

# 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 (most of you all!)
- 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"

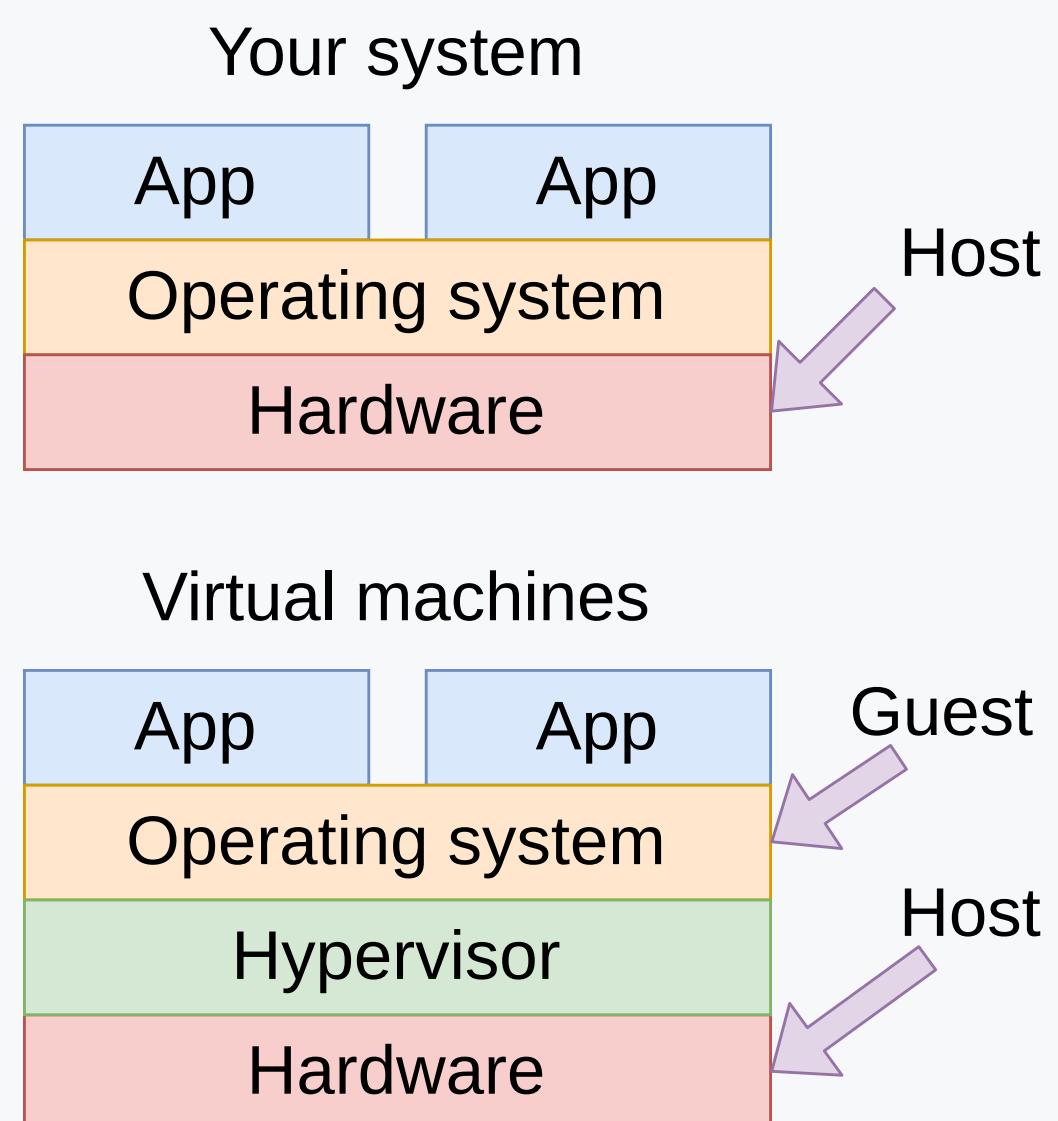
## Full system

- 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



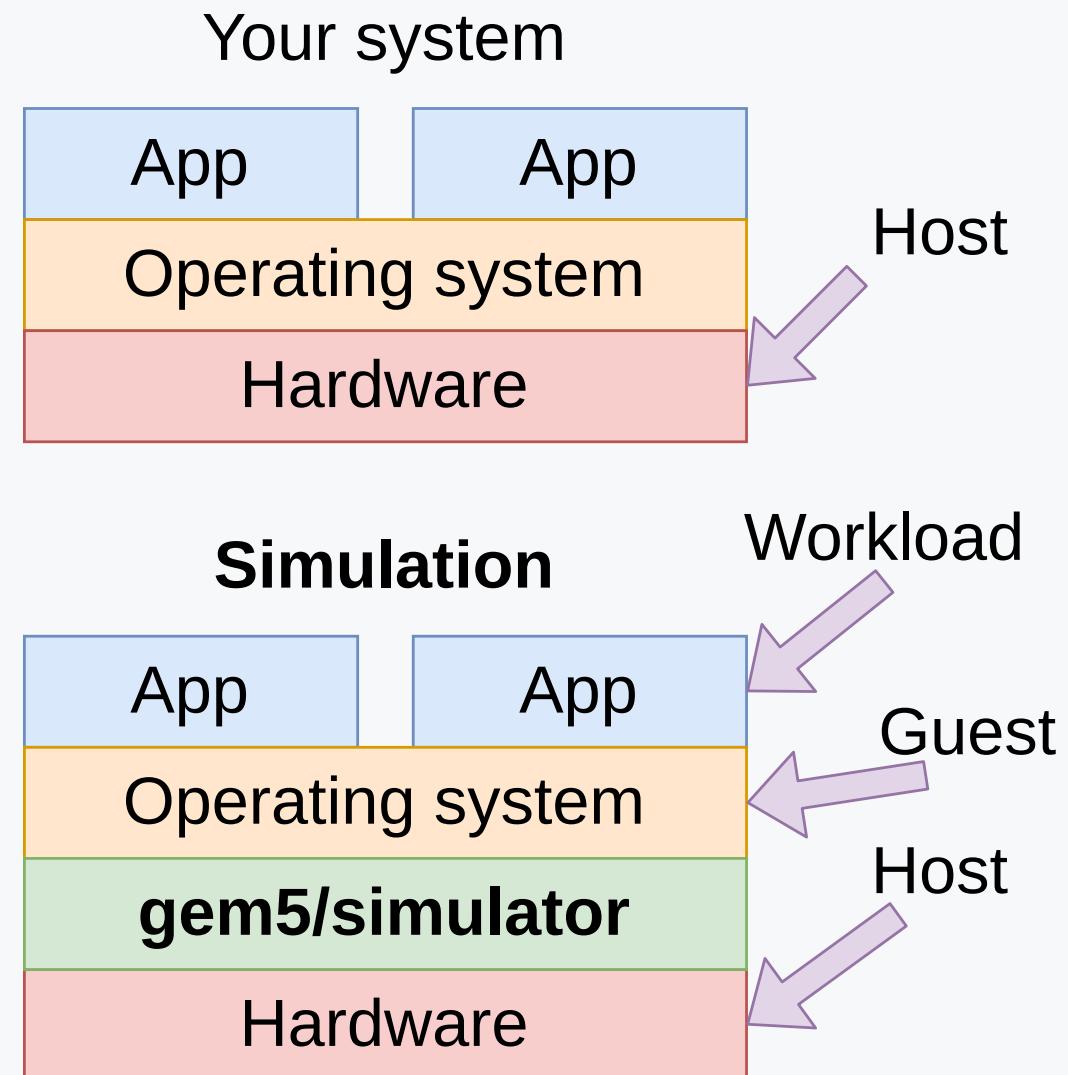
# Nomenclature (gem5)

- **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

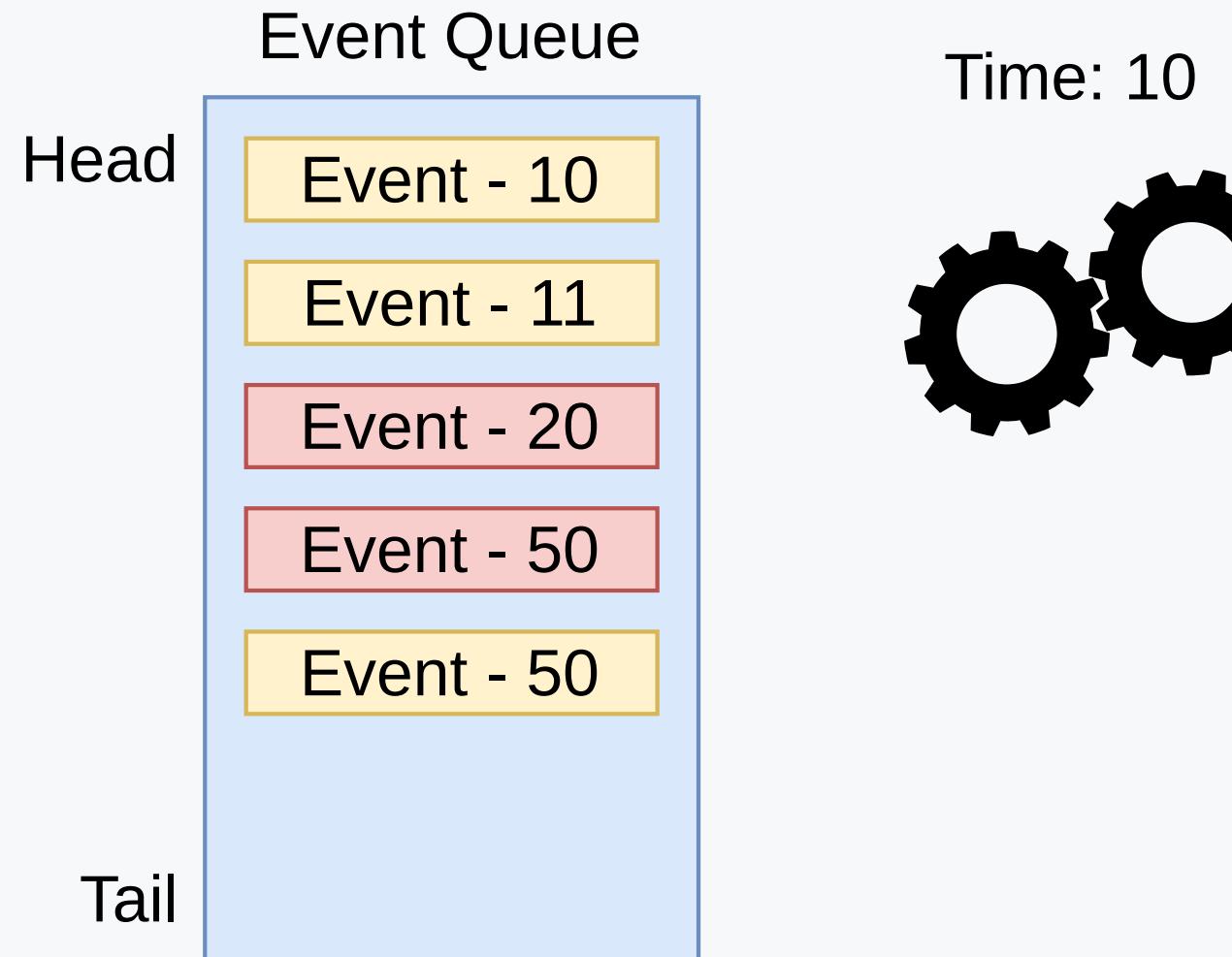
```
class i7CPU(O3CPU):  
    issue_width = 10
```

# 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



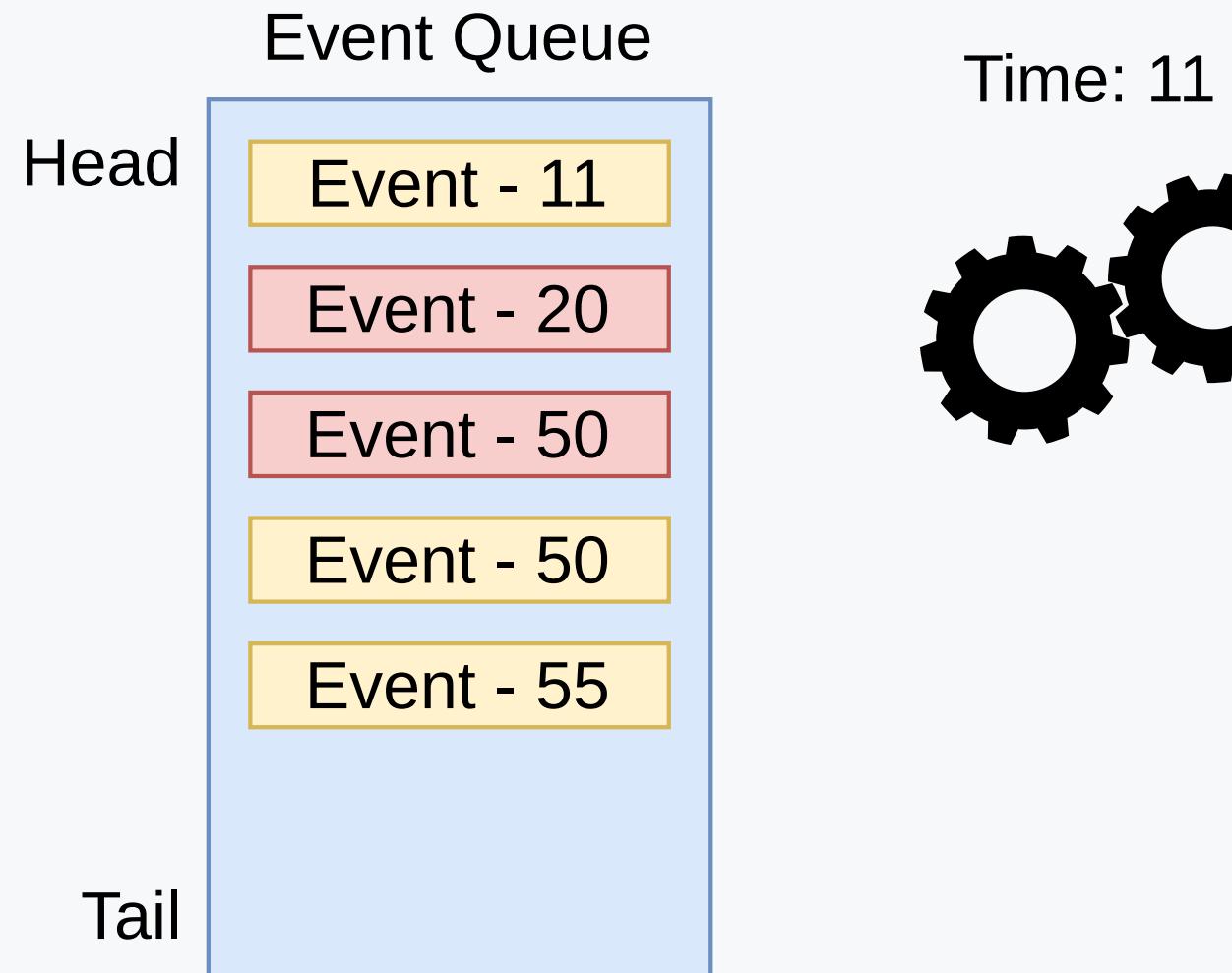
# gem5 architecture: Simulation

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](#).

