Full-Stack Optimizations for Next-Generation Deep-Learning Accelerators

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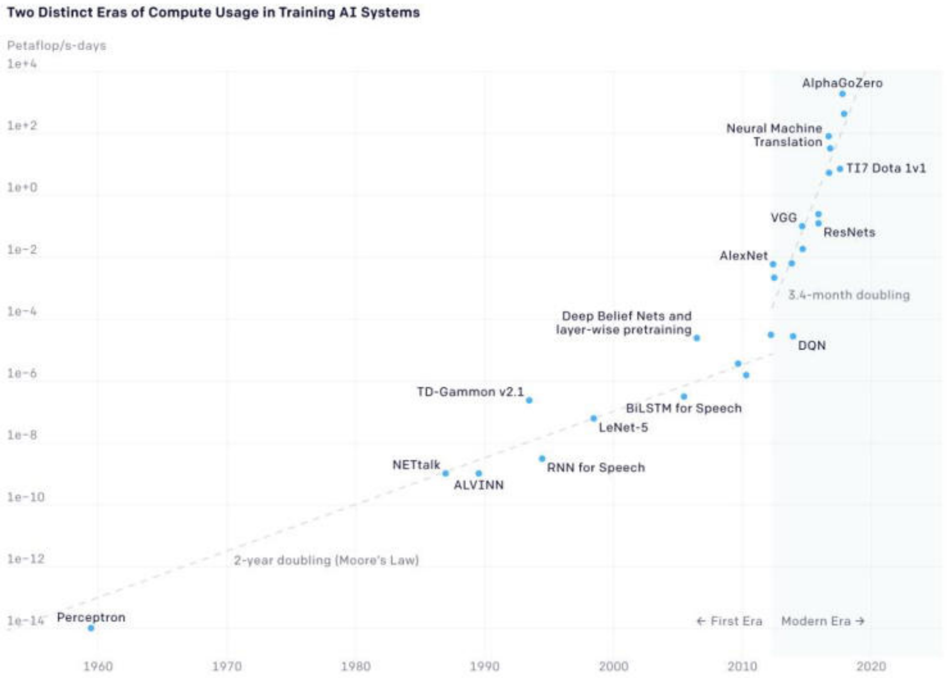
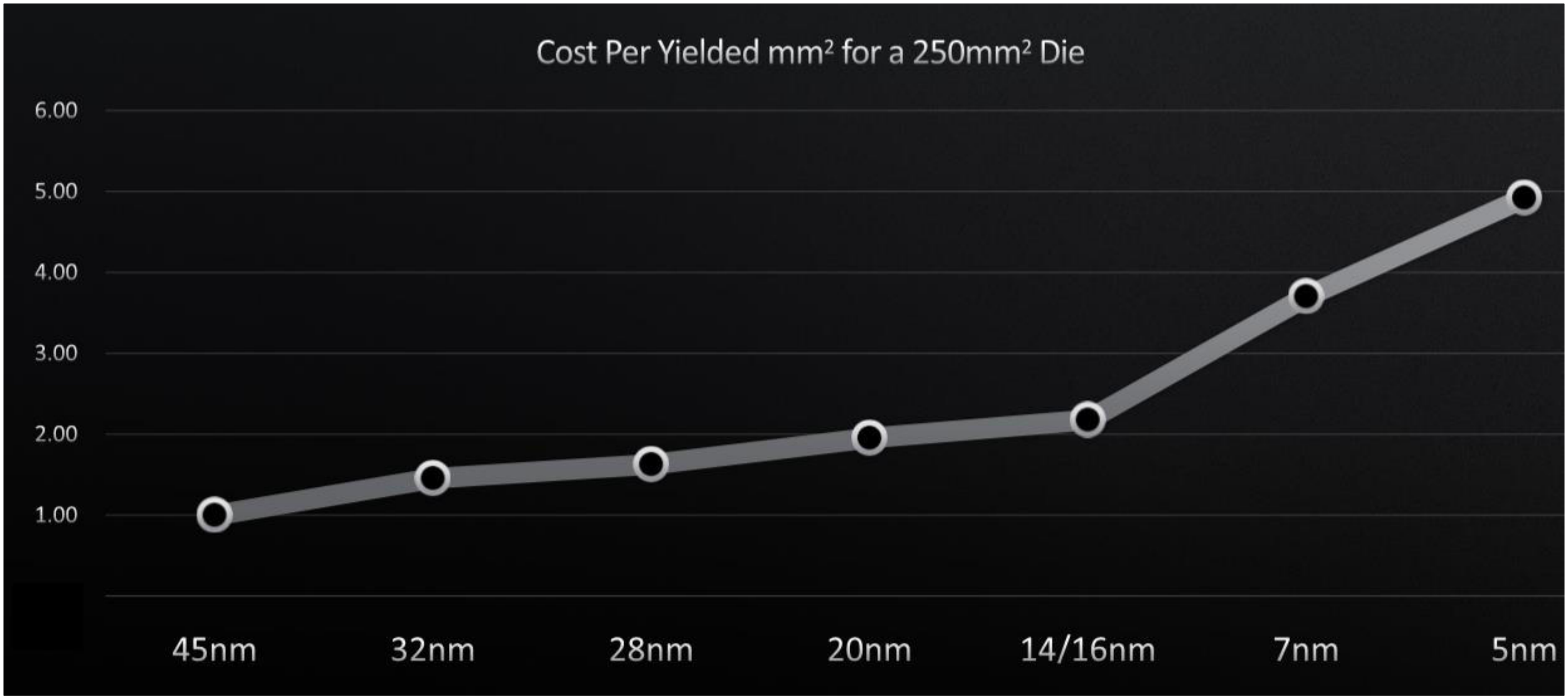
Growing Demand in Computing



Two Distinct Eras of Compute Usage in Training AI Systems

OpenAI



Slowing Supply in Computing

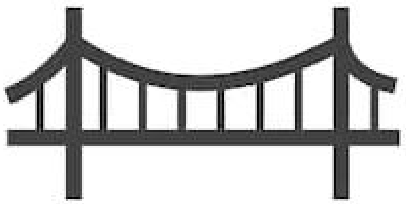
AMD, HotChips, 2019

Growing Demand in Computing + Slowing Supply in Computing = ?

Growing Demand in Computing + Slowing Supply in Computing = 💡

Domain-Specific Accelerators

Growing Demand in Computing

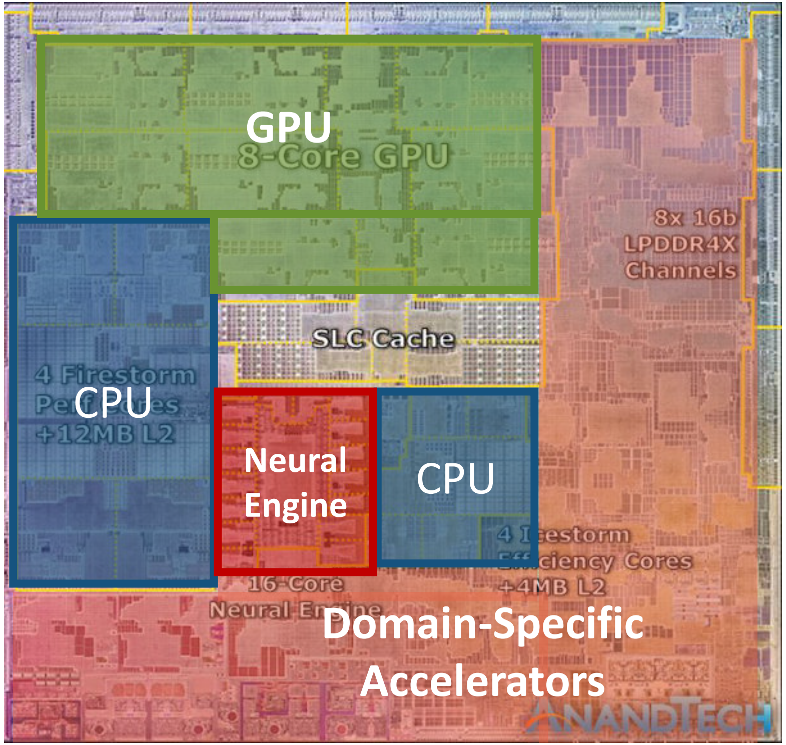


Slowing Supply in Computing

Domain-Specific Accelerators

- Customized hardware designed for a domain of applications.

Apple M1 Chip
2020



* AnandTech

Full-Stack Optimization for DL Accelerators

Design of Accelerators

- MAGNet [ICCAD’2019]
- Simba [MICRO’2019, VLSI’2019]

Integration of Accelerators

- Chipyard [IEEE Micro’2020]
- Gemmini [DAC’2021]

Scheduling of Accelerators

- CoSA [ISCA’2021]

Full-Stack Optimization for DL Accelerators

Design of Accelerators

Integration of Accelerators

Scheduling of Accelerators

Scalable Inference Accelerators

Motivation

- Need for fast and efficient inference accelerators from mobile to datacenter.

Challenge

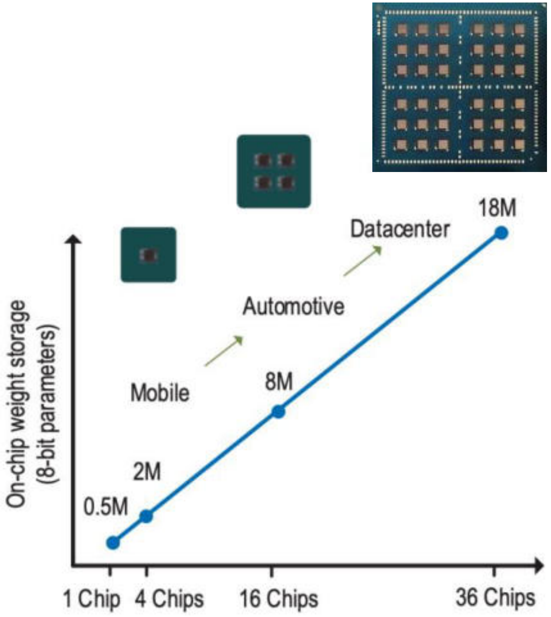
- High design cost of building unique hardware for each design target.

Opportunities

- Deep learning inference is intrinsically scalable with abundant parallelism.
- Recent advances in package-level integration for multi-chip-module-based designs.

The Multi-Chip-Module Approach

- Advantages:
  - Build systems larger than reticle limit
  - Smaller chips are cheaper to design
  - Smaller chips have higher yield
  - Faster time-to-market
- Challenges:
  - Area, energy, and latency for chip-to-chip communication



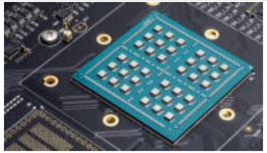
Ref: Zimmer et al., VLSI 2019

Simba: Scaling Inference with MCM-based Architecture

Best Paper Award at MICRO’2019, CACM Research Highlights

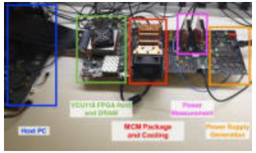
Simba Testchip:

- Package and chiplet architecture
- Processing element design
- Baseline uniform tiling across chiplets and PEs



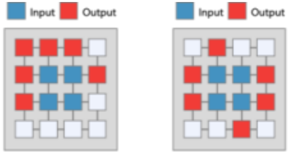
Simba Characterization:

- Comparison with GPUs
- NoP bandwidth sensitivity
- NoP latency sensitivity



Simba NoP-Aware Tiling:

- Non-uniform work partitioning
- Communication-aware data placement
- Cross-layer pipelining



Simba: Scalable MCM-Based Architecture

Package and chiplet spec

6mm^2 chiplet in TSMC 16nm

36 chiplets/package

Chip-to-chip interconnect

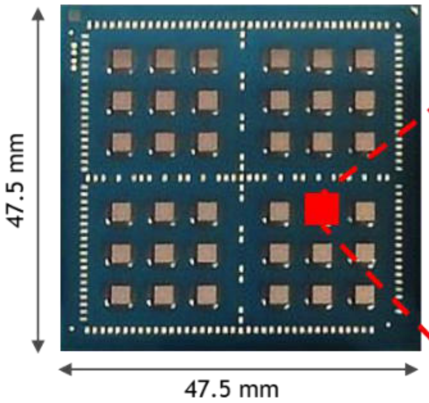
Ground-Referenced Signaling

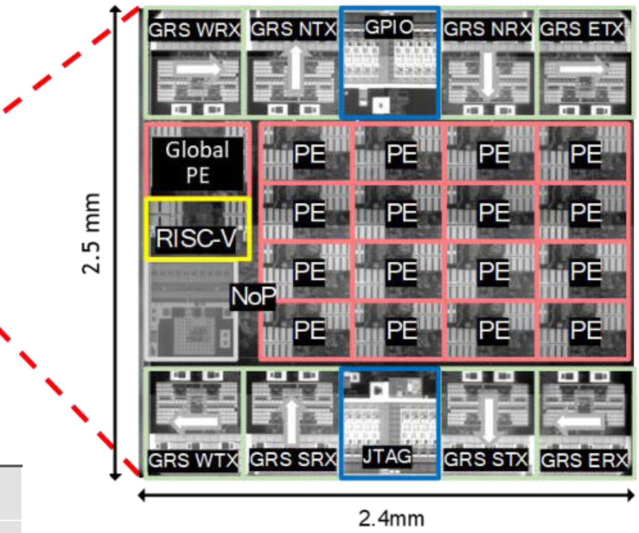
Efficient compute tiles

128 TOPS

0.11 pJ/Op

8-bit integer datapath



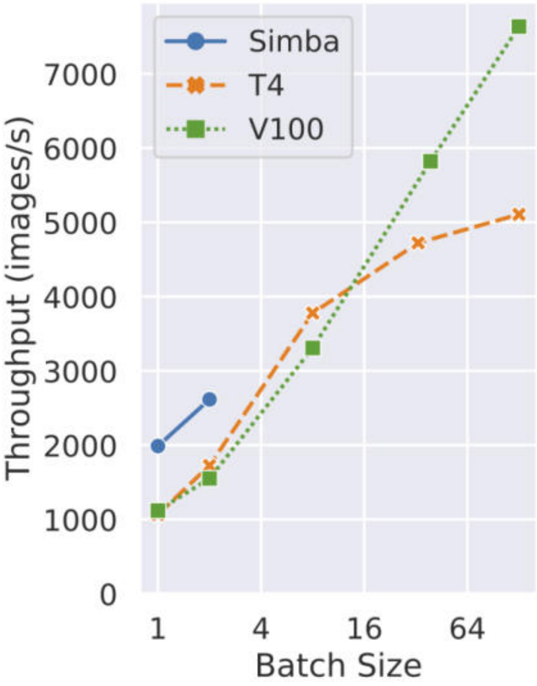


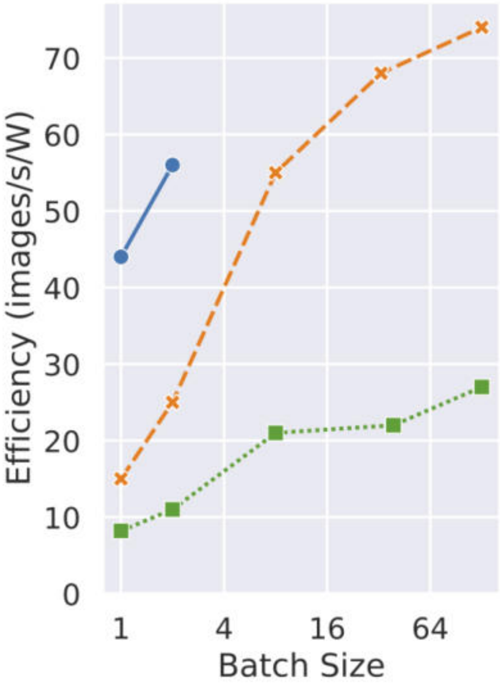
Ref: Zimmer et al., VLSI 2019

Core area	111.6 mm^2
Voltage	0.52-1.1 V
Frequency	0.48-1.8 GHz
SRAM	624KB/chip 23MB/package

Simba Characterization

- Comparison with GPUs running ResNet-50





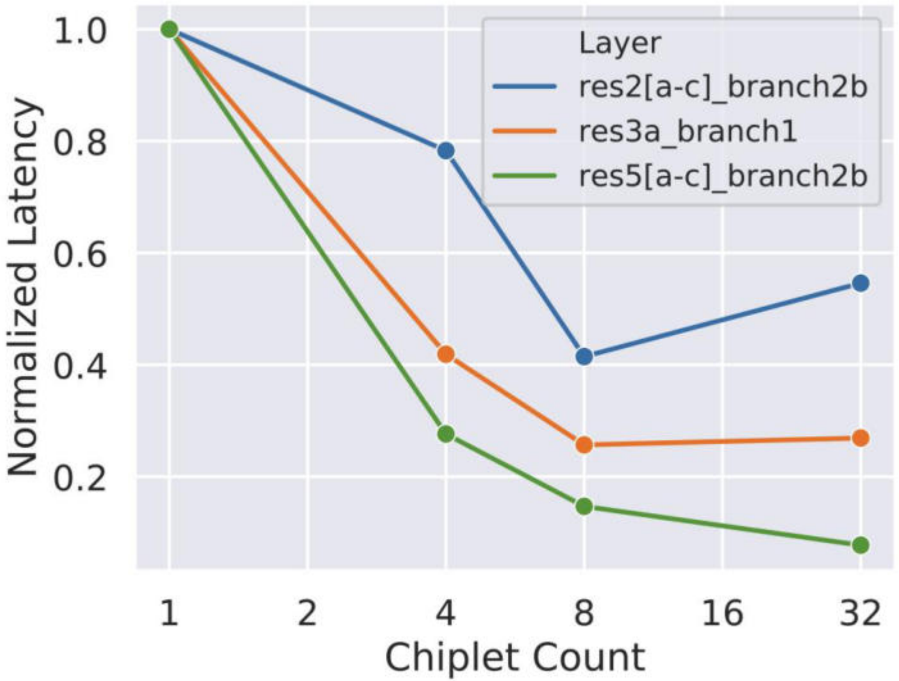
Simba Characterization

- Layer Sensitivity

- Running three ResNet-50 layers across different number of chiplets.

- Increasing the number of active chiplets does not always translate to performance gains.

- The cost of communication hinders the ability to exploit parallelism.



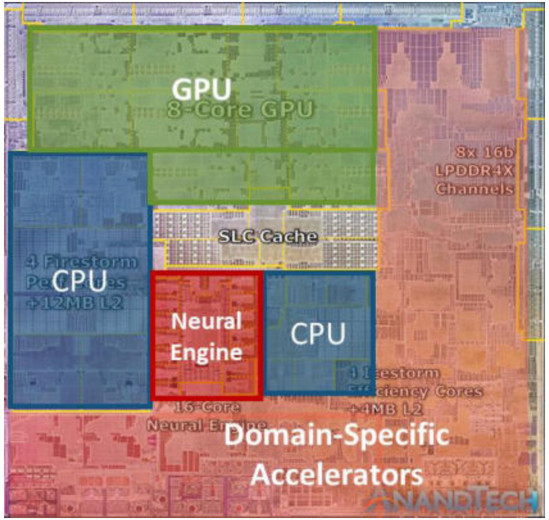
Full-Stack Optimization for DL Accelerators

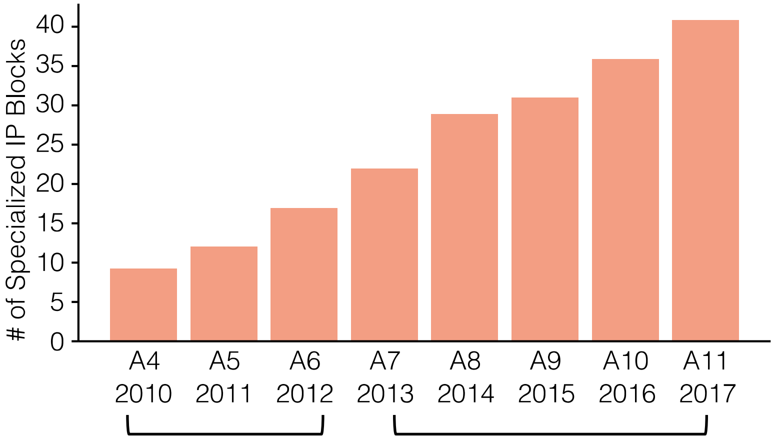
Design of Accelerators

✓ Integration of Accelerators

Scheduling of Accelerators

Accelerators don’t exist in isolation.


GPU
8-Core GPU
8x 16b LPDDR4X Channels
SLC Cache
4 Firestorm Performance Cores +12MB L2
CPU
Neural Engine
CPU
4 Icestorm Efficiency Cores +4MB L2
16-Core Neural Engine
Domain-Specific Accelerators
ANANDTECH



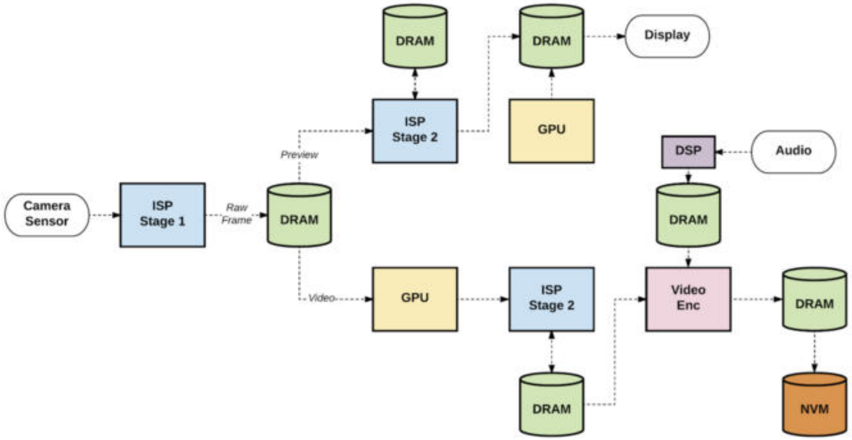
Maltiel consulting estimates

Shao et al. IEEE Micro 2015

http://vlsiarch.eecs.harvard.edu/research/accelerators/die-photo-analysis/

Mobile SoC Usecase

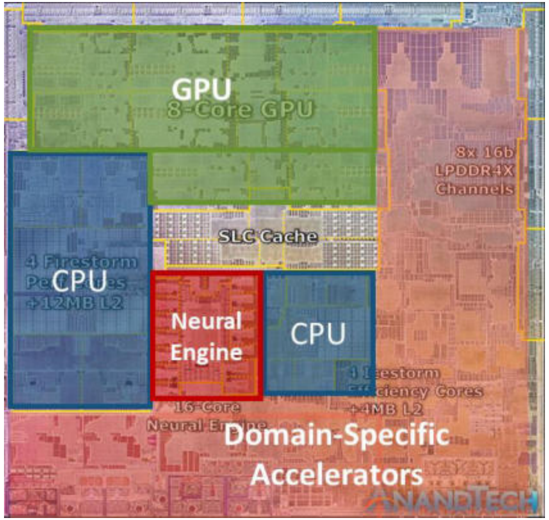
- Mainstream architecture has long focused on general-purpose CPUs and GPUs.
- In an SoC, multiple IP blocks are active at the same time and communicate frequently with each other.
- Example:
  - Recording a 4K video
  - Camera -> ISP
    - “Preview stream” for display
    - “Video stream” for storage
  - DRAM for data sharing

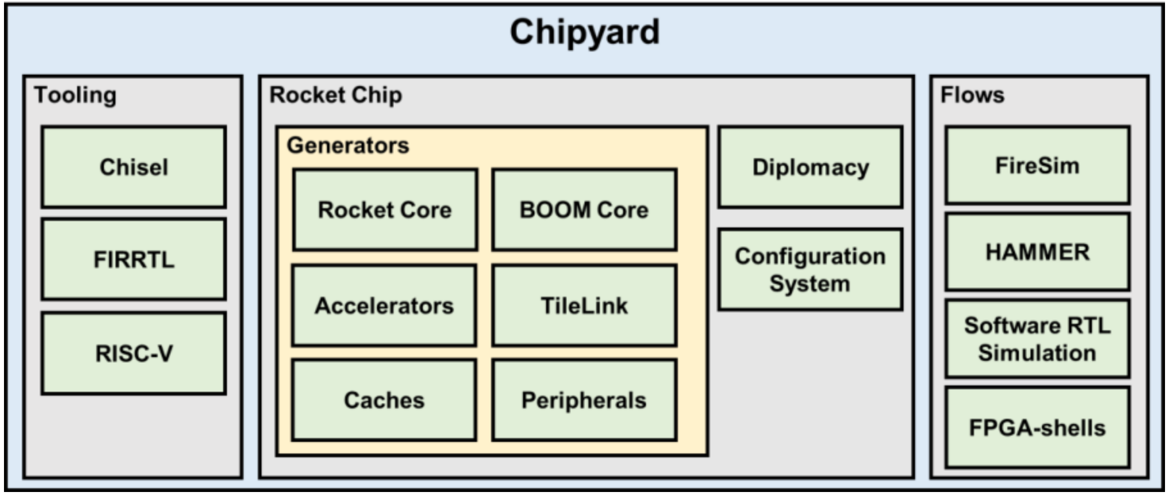


Two Billion Devices and Counting: An Industry Perspective on the State of Mobile Computer Architecture, IEEE Micro’2018

CHIPYARD SoC Framework

- Integrated **design**, **simulation** and **implementation** environment for specialized SoCs.





Chipyard

Tooling
- Chisel
- FIRRTL
- RISC-V

Rocket Chip
- Generators
  - Rocket Core
  - BOOM Core
  - Accelerators
  - TileLink
  - Caches
  - Peripherals
- Diplomacy
- Configuration System

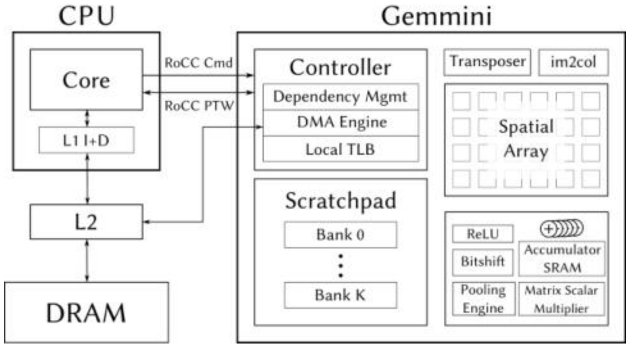
Flows
- FireSim
- HAMMER
- Software RTL Simulation
- FPGA-shells

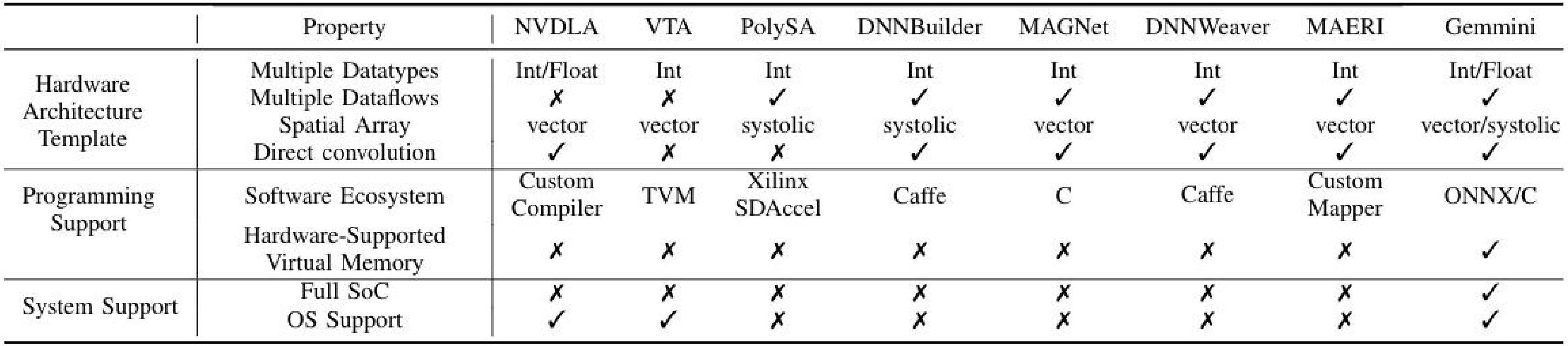
https://github.com/ucb-bar/chipyard

[IEEE Micro’2020]

Gemmini: Full-System Co-Design of Hardware Accelerators

- **Full-stack**
  - Includes OS
  - End-to-end workloads
  - “Multi-level” API
- **Full-SoC**
  - Host CPUs
  - Shared memory hierarchies
  - Virtual address translation



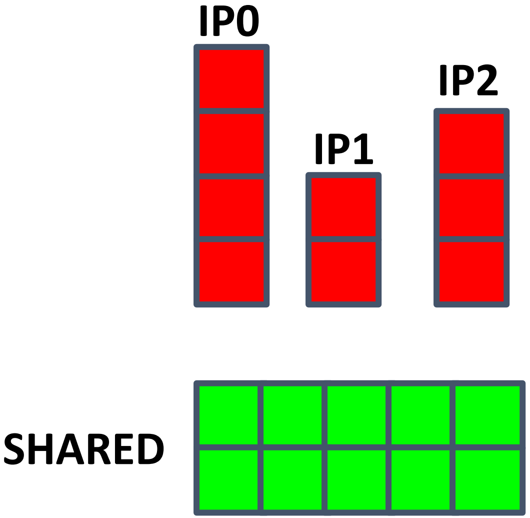


	Property	NVDLA	VTA	PolySA	DNNBuilder	MAGNet	DNNWeaver	MAERI	Gemmini
Hardware Architecture Template	Multiple Datatypes	Int/Float	Int	Int	Int	Int	Int	Int	Int/Float
	Multiple Dataflows	✗	✗	✓	✓	✓	✓	✓	✓
	Spatial Array	vector	vector	systolic	systolic	vector	vector	vector	vector/systolic
	Direct convolution	✓	✗	✗	✓	✓	✓	✓	✓
Programming Support	Software Ecosystem	Custom Compiler	TVM	Xilinx SDAccel	Caffe	C	Caffe	Custom Mapper	ONNX/C
	Hardware-Supported Virtual Memory	✗	✗	✗	✗	✗	✗	✗	✓
System Support	Full SoC	✗	✗	✗	✗	✗	✗	✗	✓
	OS Support	✓	✓	✗	✗	✗	✗	✗	✓

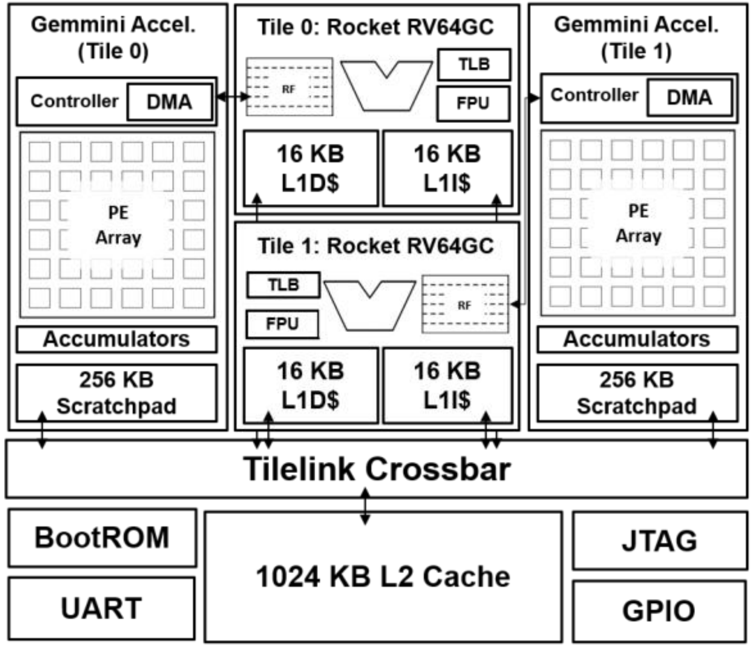
https://github.com/ucb-bar/gemmini

[DAC’2021]

Gemmini Case Study: Allocating on-chip SRAM



- **Where to allocated SRAM?**
  - Private within each IP
  - Shared



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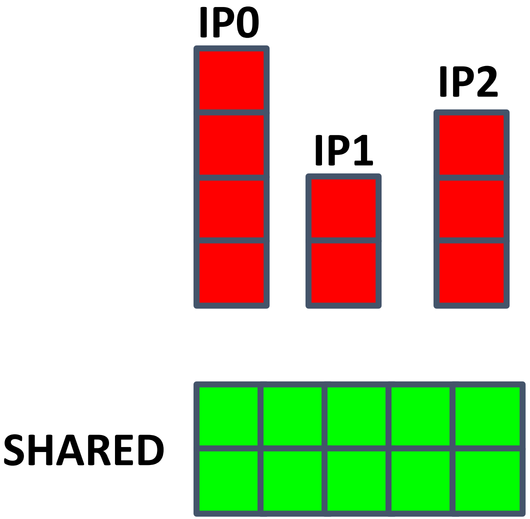
[DAC'2021]

Gemmini Case Study: Allocating on-chip SRAM


IP0

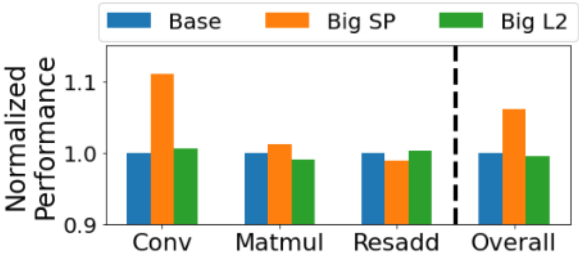
IP1

IP2

SHARED

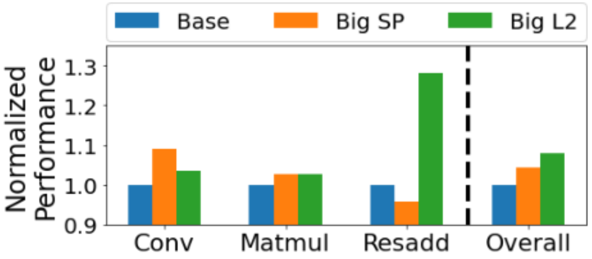
- **Where to allocated SRAM?**
  - Private within each IP
  - Shared

- **Application dependent.**



Single-Core SoC

- **SoC configuration dependent.**



Dual-Core SoC

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[DAC’2021]

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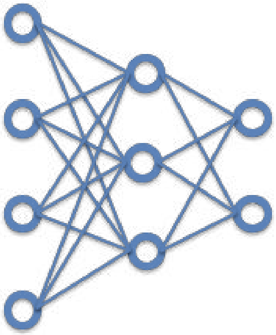
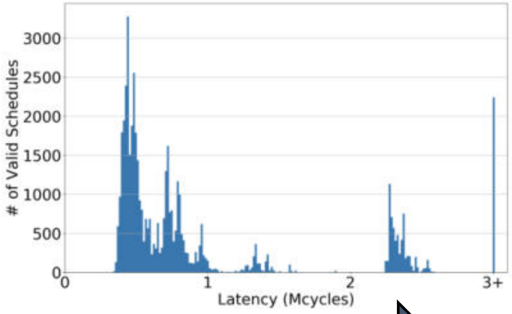
- Integration of Accelerators
- Scheduling of Accelerators

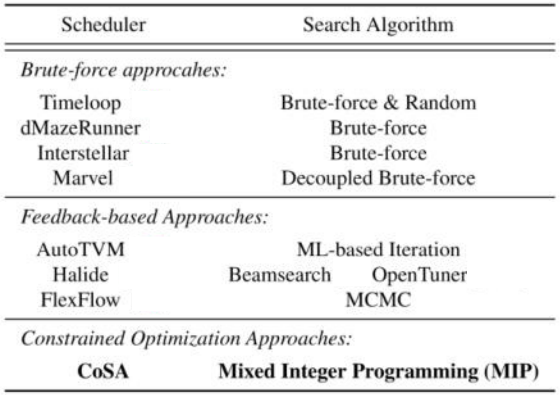
Large Space of Mapping Algorithms to ML Hardware

Algorithm





Scheduling

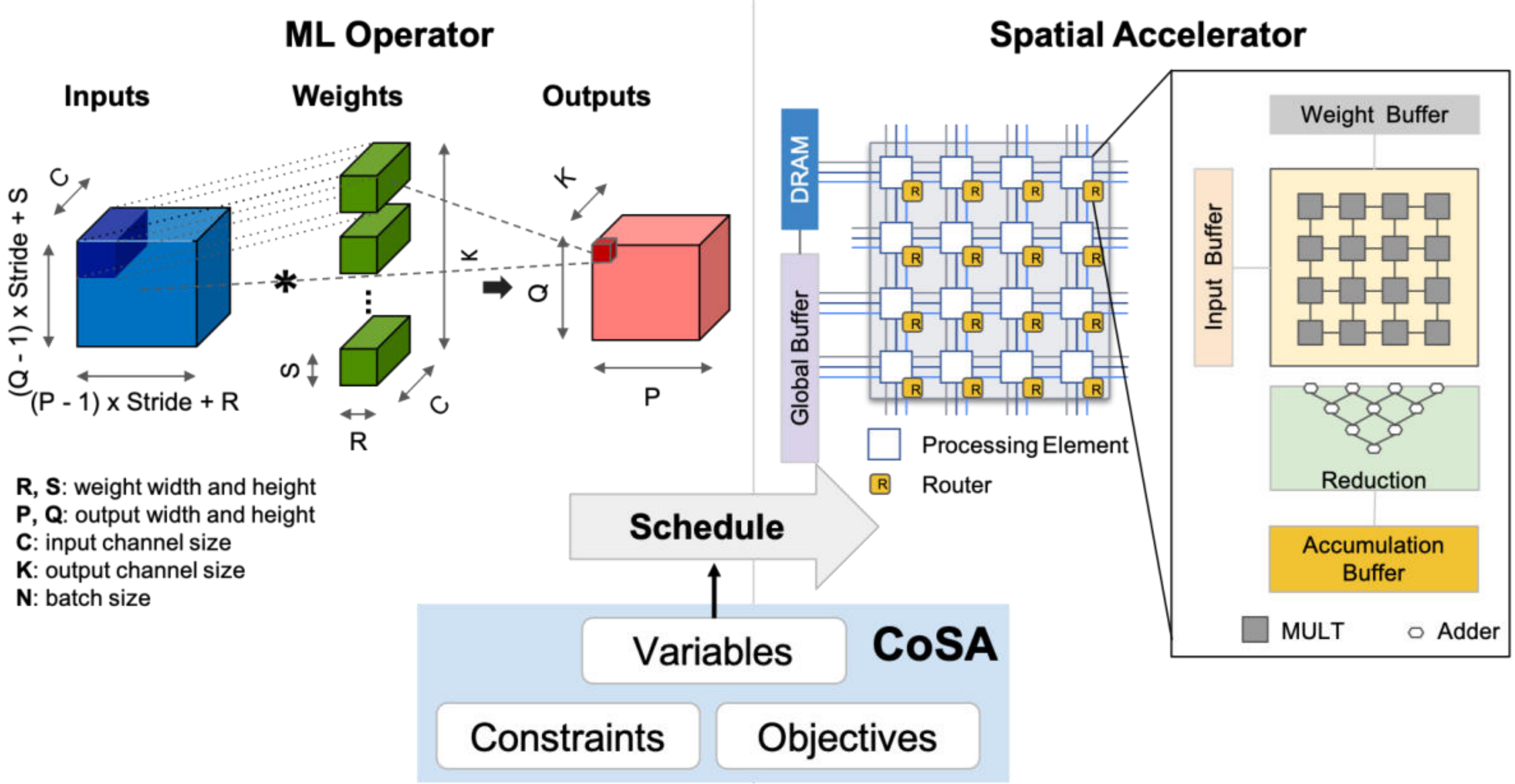


Scheduler	Search Algorithm
Brute-force approcahes:	
Timeloop	Brute-force & Random
dMazeRunner	Brute-force
Interstellar	Brute-force
Marvel	Decoupled Brute-force
Feedback-based Approaches:	
AutoTVM	ML-based Iteration
Halide	Beamsearch OpenTuner
FlexFlow	MCMC
Constrained Optimization Approaches:	
CoSA	**Mixed Integer Programming (MIP)**

Hardware

[ISCA'2021]

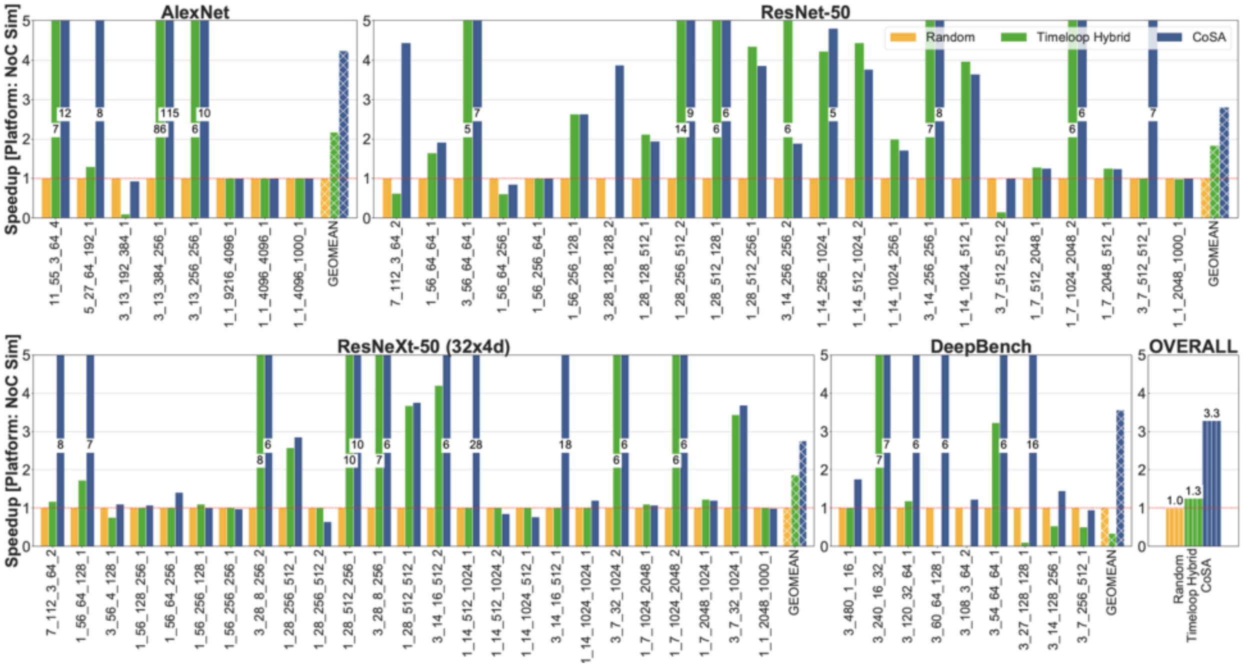
CoSA: Constrained-Optimization for Spatial Architecture



R, S: weight width and height
P, Q: output width and height
C: input channel size
K: output channel size
N: batch size

[ISCA'2021]

CoSA: Constrained-Optimization for Spatial Architecture



2.5x speedup compared to SoTA with 90x faster time-to-solution.

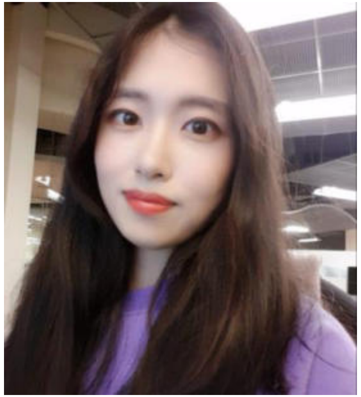
	CoSA	Random (5×)	Timeloop Hybrid
Avg. Runtime / Layer	4.2s	4.6s	379.9s
Avg. Samples / Layer	1	20K	67M
Avg. Evaluations / Layer	1	5	16K

[ISCA'2021]

Acknowledgement

Hasan Genc

Jenny Huang



Seah Kim

- Thanks collaborators from UC Berkeley and NVIDIA!

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