make the hardware
- Computer systems are complex with many interdependent parts
 - Not easy to be accurate without the full system
- Simulation can be parameterized
 - Design-space exploration
 - Sensitivity analysis

Alternatives to cycle-level simulation: Analytical modeling

Amdahl's Law

$$S_{latency}(s) = \frac{1}{(1 - p) + \frac{p}{s}}$$

Queuing theory



$$L = \lambda W$$

Kinds of simulation

- Functional simulation
- Instrumentation-based
- Trace-based
- Execution-driven
- Full system

Kinds of simulation: details

- Functional simulation
 - Executes programs correctly. Usually no timing information
 - Used to validate correctness of compilers, etc.
 - RISC-V Spike, QEMU, gem5 "atomic" mode
- Instrumentation-based
 - Often binary translation. Runs on actual hardware with callbacks
 - Like trace-based. Not flexible to new ISA. Some things opaque
 - PIN, NVBit
- Trace-based simulation
 - Generate addresses/events and re-execute
 - Can be fast (no need to do functional simulation). Reuse traces
 - If execution depends on timing, this will not work!
 - "Specialized" simulators for single aspect (e.g., just cache hit/miss)

Kinds of simulation: Execution-driven and full system

Execution-driven

- Functional and timing simulation is combined
- gem5 and many others
- gem5 is "execute in execute" or "timing directed"

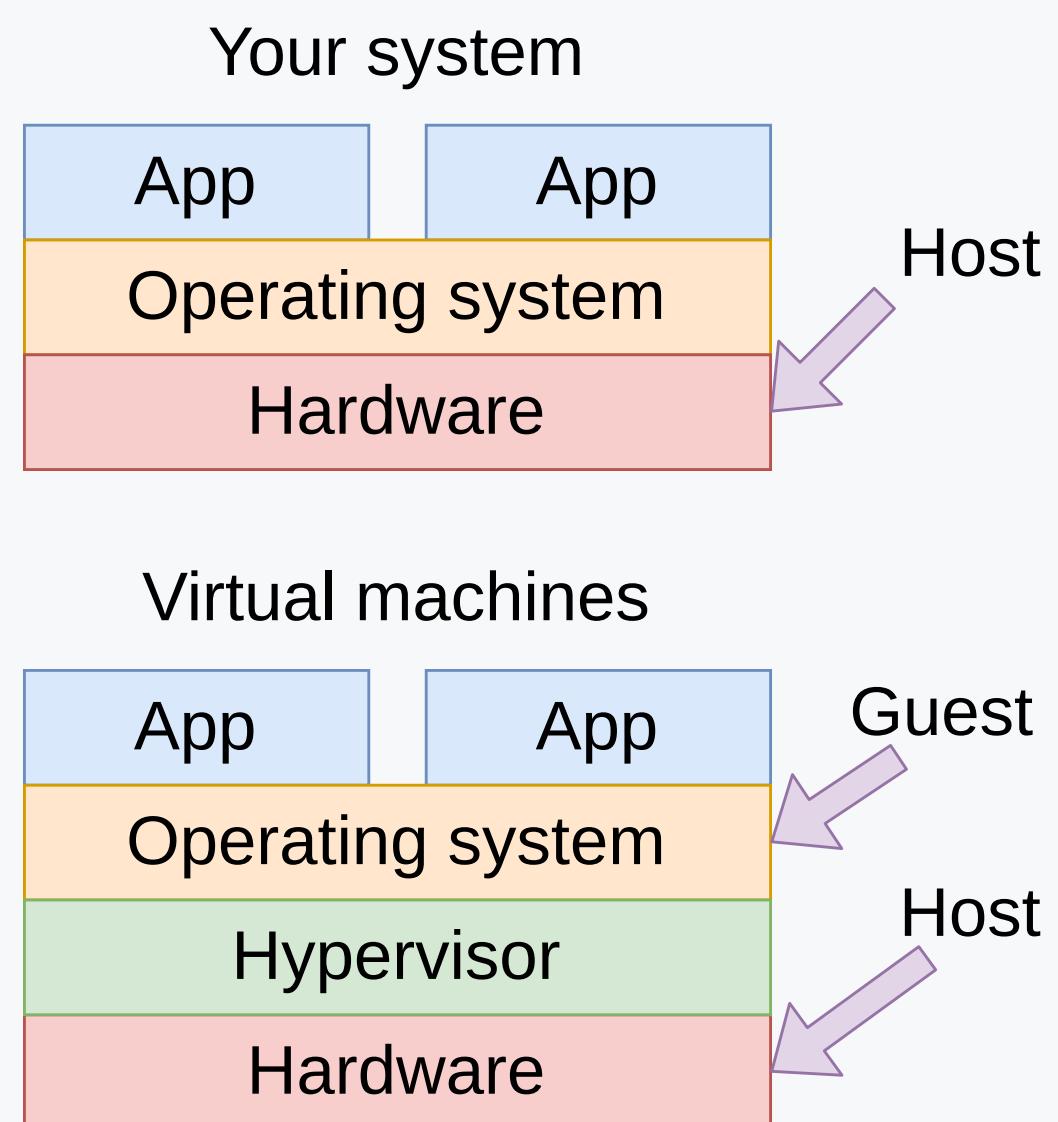
Full system

- Components modeled with enough fidelity to run mostly unmodified apps
- Often "Bare metal" simulation
- All of the program is functionally emulated by the simulator
- Often means running the OS in the simulator, not faking it

"Full system" simulators are often combine functional and execution-based

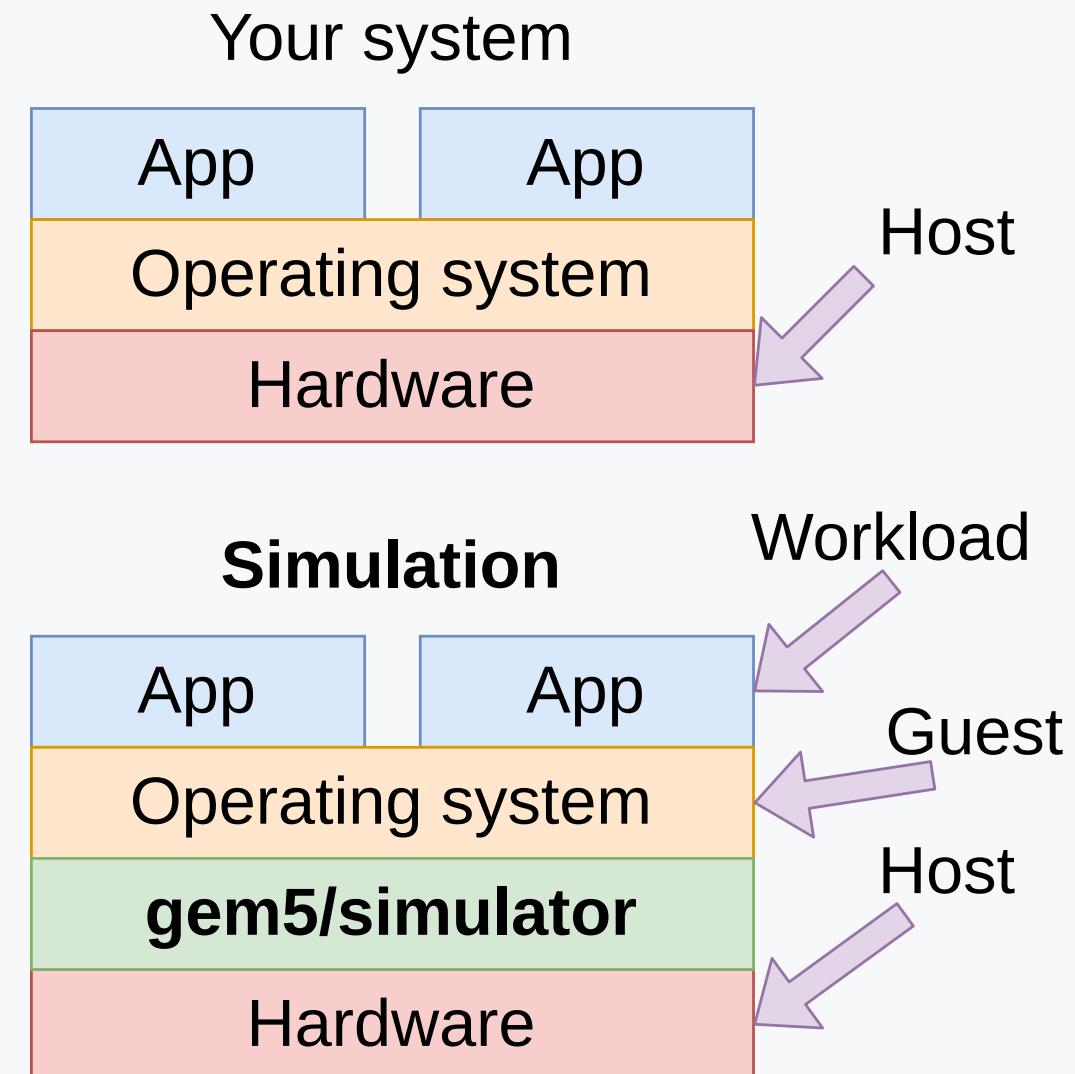
Nomenclature (VMs)

- **Host:** the actual hardware you're using
- Running things directly on the hardware:
 - **Native execution**
- **Guest:** Code running on top of "fake" hardware
 - OS in virtual machine is guest OS
 - Running "on top of" hypervisor
 - Hypervisor is emulating hardware



Nomenclature (gem5)

- **Host:** the actual hardware you're using
- **Simulator:** Runs on the host
 - Exposes hardware to the guest
- **Guest:** Code running on simulated hardware
 - OS running on gem5 is guest OS
 - gem5 is simulating hardware
- **Simulator's code:** Runs natively
 - executes/emulates the guest code
- **Guest's code:** (or benchmark, workload, etc.)
 - Runs on gem5, not on the host.



Nomenclature (more gem5)

- **Host:** the actual hardware you're using
- **Simulator:** Runs on the host
 - Exposes hardware to the guest
- **Simulator's performance:**
 - Time to run the simulation on host
 - Wallclock time as you perceive it
- **Simulated performance:**
 - Time predicted by the simulator
 - Time for guest code to run on simulator



Tradeoffs in types of simulation

- Development time: time to make the simulator/models
- Evaluation time: wallclock time to run the simulator
- Accuracy: How close is the simulator to real hardware
- Coverage: How broadly can the simulator be used?

| | Development time | Evaluation time | Accuracy | Coverage |
|--|------------------|-----------------|-----------|-----------|
| functional simulation | excellent | good | poor | poor |
| instrumentation | excellent | very good | poor | poor |
| specialized cache and predictor simulation | good | good | good | limited |
| full trace-driven simulation | poor | poor | very good | excellent |
| full execution-driven simulation | very poor | very poor | excellent | excellent |

What level should we simulate?

- Ask yourself: What fidelity is required for this question?
 - Example: New register file design
 - Often, the answer is a mix.
- gem5 is well suited for this mix
 - Models with different fidelity
 - Drop-in replacements for each other

"Cycle level" vs "cycle accurate"

RTL simulation

- RTL: Register transfer level/logic
 - The "model" is the hardware design
 - You specify every wire and every register
 - Close to the actual ASIC
- This is "cycle accurate" as it should be the same in the model and in an ASIC
- Very high fidelity, but at the cost of configurability
 - Need the entire design
 - More difficult to combine functional and timing

Cycle-level simulation

- Models the system cycle-by-cycle
- Often "event-driven" (we'll see this soon)
- Can be highly accurate
 - Not the exact same cycle-by-cycle as the ASIC, but similar timing
- Easily parameterizable
 - No need for a full hardware design
- Faster than cycle-accurate
 - Can "cheat" and functionally emulate some things

gem5's software architecture

Software architectures

C++

Models

gem5 has 100s
of models

Cache

parameters:
size

Core

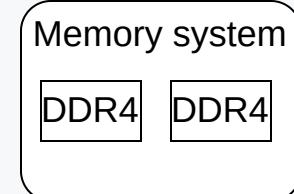
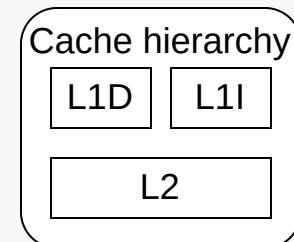
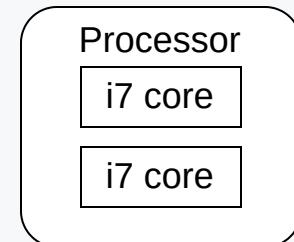
parameters:
LSQ
stages
ROB

DRAM

parameters:
tRAS
tCAS
tRCD

Python

Specify the values
of parameters in
python



Standard library

Python

Control the simulation

sim.start()

sim.dump_stats()

sim.stop_at_inst(...)

Develop experiments
with the key parameters

gem5 architecture: SimObject

Model

This is the `C++` code in `src/`

Parameters

Python code in `src/`

In SimObject declaration file

Instance or Configuration

A particular choice for the parameters

In standard library, your extension, or Python runscript

Model vs parameter

- **Model:** The `C++` code that does the timing simulation
 - Generic
- Expose **parameters** to Python
- Set **parameters** and connections in Python



Some nomenclature

You can **extend** a model to model new things

In this case, you should *inherit* from the object in C++

```
class O3CPU : public BaseCPU  
{
```

You can **specialize** a model to model with specific parameters

In this case, you should *inherit* from the object in Python

```
class i7CPU(O3CPU):  
    issue_width = 10
```

gem5 architecture: Simulation

gem5 is a *discrete event simulator*

At each timestep, gem5:

1. Event at the head is dequeued
2. The event is executed
3. New events are scheduled

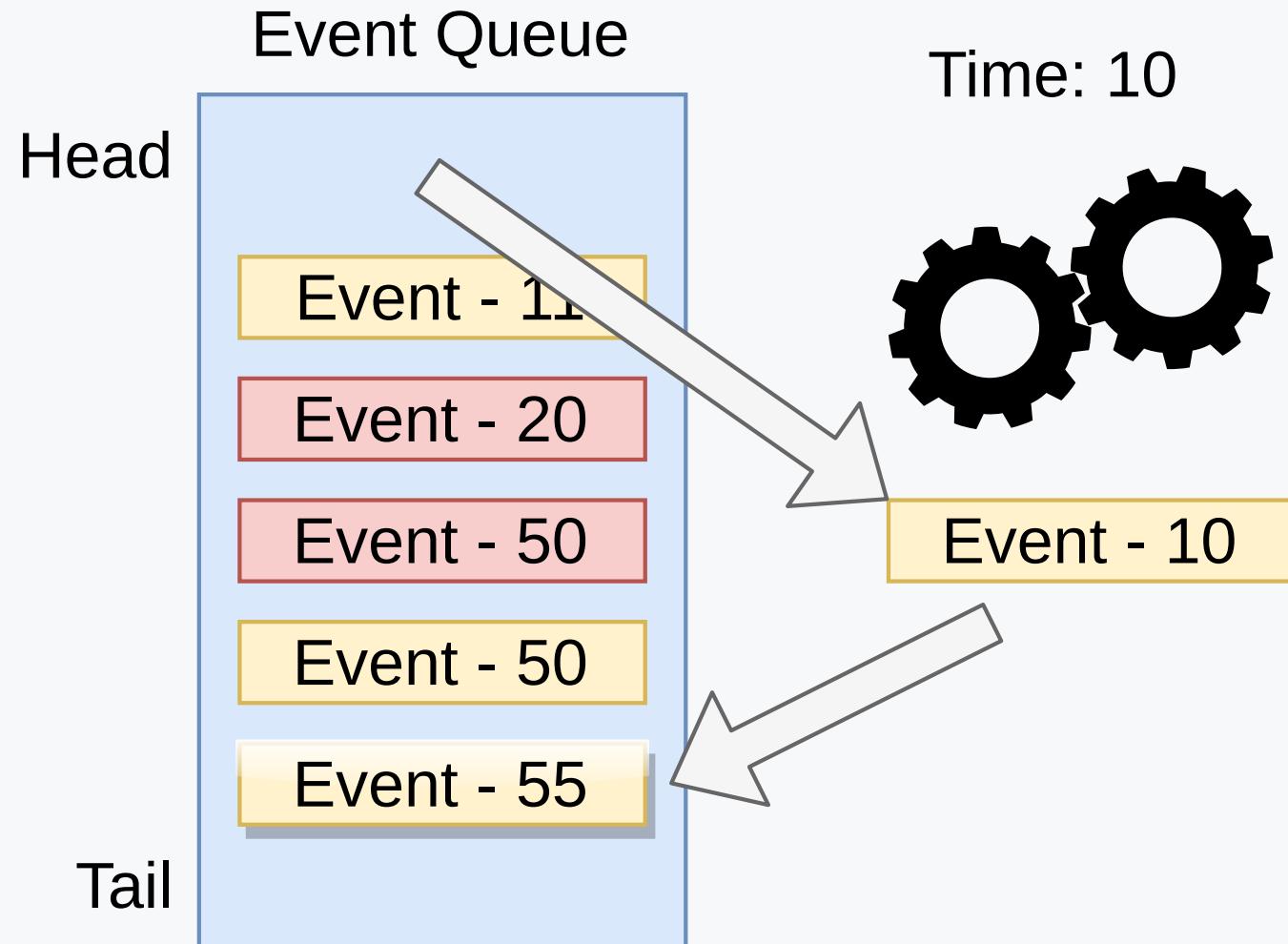


gem5 architecture: Simulation

gem5 is a *discrete event simulator*

At each timestep, gem5:

1. Event at the head is dequeued
2. The event is executed
3. New events are scheduled



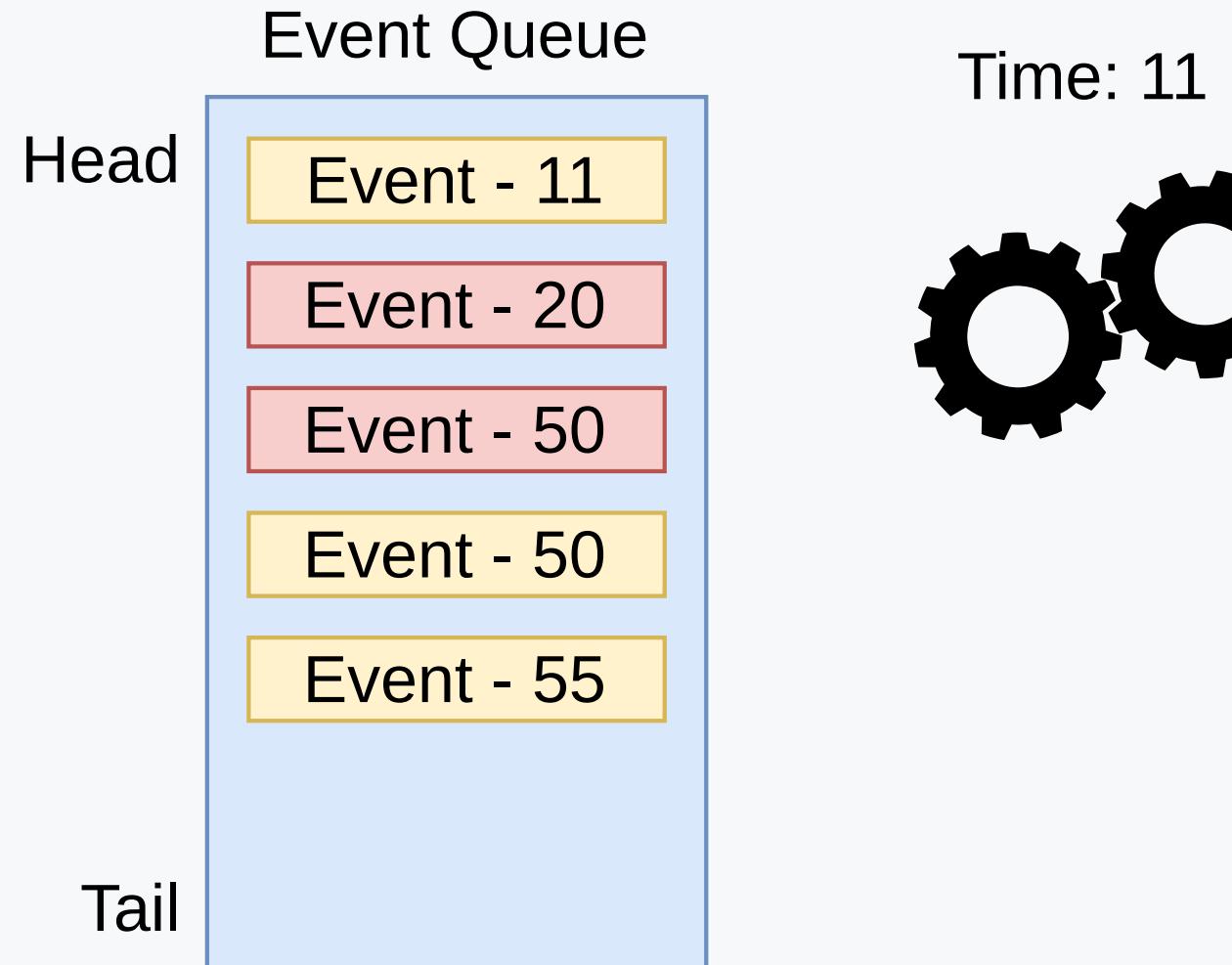
gem5 architecture: Simulation

gem5 is a *discrete event simulator*

At each timestep, gem5:

1. Event at the head is dequeued
2. The event is executed
3. New events are scheduled

All SimObjects can enqueue
events onto the event queue



Discrete event simulation example



Discrete event simulation example



Discrete event simulation example



To model things that take time, schedule the *next* event in the future (latency of current event). Can call functions instead of scheduling events, but they occur *in the same tick*.

Discrete event simulation

"Time" needs a unit.

In gem5, we use a unit called a "Tick".

Need to convert a simulation "tick" to user-understandable time

E.g., seconds.

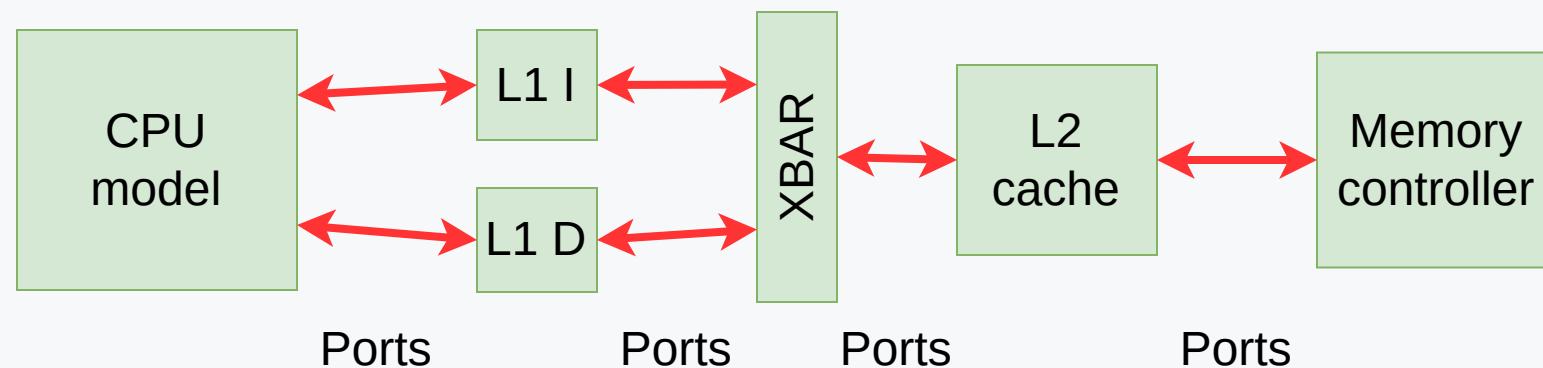
This is the global simulation tick rate.

Usually this is 1 ps per tick or 10^{12} ticks per second

gem5's main abstractions: Memory

Memory requests

- **Ports** allow you to send requests and receive responses.
- Ports are unidirectional (two types, request/response).
- Anything* with a Request port can be connected to any Response port.
- More on this in [Ports and memory-based SimObjects](#).



gem5's main abstractions: CPU

ISA vs CPU model

- ISAs and CPU models are orthogonal.
- Any ISA should work with any CPU model.
- "Execution Context" is the interface.
- More on this in [modeling cores](#).

