PowerPULP Hands-on Session

OPRECOMP at NiPS Summer School

Fabian Schuiki, Stefan Mach
ETH Zürich

July 16-20, 2018 in Perugia, Italy

This project is co-funded by the European Union's H2020-EU.1.2.2. - FET Proactive research and innovation programme under grant agreement #732631.

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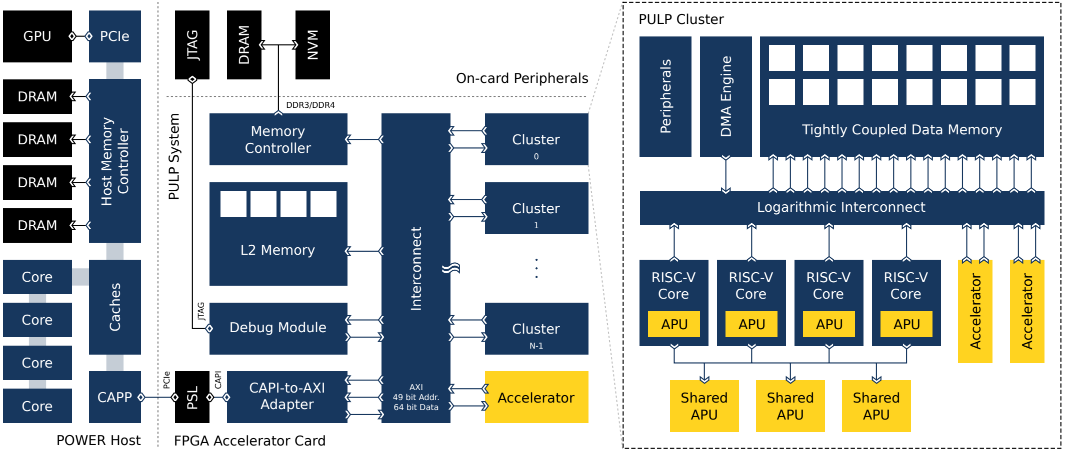
- Schedule:
  - 09:00-10:30 – PowerPULP (aka kW platform, *Fabian Schuiki, ETH*)
  - 11:00-12:30 – GAP (aka mW platform, *Francesco Paci, GWT*)

Introduction

The Big Picture



- Transprecision float unit (float8, float16, float16alt)
- NTX streaming processor (float32 now, others later)
- Dedicated accelerators?

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IBM POWER8 Minsky:

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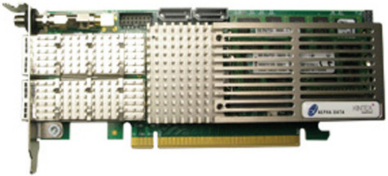
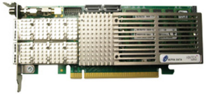
Accelerator Cards

Alpha Data 8K5:

Alpha Data KU3:



Accelerator Cards

		
	8KU	**KU3**
FPGA:	XCKU115-2-FLVA1517E	XCKU060-FFVA1156
CLBs	1451 k	726 k
DSP Slices	5520	2760
Block RAM	75.9 Mbit	38.0 Mbit
DRAM:	16 GiB DDR4-2400	8 GiB DDR3-1600
PCIe:	Gen3 x8	Gen3 x8
PULP Clusters:	4	2
Speed:	50 MHz	50 MHz
Where:	ETH/QUB	IBM Cloud

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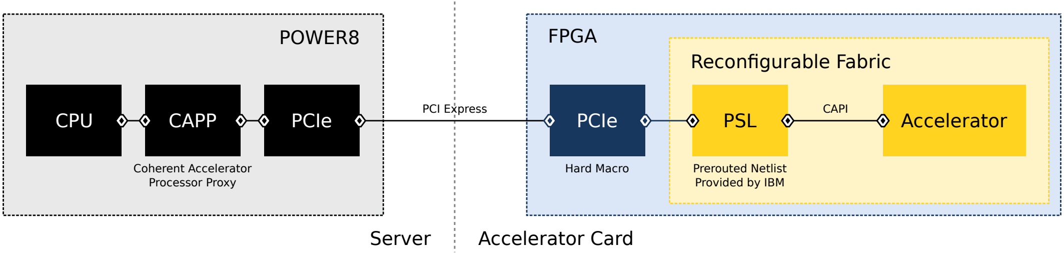
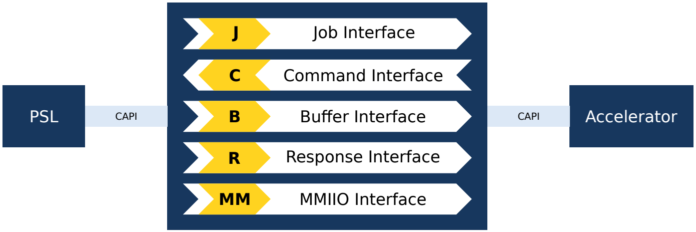


CAPI Channels

CAPI consists of five communication channels:

J: Job interface (reset, work element descriptor)



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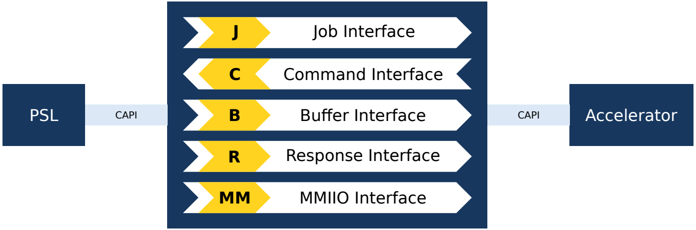

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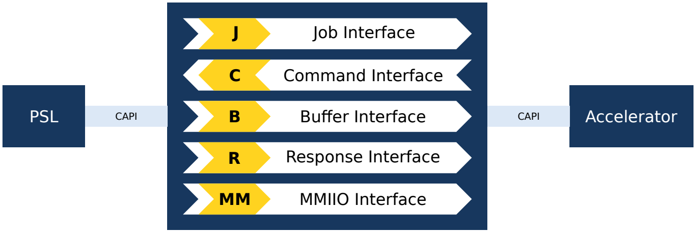

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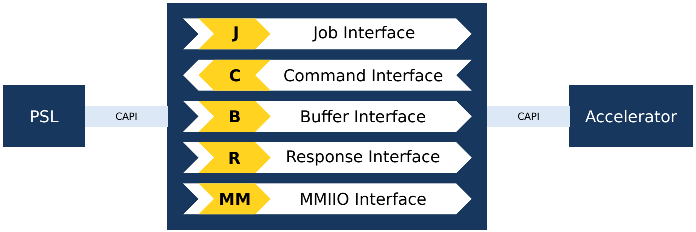

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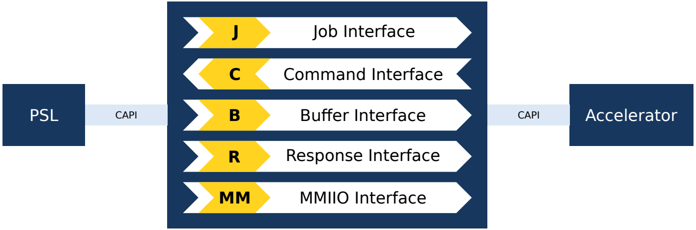
- MM: MMIO interface (side channel for configuration and register reading/writing)



Interaction with CAPI Accelerator on Linux

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Caution: Flashing requires working PSL on the FPGA; if a broken image is flashed, the card bricks → JTAG cable required to unbrick.

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- POWER8 has *limited access* to a few registers in the accelerator (CAPI MM).

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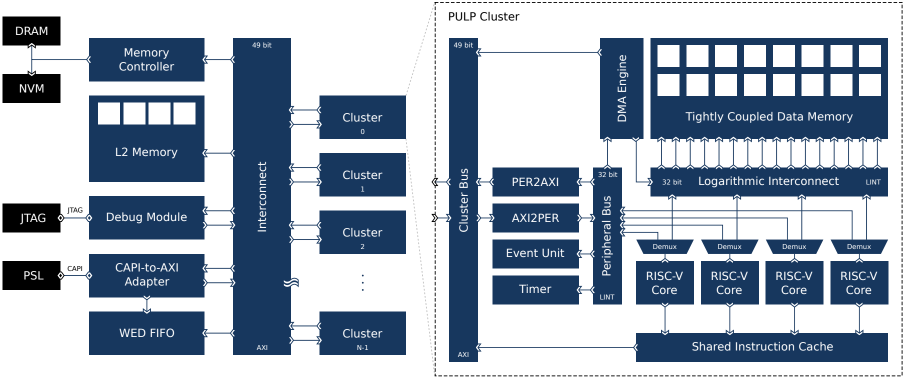
Integration of PULP and CAPI

- PULP system interconnect is AXI4-based



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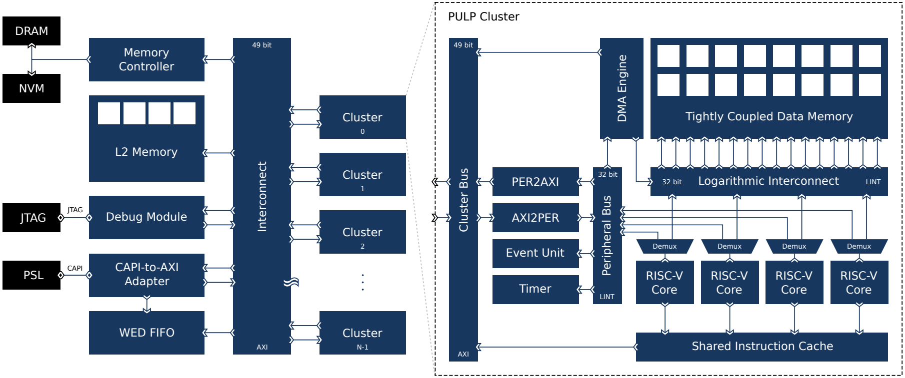
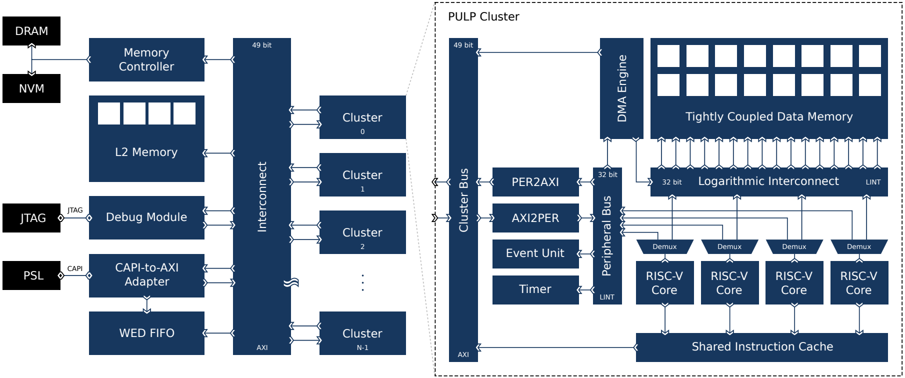
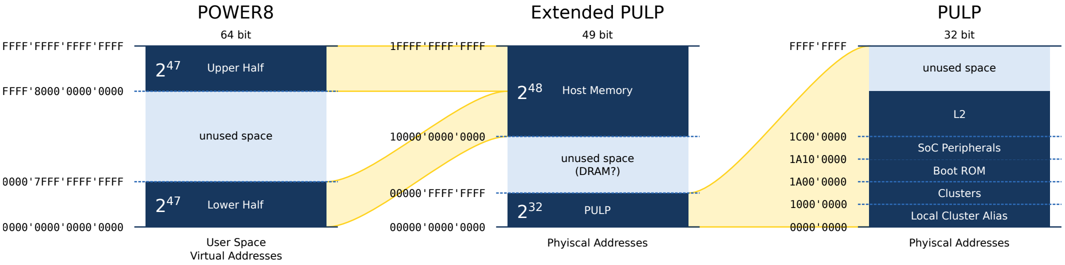


Integration of PULP and CAPI

- PULP system interconnect is AXI4-based
- *AXI-to-CAPI adapter* gives PULP access into POWER8 memory space
- Jobs from POWER8 are added to a *WED FIFO* where PULP can fetch them (woken up by interrupt)



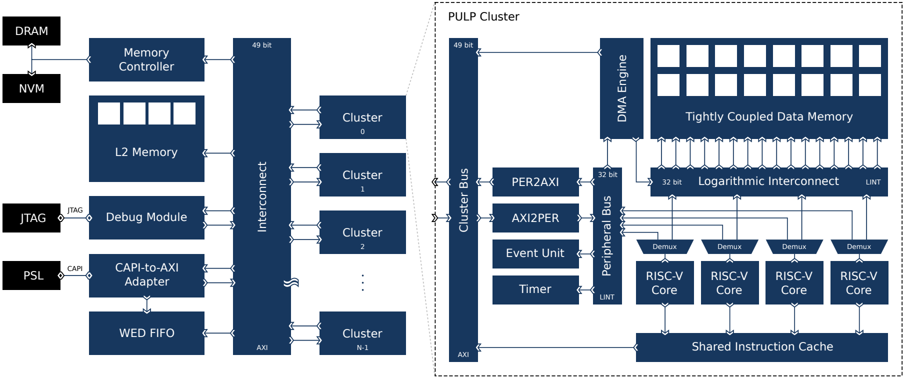
Memory Map



- POWER8 uses only lower 48 bits of address; upper bits sign-extension
- PULP itself is 32 bit (processors, clusters, peripherals)
- Selectively extend system-level interconnects to 49 bit
- MSB decides whether to access POWER8 or PULP memory
- Gained space in PULP memory can be used for on-board DRAM/NVM

PULP 32 bit vs 64 bit

- PULP RISC-V cores and cluster peripherals are 32 bit



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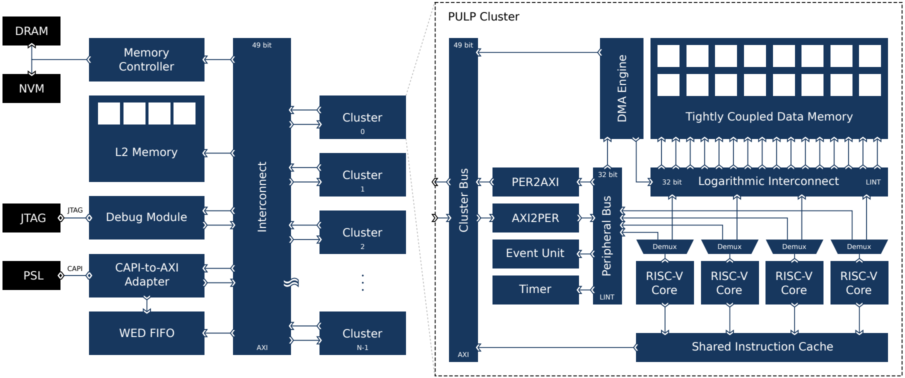
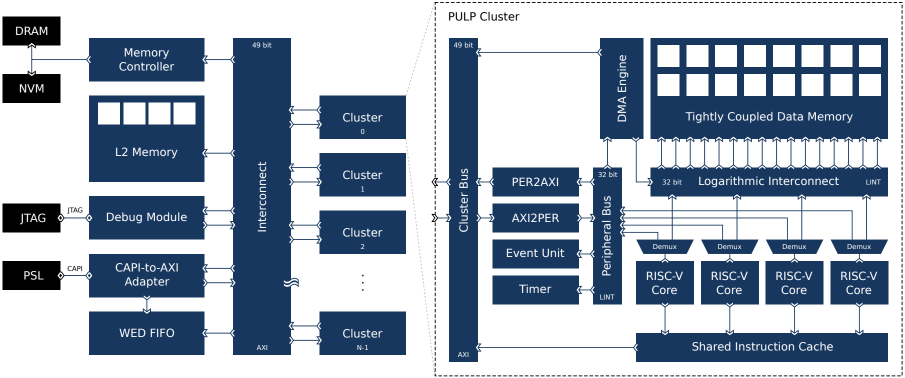


PULP 32 bit vs 64 bit

- PULP RISC-V cores and cluster peripherals are 32 bit
- DMA engine extended to support 64 bit
- **Caveat:** PULP cores cannot directly access POWER8 memory or DRAM; use DMA to copy data into cluster TCDM before crunching numbers



Offloading – How PULP Boots

- All cores start execution at the same internal address.
- Cores cannot directly execute code from host memory $\rightarrow$ kernel needs to be in PULP memory.
- Don't want to embed kernels into FPGA bitstream; would need to regenerate bitstream for every kernel change
- Embed a bootloader program into a ROM in the bitstream
- Send the PULP binary to execute with every WED
- Bootloader copies binary from POWER8 memory into PULP memory

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3. Copy section offsets and sizes into a *section table*, and create a new WED:

```
struct wed {
  struct sec *sec_ptr;
  size_t sec_num;
  void *wed; // WED to be passed to loaded binary
};

struct sec {
  void *src;    // host memory
  uint32_t dst; // PULP memory
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4. Send to PULP as WED; bootloader then copies sections

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2. Wait for a WED pointer (interrupt from job FIFO)
3. Copy WED from POWER8 memory into the scratchpad with DMA
4. Copy the section table from POWER8 memory into the scratchpad with DMA
5. Copy every section in the table from POWER8 to PULP
   - Copy section in chunks into buffer in scratchpad with DMA
   - Write chunk to appropriate destination address in PULP memory space with DMA

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5. Copy every section in the table from POWER8 to PULP
   - Copy section in chunks into buffer in scratchpad with DMA
   - Write chunk to appropriate destination address in PULP memory space with DMA
6. All cores jump to the start of the loaded binary

Offloading – liboprecomp API

We bundled the binary loading, parsing, and offloading code as a C library:

```
// liboprecomp

/* Binary loading and parsing */
opc_kernel_new          // create new kernel
opc_kernel_load_file    // parse binary from file
opc_kernel_load_buffer  // parse binary from memory
opc_kernel_free         // destroy kernel

/* Offloading onto PULP */
opc_dev_new             // create new device (= accelerator)
opc_dev_open_any        // open any device on the system
opc_dev_open_path       // open device by '/dev/cxl/...' path
opc_dev_launch          // offload kernel onto device
opc_dev_wait            // wait for completion of one kernel
opc_dev_wait_all        // wait for completion of all kernels
opc_dev_free            // destroy device
```

Wraps around *libcxl*, so this should be the only thing you need to interface with PULP.

Offloading – liboprecomp Usage Example

```
// Error handling omitted for brevity.
// (Shame on me!)
#include <liboprecomp.h>

// Load the kernel.
const char *elf_path = "hello_world";
opc_kernel_t knl = opc_kernel_new();
opc_kernel_load_file(knl, elf_path);

// Open any accelerator on the system.
opc_dev_t dev = opc_dev_new();
opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel

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opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel
2. Load kernel binary

Offloading – liboprecomp Usage Example

```c
// Error handling omitted for brevity.
// (Shame on me!)
#include <liboprecomp.h>

// Load the kernel.
const char *elf_path = "hello_world";
opc_kernel_t knl = opc_kernel_new();
opc_kernel_load_file(knl, elf_path);

// Open any accelerator on the system.
opc_dev_t dev = opc_dev_new();
opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel
2. Load kernel binary
3. Allocate new device

Offloading – liboprecomp Usage Example

```c
// Error handling omitted for brevity.
// (Shame on me!)
#include <liboprecomp.h>

// Load the kernel.
const char *elf_path = "hello_world";
opc_kernel_t knl = opc_kernel_new();
opc_kernel_load_file(knl, elf_path);

// Open any accelerator on the system.
opc_dev_t dev = opc_dev_new();
opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel
2. Load kernel binary
3. Allocate new device
4. Open device

Offloading – liboprecomp Usage Example

```c
// Error handling omitted for brevity.
// (Shame on me!)
#include <liboprecomp.h>

// Load the kernel.
const char *elf_path = "hello_world";
opc_kernel_t knl = opc_kernel_new();
opc_kernel_load_file(knl, elf_path);

// Open any accelerator on the system.
opc_dev_t dev = opc_dev_new();
opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel
2. Load kernel binary
3. Allocate new device
4. Open device
5. Offload kernel

Offloading – liboprecomp Usage Example

```c
// Error handling omitted for brevity.
// (Shame on me!)
#include <liboprecomp.h>

// Load the kernel.
const char *elf_path = "hello_world";
opc_kernel_t knl = opc_kernel_new();
opc_kernel_load_file(knl, elf_path);

// Open any accelerator on the system.
opc_dev_t dev = opc_dev_new();
opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel
2. Load kernel binary
3. Allocate new device
4. Open device
5. Offload kernel
6. Wait for completion

Offloading – liboprecomp Usage Example

```c
// Error handling omitted for brevity.
// (Shame on me!)
#include <liboprecomp.h>

// Load the kernel.
const char *elf_path = "hello_world";
opc_kernel_t knl = opc_kernel_new();
opc_kernel_load_file(knl, elf_path);

// Open any accelerator on the system.
opc_dev_t dev = opc_dev_new();
opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel
2. Load kernel binary
3. Allocate new device
4. Open device
5. Offload kernel
6. Wait for completion
7. Destroy device

Offloading – liboprecomp Usage Example

```c
// Error handling omitted for brevity.
// (Shame on me!)
#include <liboprecomp.h>

// Load the kernel.
const char *elf_path = "hello_world";
opc_kernel_t knl = opc_kernel_new();
opc_kernel_load_file(knl, elf_path);

// Open any accelerator on the system.
opc_dev_t dev = opc_dev_new();
opc_dev_open_any(dev);

// Offload a job and wait for completion.
uint64_t wed = 0xdeadbeeffacefeed;
opc_dev_launch(dev, knl, &wed, NULL);
opc_dev_wait_all(dev);

// Clean up.
opc_dev_free(dev);
opc_kernel_free(knl);
```

1. Allocate new kernel
2. Load kernel binary
3. Allocate new device
4. Open device
5. Offload kernel
6. Wait for completion
7. Destroy device
8. Destroy kernel

Example 1

Hello World

Let’s get started

Grab yourself a terminal, and:

```
cd; ./install.sh
```

Structure of the Examples

```
# tree
.
+-- host
|   +-- host.c
|   +-- Makefile
+-- Makefile
+-- pulp
    +-- Makefile
    +-- pulp.c

2 directories, 5 files
```

- `host`: contains the POWER8 code
- `pulp`: contains the PULP code
- `Makefile`:
  - calls `host/Makefile`
  - calls `pulp/Makefile`
  - emulates execution

Code – POWER8 Side

```
#include <liboprecomp.h>

int main(int argc, char **argv) {

  // Load the kernel.
  opc_kernel_t knl = opc_kernel_new();
  opc_kernel_load_file(knl, argv[1]);

  // Open any accelerator on the system.
  opc_dev_t dev = opc_dev_new();
  opc_dev_open_any(dev);

  // Offload a job and wait for completion.
  opc_dev_launch(dev, knl,
    (void*)0xdeadbeeffacefeed, NULL);
  opc_dev_wait_all(dev);

  // Clean up.
  opc_dev_free(dev);
  opc_kernel_free(knl);

  return 0;
}
```

1. Load PULP binary (argv[1])

Code – POWER8 Side

```c
#include <liboprecomp.h>

int main(int argc, char **argv) {

  // Load the kernel.
  opc_kernel_t knl = opc_kernel_new();
  opc_kernel_load_file(knl, argv[1]);

  // Open any accelerator on the system.
  opc_dev_t dev = opc_dev_new();
  opc_dev_open_any(dev);

  // Offload a job and wait for completion.
  opc_dev_launch(dev, knl,
    (void*)0xdeadbeeffacefeed, NULL);
  opc_dev_wait_all(dev);

  // Clean up.
  opc_dev_free(dev);
  opc_kernel_free(knl);

  return 0;
}
```

1. Load PULP binary (argv[1])
2. Connect to PULP on FPGA board

Code – POWER8 Side

```
#include <liboprecomp.h>

int main(int argc, char **argv) {

  // Load the kernel.
  opc_kernel_t knl = opc_kernel_new();
  opc_kernel_load_file(knl, argv[1]);

  // Open any accelerator on the system.
  opc_dev_t dev = opc_dev_new();
  opc_dev_open_any(dev);

  // Offload a job and wait for completion.
  opc_dev_launch(dev, knl,
    (void*)0xdeadbeeffacefeed, NULL);
  opc_dev_wait_all(dev);

  // Clean up.
  opc_dev_free(dev);
  opc_kernel_free(knl);

  return 0;
}
```

1. Load PULP binary (argv[1])
2. Connect to PULP on FPGA board
3. Run the computation

Code – POWER8 Side

```
#include <liboprecomp.h>

int main(int argc, char **argv) {

  // Load the kernel.
  opc_kernel_t knl = opc_kernel_new();
  opc_kernel_load_file(knl, argv[1]);

  // Open any accelerator on the system.
  opc_dev_t dev = opc_dev_new();
  opc_dev_open_any(dev);

  // Offload a job and wait for completion.
  opc_dev_launch(dev, knl,
    (void*)0xdeadbeeffacefeed, NULL);
  opc_dev_wait_all(dev);

  // Clean up.
  opc_dev_free(dev);
  opc_kernel_free(knl);

  return 0;
}
```

1. Load PULP binary (argv[1])
2. Connect to PULP on FPGA board
3. Run the computation
4. Offload kernel and wait (or do something else)

Code – POWER8 Side

```c
#include <liboprecomp.h>

int main(int argc, char **argv) {

  // Load the kernel.
  opc_kernel_t knl = opc_kernel_new();
  opc_kernel_load_file(knl, argv[1]);

  // Open any accelerator on the system.
  opc_dev_t dev = opc_dev_new();
  opc_dev_open_any(dev);

  // Offload a job and wait for completion.
  opc_dev_launch(dev, knl,
    (void*)0xdeadbeeffacefeed, NULL);
  opc_dev_wait_all(dev);

  // Clean up.
  opc_dev_free(dev);
  opc_kernel_free(knl);

  return 0;
}
```

1. Load PULP binary (argv[1])
2. Connect to PULP on FPGA board
3. Run the computation
4. Offload kernel and wait (or do something else)
5. Clean up

Code – PULP Side

```c
#include <stdint.h>
#include <stdio.h>

int main(uint64_t wed) {

  printf("Hello, World!\n");
  printf("You sent me me 0x%x\n", wed);

  return 0;
}
```

1. WED pointer passed to `main` as argument
2. A simple `printf` call
3. Print the pointer for reference (wed)

- Beware 64 bit and float caveats of the runtime for now!

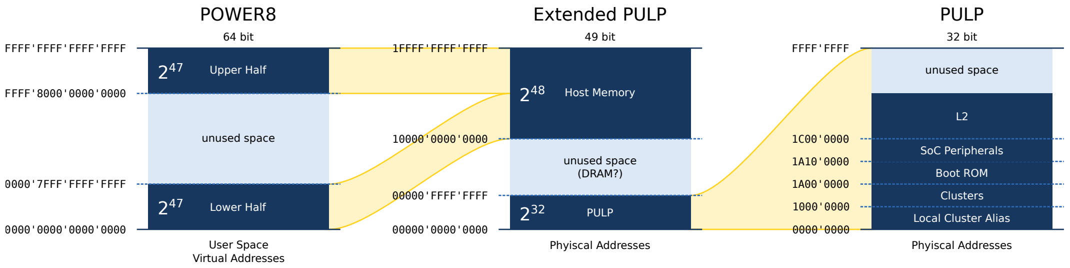
Your Turn!

1. **Goal:** Have PULP say hello
2. Boot into your virtual machine
3. **`cd`** `~/summerschool/ex1-hello`
4. Edit `host/host.c` and `pulp/pulp.c`
5. `make run`

Example 2

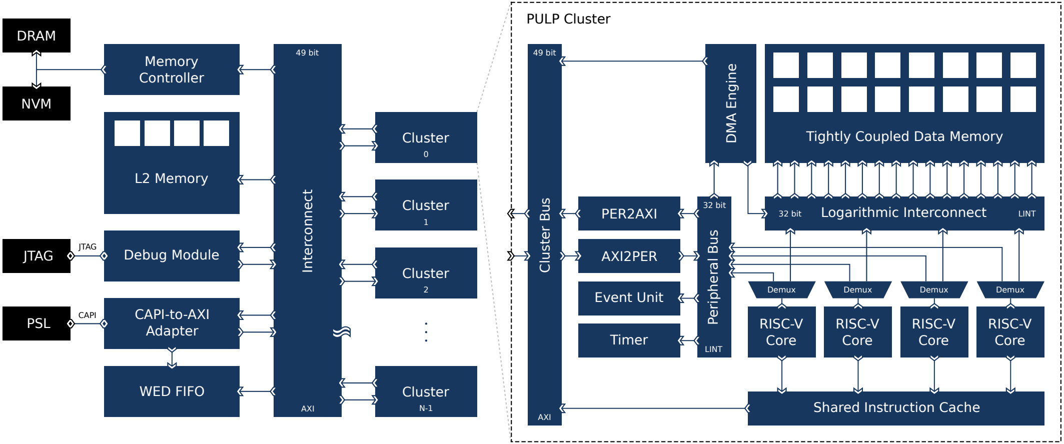
Data Movement

Memory Map



- PULP is 32 bit
- POWER8 is 64 bit
- POWER8 uses only lower 48 bits of address; upper bits sign-extension
- POWER8 memory mapped into upper part of 64 bit address space
- Cannot directly access its memory from PULP code
- **Solution:** Use the DMA!

Memory Hierarchy



- PULP cores operate directly on TCDM
- No direct access to host memory (32 bit limitation)
- DMA engine can do non-blocking copies
- L2 memory

Work Element Descriptors

- Only one 64 bit pointer can be passed to PULP
- memcpy requires at least:
  - source address
  - destination address
  - size of the block
- **Solution:** Work Element Descriptor
- Small struct prepared in POWER8 memory
- Contains all the information
- Pass WED pointer to PULP
- First step on PULP: Copy over WED from POWER8

```
// POWER8 side
struct wed {
  uint64_t num_words;
  float *input;
  float *output;
};

struct wed wed = { ... };
opc_dev_launch(dev, knl, &wed, NULL);
```

```
// PULP side
struct wed { ... };

struct wed wed;
int id = plp_dma_memcpy(
  host2local(wedptr), // remote
  (uint32_t)&wed,     // local
  sizeof(wed),        // size
  1                   // remote to local
);
plp_dma_wait(id);
```

Code – POWER8 / PULP

```
// Load binary
opc_kernel_new();
opc_kernel_load_file(...);

// Define WED
struct wed {
  uint64_t size;
  int64_t *input;
  volatile int64_t *output;
};
struct wed wed = { ... };

// Allocate input and output buffers
wed.input = calloc(...);
wed.output = calloc(...);

// Run PULP program.
opc_dev_new();
opc_dev_open_any(...);
opc_dev_launch(...);
opc_dev_wait_all(...);

// Check the results.
wed.input[i] == wed.output[i];
```

```
// PULP side
// Load Work Element Descriptor
struct wed wed;
plp_dma_memcpy(
  host2local(wedptr), // remote
  (uint32_t)&wed,     // local
  sizeof(wed),        // size
  1                   // remote to local
);

// Allocate a local buffer on PULP to
  hold the data.
void *buffer = malloc(wed.size);

// Copy data from host to buffer and
  back to host.
plp_dma_memcpy(..., 1);
plp_dma_wait(...);
plp_dma_memcpy(..., 0);
plp_dma_wait(...);
```

Your Turn!

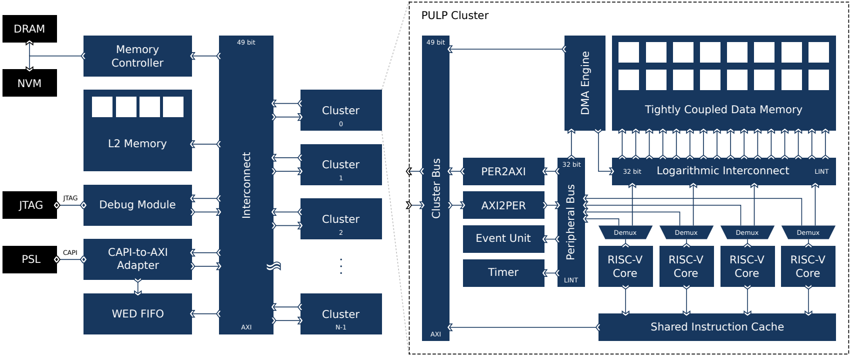
1. **Goal:** Offload `memcpy` to PULP
2. **`cd`** `~/summerschool/ex2-dma`
3. Edit `host/host.c` and `pulp/pulp.c`
4. `make run`

Example 3

Simple Computation

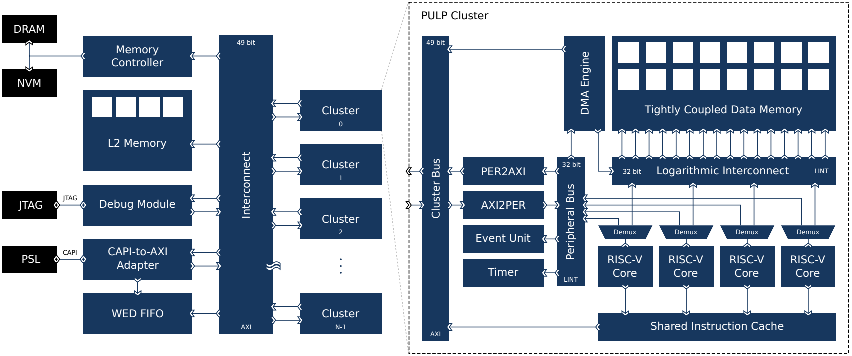
Let’s do some computation

- Last example moved data through PULP
- Opportunity to do some computation while we have the data
- Memory size limited; **how can we handle arbitrary amounts of data?**



Tiling

- Memory limited (64 kB L1, 256 kB L2)
- Data does not fit into fast small memories
- **Solution:** Divide input data into tiles
- Operate tile-by-tile
- In CPUs/GPUs the cache implicitly does this (but costs energy!)



Your Turn!

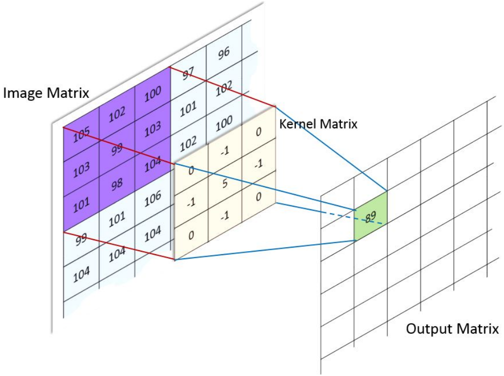
1. **Goal:** Implement a kernel that squares each value in an arbitrarily sized buffer
2. `cd ~/summerschool/ex3-square`
3. Edit `host/host.c` and `pulp/pulp.c`
4. `make run`

Example 4

Convolution

Convolution in 2D

- Very popular in Deep Neural Networks
- Usually: Apply a filter with local response to an image
- A kind of stencil operation
- $y = x * w$
- For example: Edge detection



$$w_{u,v} = \begin{pmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{pmatrix}$$

Code – Simple

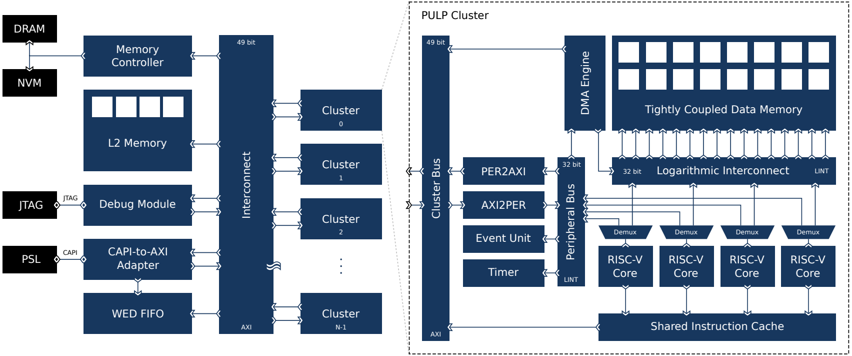
- Input/output image has 3 dimensions:
  - width M
  - height N
  - channels K
- Filter kernel has 2 dimensions
  - width V
  - height U
- 1 output pixel influenced by 9 input pixels
- Strategy:
  - Iterate over each output pixel (K,N,M)
  - Multiply-add pixels in the neighborhood (U,V)
- **Careful about zero-padding!**

```
float x[K][N][M];
float w[U][V];
float y[K][N][M];

for (int k = 0; k < M; ++k)
for (int n = 0; n < N; ++n)
for (int m = 0; m < M; ++m) {
  float a = 0f;
  for (int u = 0; u < U; ++u)
  for (int v = 0; v < V; ++v) {
    int n_ = n+u-U/2;
    int m_ = m+v-V/2;
    if (n_ < 0 || m_ < 0 || n_ >= N || m_ >= M)
      continue;
    a += x[n_][m_][k] * w[u][v];
  }
  y[n][m][k] = a;
}
```

Tiling

- Memory limited (64 kB L1, 256 kB L2)
- Data does not fit into fast small memories
- **Solution:** Divide input image into 2D tiles
- Operate tile-by-tile
- In CPUs/GPUs the cache implicitly does this (but costs energy!)



Code – Tiled

- Split image dimensions into tiles that fit into memory
- Tile size TS
- Process tile-by-tile
- Use the DMA's 2D transfer capability
- Assume image a multiple of the tile size

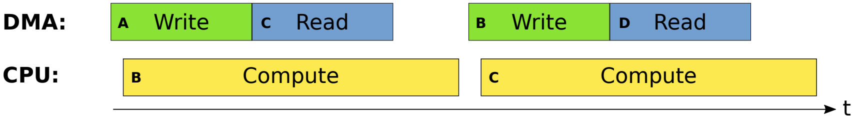
```
// ...
const int TS = 64; // tile size

for (int k = 0; k < M; ++k)
for (int n1 = 0; n1 < N/TS; ++n1)
for (int m1 = 0; m1 < M/TS; ++m1) {
  // Load tile here
  for (int n2 = 0; n2 < TS; ++n2)
  for (int m2 = 0; m2 < TS; ++m2) {
    float a = 0f;
    for (int u = 0; u < U; ++u)
    for (int v = 0; v < V; ++v) {
      int n_ = n1*TS + n2 + u-U/2;
      int m_ = m1*TS + m2 + v-V/2;
      // ...
    }
    y[n][m][k] = a;
  }
  // Store tile here
}
```

Double Buffering

- Overlay data movement and computation
- Hides latency of memory system
- Implicit in GPUs/CPUs, explicit in PULP
- Recipe:

1. Load input data (background)
2. Block and wait for DMA
3. Trigger last write (background)
4. Compute
5. Schedule write of output data



Double Buffering – Implementation

```c
static struct {
  void *src;
  uint64_t dst;
  size_t size;
} writeback = {
  .src = NULL,
  .dst = 0,
  .size = 0
};

void writeback_schedule(
  void *src,
  uint64_t dst,
  size_t size
) {
  writeback_trigger();
  writeback.src = src;
  writeback.dst = dst;
  writeback.size = size;
}
```

```c
void writeback_trigger() {
  if (writeback.size == 0) return;
  plp_dma_memcpy(
    host2local(writeback.dst),
    (uint32_t)writeback.src,
    writeback.size,
    PLP_DMA_LOC2EXT
  );
  writeback.size = 0;
}

// In your code:
for (int i = 0; i < N; ++i) {
  // load tile (1)
  plp_dma_barrier(); // (2)
  writeback_trigger(); // start write-back (3)
  // do computation (4)
  writeback_schedule(...); // schedule write-back (5)
}
writeback_trigger(); // final write-back
plp_dma_barrier();
```

Your Turn!

1. **Goal:** Implement a convolution filter
2. Use tiling to fit into memory
3. Use double buffering to hide latency
4. `cd ~/summerschool/ex4-conv`
5. Edit `host/host.c` and `pulp/pulp.c`
6. `make run`

Coming Soon

- Multicore & multicluster examples
- `float{8,16,16alt}` support in the virtual platform
- Transprecision unit in the actual hardware (FPGA bitstream)
- More examples as benchmarks get ported

- We're happy to help:

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`smach@iis.ee.ethz.ch`

- We'd love your input on API improvements!

Thanks! Questions?

OPRECOMP
Open Transprecision Computing