

RISCBoy Documentation

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1 Introduction

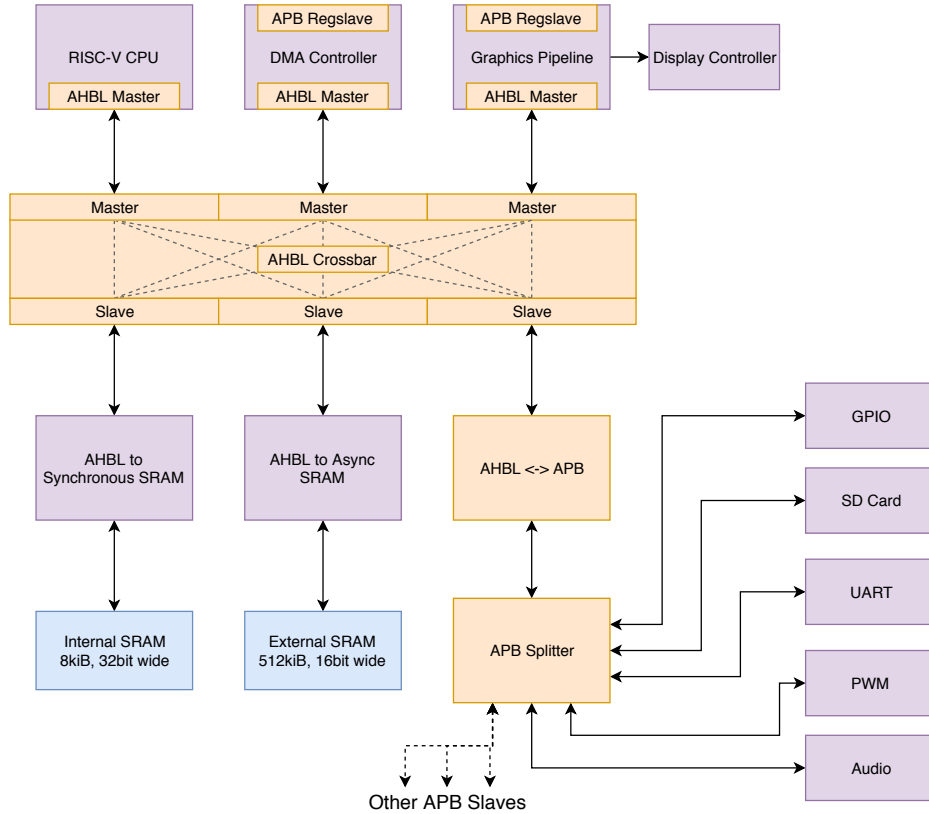
RISCBoy is an open source portable games console, designed from scratch:

- An open source CPU, graphics and bus architecture
- Based on the RISC-V open source instruction set
- FPGA synthesis, place and route with icestorm open source FPGA toolchain
- An open source PCB layout
- PCB designed with KiCAD open source PCB software
- It's open source

If you say open source one more time I'm gonna nut instantly - Oscar Wilde

1.1 Digital Design

Figure 1: System-level block diagram



The heart of the design is a Lattice iCE40-HX8k FPGA, containing 7680 LUT4s and flipflops. The logic was designed in synthesisable Verilog, with no dependencies on FPGA vendor IP; the contents of this GitHub repository could be taped out onto a chip. This includes:

- RV32IC-compatible 32-bit CPU design
 - RISC-V instruction set
 - 32I: base integer ISA profile
 - C: compressed instruction extension, for higher code density

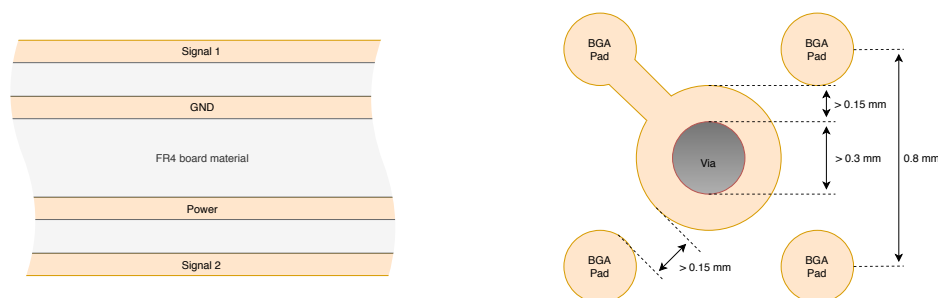
- Vectored interrupts (save/restore of PC, RA only)
- 5-stage pipeline, similar to textbook RISC
- Single AHB-Lite master port
- Graphics pipeline
 - Don't expect much, it's about as powerful as a Gameboy Advance
 - Includes some MODE7-like functionality which allows drawing perspective-mapped textured planes, by providing per-scanline affine texture transformation. Think MarioKart
- AMBA 3 AHB-Lite compatible multi-master busfabric
- Peripherals:
 - DMA master
 - External asynchronous SRAM controller (GS74116 or similar)
 - Display controller (ILI9341)
 - GPIO (bitbanging, peripheral muxing)
 - SD card controller
 - UART
 - PWM
 - Basic audio: voices + samples, noise-shaped PWM output

This document attempts to describe some of these, but if you need nitty-gritty detail, the best documentation is the files ending with `.v`.

That a free synthesis tool can cram this into one of the cheapest FPGAs on the market is tremendous. I hope for a situation like software compilers, where free tools such as GCC and LLVM are industry standards.

1.2 PCB

Figure 2: PCB stackup (left), and BGA-to-via critical clearances and dimensions (right)



The board has a 4-layer stackup, illustrated in figure 2. It targets low-cost PCB prototyping services such as iTead, and makes compromises to achieve this, chiefly escape routing from the FPGA (11×11 0.8 mm BGA). To meet iTead's copper-clearance, minimum via drill, and minimum annular ring specifications, the BGA pads must be sized down to 0.23 mm. Reflow this component by hand, with a hot air gun and plenty of flux; your toaster oven isn't going to cut it.

Schematic and layout files are in the `board/` subdirectory of the git repository.

1.3 Licensing

The Verilog source to this project has no dependencies, and is distributed under the DWTFPL version 3. This is a *very* permissive open-source licence, and its text is included in full at the top of the source files. This license is very similar to the original DWTFPL, which more readers may be familiar with, but has an added indemnification clause.

This license is also known by its more formal name, as the “Do What The Fuck You Want To And Don’t Blame Us Public License”.

2 CPU Architecture

Hazard5 is a 32-bit processor based on the RISC-V instruction set architecture. It accesses the system through a single AMBA 3 AHB-Lite master port. Those familiar with the textbook 5-stage RISC pipeline will find Hazard5 mostly straightforward, but hopefully will still find some interesting tricks. We will use the following symbols to refer to the 5 stages:

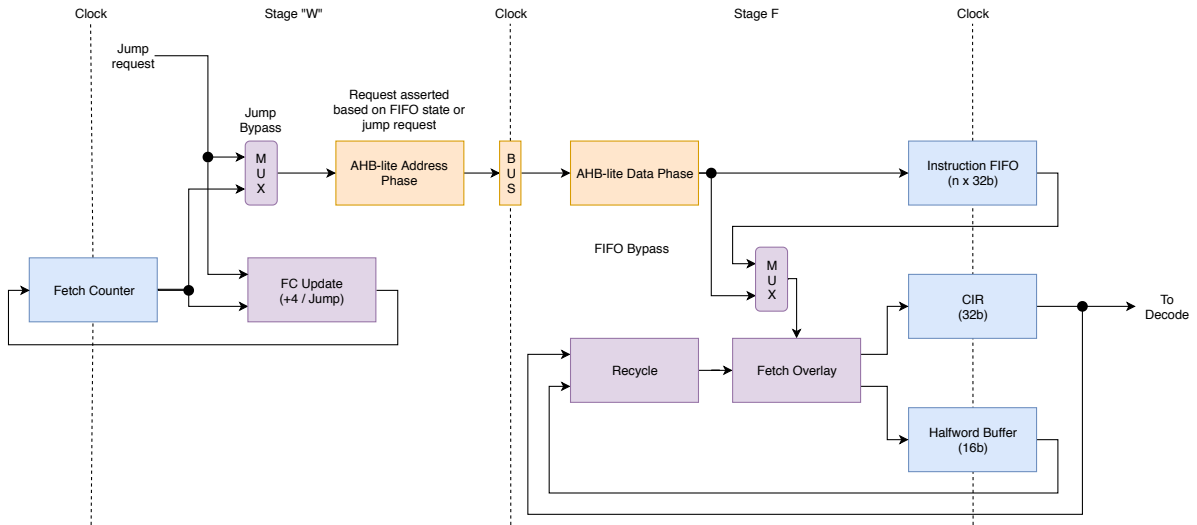
- F: fetch
- D: decode
- X: execute
- M: memory access (load/store)
- W: register writeback, fetch address generation

Hazard5 supports the RV32IC instruction set, whose encoding is variable-width. The C extension typically reduces instruction bandwidth by $\sim 25\%$, which helps to maintain performance when sharing bus access between fetch and load/store.

Branches are speculated, but there is currently no dynamic branch predictor. Instead, we use the static prediction scheme described in the RV ISA manual (based on sign of branch offset).

2.1 Frontend

Figure 3: Hazard5 processor frontend, block diagram



The frontend (figure 3) consists of stage F and an additional stage which performs the AHB address phase, and can be considered part of W. Its purpose is to feed D with instructions, whilst meeting the following constraints:

- No combinatorial path from AHB-Lite data phase to address phase (e.g. `hready` \rightarrow `htrans`)
- AHB-Lite compliant: no unaligned transfers, no deassertion or change of active requests
- Provide up to 32 bits of instruction data per clock in steady state, even if instructions are unaligned
- 0-cycle jump/flush to AHB address phase assertion (with minimal logic on this path)
- No performance penalty for unaligned jump to 16-bit instruction
- Attempt to maintain performance when competing with the load/store unit and AHB-Lite busmaster peers

The main source of complexity is that a RISC-V *C instruction stream is not naturally-aligned, i.e. instruction address modulo instruction size is not always zero. We spend gates here to optimise the common case of sequential execution, and to lessen the effects of fetch starvation due to load-store activity.

To meet these constraints, the frontend performs almost exclusively word accesses, which must be aligned. The only exception is a jump (or similar, e.g. mispredict recovery) to a non-word-aligned address. In this case, a halfword fetch from the target address is performed.

2.1.1 Prefetch Queue

The frontend queues up fresh instruction data which is waiting to be decoded. The pipelined nature of AHB-Lite means that the bus transfers run ahead of D by at least two clocks, and the prefetch queue is able to buffer these in-flight transfers if D stalls against a later pipe stage. The queue also decouples D's stall logic (which is a function of `hready`) from the address phase request, and finally, the queue helps keep D supplied with instructions while the busmaster is busy with load/stores from X.

There are three parts to the queue:

- A 32-bit FIFO. The depth is configurable, and can be as little as 1 word.
- A halfword buffer which may store the higher-addressed half of a recently-popped FIFO word
- The upper half of the current instruction register (CIR), if the previous instruction was 16-bit

These three sources should service the majority of instruction fetches, and fresh bus data is written only to the FIFO. However, following jumps, flushes, or fetch starvation (either due to load/store activity or bus wait states), bus data can be forwarded directly to CIR.

2.1.2 Program Counter

Hazard5 does *not* use the program counter (PC) for code fetching, during sequential execution. PC is used exclusively for the link value in JAL(R), mispredict recovery, and PC-relative addressing; it is physically located in D.

The frontend fetches instruction data from consecutive word-aligned addresses, paced by backpressure from the instruction FIFO; PC is not involved. However, as a special case, it *does* need the full jump target address (which becomes the new PC), as unaligned jumps require special attention.

2.1.3 Arbitration of Fetch and Load/Store

The single AHB master port asserts transactions from two sources: the frontend, whose address phase is in W, and the load/store unit, whose address phase is in X. Frontend requests may be linear or non-linear (e.g jumps). The rules are:

1. If a jump or mispredict recovery is asserted by M, this wins.
 - Any requests from earlier stages are logically later in program order.
 - If M wants to jump then these instructions are being executed in error, so should certainly not be permitted to access the bus.
2. Else if a load/store is asserted by X, this wins.
 - Stalling instruction fetch *may* be covered by the prefetch queue, in which case we've lost nothing
 - Stalling a load/store will always increase execution time
 - If instead X stalled, and instruction fetch ran ahead, what would we do with the fetched instructions?
3. Otherwise, perform any other access requested by the frontend.
 - Always Be Fetching

The fetch and load/store interfaces are well-decoupled; it would be simple to remove the arbiter and create a 2-master processor configuration. (TODO: add a wrapper that does this!)

2.1.4 Jumps and Branches

Due to the pipelined nature of AHB, we are unable to jump or to take branches in fewer than 2 cycles (without adding sophisticated prediction):

- Cycle 0: AHB data phase for fetch of jump/branch. Next instruction is in address phase concurrently.
- Cycle 1: Jump/branch instruction is now available to D
 - (Quickly) use to control the new address phase
 - The immediately following instruction is already in data phase
- Cycle 2: Data phase for jump target instruction
- Cycle 3: Jump target is presented to D and decoded.

We knew the jump target on cycle 1, but did not begin decoding the targeted instruction until cycle 3. We also made one wasted code fetch. This is suboptimal, but fetching the jump target *before* decoding the jump is tricky, and there are lower-hanging fruit in terms of performance per LUT.

Jumps physically occur in W, directly in front of the fetch address generator. There are two reasons to jump:

- Inspecting the CIR in F/D pipe register (JAL, speculated taken branches)
- Inspecting X/M pipe register (JALR, branch mispredict recovery)

JALR (indirect jump) is taken later because it uses the register file and the ALU to compute its target.

If both of these sources attempt to jump in the same cycle, X/M takes priority, since it is executing an older instruction. In both cases, the part of the pipeline in the hazard shadow is invalidated; i.e., $W \rightarrow F$, or $W \rightarrow X$. Invalidation is performed by clobbering the pipeline control signals in such a way that these instructions will have no side effects.

The branch prediction scheme is static: take backward branches, and do not take forward branches. The cycle costs are as follows:

Jump Type	Cycles (Execution + Penalty)
Direct jump	2
Predicted, non-taken branch	1
Predicted, taken branch (same as jump)	2
Indirect jump	4
Branch mispredict	4

Upon jumping, we need some mechanism to invalidate parts of the pipeline: this is described in section 2.2.2.

2.1.5 CIR Locking

There is a landmine in the following tableau:

- M contains a load (in data phase), and the bus is stalled
- X contains an instruction dependent on the load result; say an AND
- D contains a branch which is mispredicted taken

For example, say we are polling a status bit in an IO register, looping until some bit is high. The instruction in X must stall for at least two cycles due to the bus stall and load-use hazard. Due to a frontend design constraint from 2.1 – “No combinatorial path from AHB-Lite data phase to address phase (e.g. `hready` \rightarrow `htrans`)” – we must not use X’s stall signal to gate the jump request, as this would create such a path. However, *not* gating the jump request is fatal, as new fetches will clobber CIR before the branch instruction can proceed into X, so the mispredict will never recover. JAL has the same problem: it will jump, but not produce a link address.

Hazard5 resolves this with CIR locking. D signals to F that CIR and its validity count must not change on the next clock edge, and uses this same signal to inhibit repeated assertion of its own jump request. In the fetch path, this is achieved by steering the controls on the existing shift/overlay logic in the frontend, and requires no additional muxing.

Whilst the CIR is locked, the frontend is still free to act on the jump request, and fetch ahead along the new code path (more useful for JAL); this data is buffered in the FIFO. Once the roadblock ahead of D clears, the branch instruction proceeds down the pipeline, and the lock is released simultaneously.

Note also that a bus stall does not cause the frontend to block jump requests, as this too would create a combinatorial path, since requests are forwarded straight to the bus (due to another constraint from 2.1). The frontend's response to bus stall on jump request is simply to not increment the target before storing to FC, so that the target address continues to be asserted on subsequent cycles. Registered feedback blocks *subsequent* jump requests until the first request completes its address phase.

2.1.6 Instruction Barrier (FENCE.I)

If the program stores to instruction addresses about to be executed from, which potentially exist in the prefetch queue, a stale instruction will be executed. FENCE.I cannot be decoded as a nop, and requires special handling.

Hazard5 decodes FENCE.I as “jump to PC + 4”. The jump invalidates the prefetch queue, and the following instruction will be re-fetched from memory.

Timing analysis shows that calculating a jump target, between CIR and the address bus, is generally on the critical path. To avoid more logic on this path, FENCE.I is instead implemented by spoofing a branch-taken mispredict, which has the same effect. This adds two cycles to the execution time, but performance of this instruction is decidedly noncritical.

2.2 Backend

The backend is the hardware which manipulates the processor's architectural state according to the stream of instruction data from the frontend. Architectural state refers to the state you will read about in the ISA manual, and includes the register file and program counter; the backend also contains some non-architectural state, e.g. holding intermediate results in between pipeline stages.

The backend consists of stages D, X, M. Its overall structure is depicted by figure 4. This is a pretty large figure – too large to print really – so you can view it separately at https://github.com/Wren6991/RISCB0y/raw/master/doc/diagrams/cpu_backend.pdf

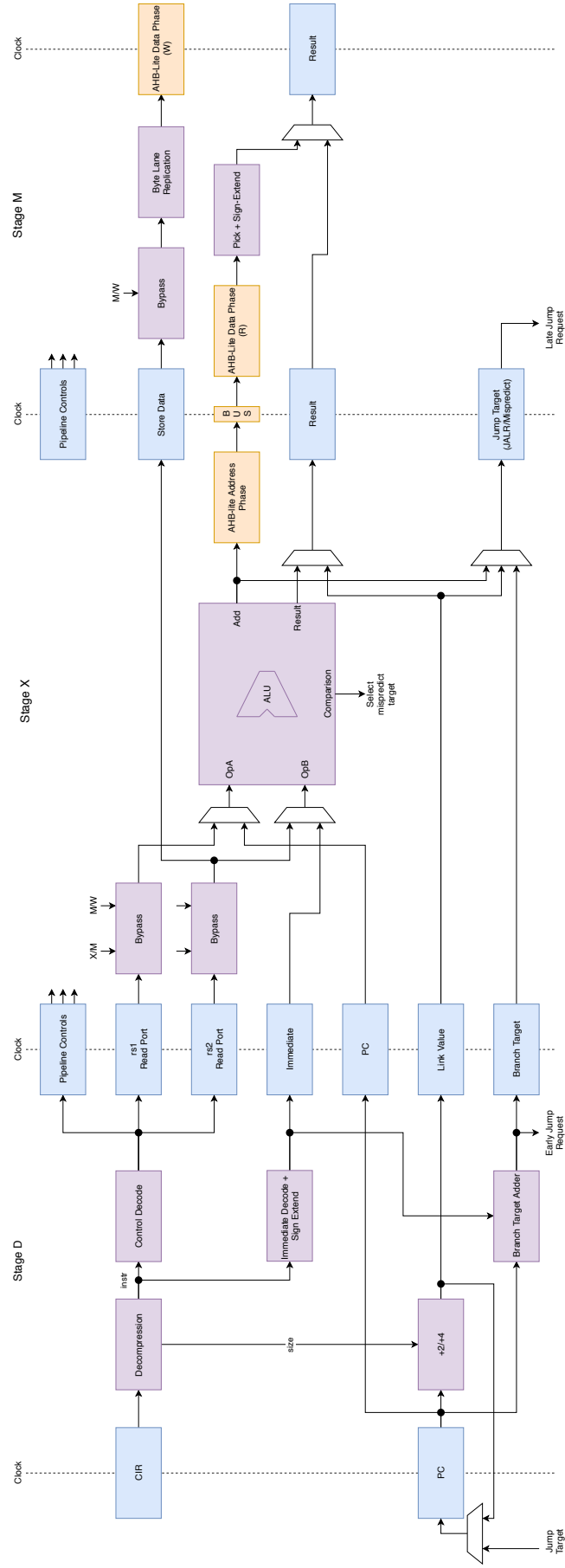


Figure 4: Hazard5 processor backend, block diagram

2.2.1 Operand Bypass

Hazard5 possesses an operand bypass (forwarding) network. Register writes must always be visible to later instructions, even before an earlier instruction reaches register writeback. One solution is to detect that one instruction depends on the result of an earlier instruction (a read-after-write, or RAW hazard) and stall the later instruction until the earlier one completes. This is safe, but incurs a hefty performance penalty; a more elegant solution is to pluck the result of the earlier instruction straight from the pipeline, before it finishes executing (but after the result is valid!).

Locations of bypasses are shown in figure 4. The following bypasses are available:

- $X/M \rightarrow X$
- $M/W \rightarrow X$
- $M/W \rightarrow M$
- $W/X \rightarrow X$

The last is in lieu of a write-to-read bypass in the register file; some tools (not Yosys!) struggle with inferring memories from transparent memory models, so it's better to be explicit.

To control the bypassing, some of the register specifiers from CIR are passed down the pipeline alongside the data. `rs1`, `rs2`, `rd` (operand sources and destination) are passed down as far as `X`. `rs2`, `rd` make it to `M`, and only `rd` makes it to `W`.

The upshot is:

- Back-to-back ALU operations execute at 1 CPI
- Loads insert 1 stall cycle if immediately required by the ALU. 1 CPI otherwise.
- Stores execute at 1 CPI (bus stall notwithstanding)
- In a load + store pair, the load takes only one cycle, since the `M` stage has self-forwarding

Various interesting strategies can alleviate load-use penalty in in-order pipelines, such as adding a second, “late” ALU in the `M` stage. In our case we judge this to not be worth the LUTs.

Another interesting strategy is to add muxing at the register file write port, to select which stage to retire from. This has the dual benefit of firstly simplifying the operand bypass, and secondly reducing dynamic power, since there is no need to pass data through unused stages (and they can be clock gated). Hazard5 does not use this strategy either – maybe the next project.

2.2.2 Pipeline Stalling and Flushing

Our terminology: stalling means a pipeline stage does not advance its state until some blocking condition has cleared. The instruction residing in this stage will not progress to the next stage, and the previous stage will not write *its* instruction into this stage. Flushing is when in-flight instructions in some stages are replaced with NOPs, and their results are discarded.

The frontend is decoupled from other stages’ stall logic via the prefetch queue. This is important: `hready` is an input to that stall logic, and the the frontend’s address-phase request must not be a function of `hready`.

The frontend may not be able to immediately accept a jump request, which may cause other pipe stages to stall if it is low. One cause is the frontend holding an existing address-phase request stable until the cycle *after* `hready`, which is required for AHB-Lite compliance.

For the backend, the stall logic is more intricate, as signals such as `hready` are used in-cycle to determine whether an instruction progresses to the next pipeline stage:

- `D`:
 - CIR does not contain a valid instruction (either no data, or half of a 32-bit instruction)

- D asserts jump, but frontend rejects the jump request
- X is stalled
- X:
 - `hready` low and X address-phase request asserted
 - RAW hazard on M (load-use)
 - M is stalled
- M:
 - `hready` low and data-phase active
 - M asserts jump, but frontend rejects the jump request
- W: does not stall

If a given stage is stalled, but the following stage is not, it must insert a bubble. Bubbles are created by zeroing out control fields, such as `rd`, so that the instruction cannot affect system or processor state.

There are two cases where we must flush:

- Branch/jump taken from D; frontend invalidates prefetched data
- Jump/mispredict taken from M; must flush frontend, D, X

And the flushing mechanisms for each stage are as follows:

- D: destination register `rd` cleared, which makes result invisible to register file and operand bypass. `memop`, `branchcond` pipe flags are cleared.
- X: same as D (except for `branchcond`, which does not pass on to M anyway).

Flushing and bubble insertion are very similar in mechanism.

2.3 Unaligned Memory Accesses

Alignment is the constraint that the address of a memory access be equal to zero, modulo some size. Where no size is specified, we refer to *natural* alignment, i.e. modulo the size of this particular memory operation. RISC-V requires that memory is byte-addressable.

The frontend goes to some length (section 2.1) to maintain high throughput. RV-C instruction streams are *always* unaligned, and *every* instruction must be fetched before it is executed, so Amdahl says it's worth it. On the other hand load/stores are less than 100% of all instructions, and the vast majority are unaligned; consequently, Hazard5 does not have hardware support for unaligned load/stores. These are trapped (TODO) and handled in software if and when they occur.

2.4 Control and Status Registers (CSRs)

Hazard5 possesses the standard `Zicsr` extension, which provides atomic access to the CSRs. Only M-mode CSRs are implemented. Access to an unimplemented CSR (e.g. a U-mode or S-mode CSR) causes an illegal instruction exception. The implementation is minimally legal: WARL fields are widely exploited, to reduce logic and state overhead. Module parameters can reduce CSR support, or remove it entirely, as per relative importance of compliance versus area in your application. Note that some features, such as interrupts and exceptions, require CSR support.

When the counter CSRs are present, `mtime` and `mcycle` are aliased to the same counter. 64-bit counters are prohibitively large in a compact 32-bit processor. The `mcountinhibit` (WARL) register is tied to zero: `mtime` must run freely, hence the `mcycle` alias of this counter cannot be halted either. `minstret` is fully implemented, but its `mcountinhibit` bit is also tied low. The width of the counters can be reduced from 64 bits to save logic (*noncompliant*), although the full 64 CSR bits remain writeable, which leaves some opportunity for software emulation.

TODO: full table of CSRs we implement, and to what extent they are implemented/WARL'd

2.5 Interrupts and Exceptions

Hazard5 has simple exception and interrupt support, compliant with the RISC-V privileged ISA spec (M-mode only). Here we follow the terminology set out in the RISC-V user-level spec: an *exception* is a condition caused by executing an instruction, which requires control transfer; an *interrupt* request is some external, asynchronous event, which requires control transfer; a *trap* is the transfer of control to a handler, used to service either an interrupt or an exception. Hazard5 implements interrupts and exceptions as follows:

- Trap entry causes a jump to a location in the trap vector table (addressed by `mtvec`), simultaneously stashing the PC in `mepc`
 - Other CSR state is also modified, e.g. `mcause`, `mstatus`
 - The physical mechanism for this jump is the same as a branch mispredict. This simplifies so-called invisible traps, which are fully synchronous with the instruction stream, and are required for some exceptions.
- Trap exit, via the `mret` instruction, causes a jump to `mepc`
 - `mret` also modifies some diagnostic CSR state, e.g. `mstatus`, as per the privileged ISA specification
- Only vectored mode is available. I.e., the LSBs of `mtvec` are tied to 0x1.
- When written, `mtvec` is rounded down to a 4kB boundary. This saves an adder when generating the trap vector address.
- Besides PC, the hardware saves/restores no architectural state on entry/exit. Software is responsible for stacking/unstacking the GPRs.

A custom M-mode CSR `mimsk0` is provided for masking interrupt requests (IRQs):

- `mimsk0` is located at address 0xbc0. Addresses 0xbc1...0xbc7 are reserved for more interrupt masks, for > 32 interrupts.
- One bit is provided per external IRQ. 1 = enabled, 0 = disabled
- All bits are 0 at reset
- Each IRQ has its own slot in the vector table

Trap handlers do not preempt one another. After a trap returns, the highest-priority active trap request is selected, and entered. Normal execution continues while there are no active trap requests. Exceptions take priority over IRQs, and lower-numbered IRQs are higher priority. An illegal instruction exception encountered while handling an illegal instruction exception causes a lockup of the core (details TBD). TODO: table of the exception/interrupt space

2.6 Plugin Interface

Plugins are pieces of hardware attached to the Hazard5 pipeline to extend its functionality, and instruction set. For example, the M extension (multiply and divide) is implemented using a plugin.

Plugins interact with three pipe stages:

- D
 - Plugins see the current instruction, so that they can decode it
 - Plugins notify D that an instruction it does not recognise is, in fact, valid
- X
 - Plugins can see the `rs1` and `rs2` operand bypasses

- Additional control signals provide functionality such as killing an in-progress operation so that e.g. an interrupt can run
- M
 - All plugins retire their results into M.
 - This adds a 1-cycle RAW stall if the immediately-following instruction is dependent, but on current iCE40 implementations, X is already near-critical-path and very mux heavy.
 - Plugins can stall M if they need more cycles to produce a result.

There is no hard limit to the number of plugins that can be added, but the additional muxing and fanout is not free, which constrains practical implementations.

2.6.1 M-small Plugin

The M-small plugin implements the RISC-V M standard extension (multiply and divide). To save area, the plugin employs a combined multiply/divide unit which performs the required calculations at 1 bit per clock.

2.6.2 M-fast Plugin

The Mfast plugin also implements the M extension, but uses a fast Wallace tree to perform multiplication, allowing a throughput of 1 32-bit multiply per clock.

Other details TBD

3 Pixel Processing Unit (PPU)

WARNING: This section rambles incoherently over a piece of hardware that does not yet exist, marking a complete departure from the preceding documentation

Figure 5: Pixel processing unit, block-level diagram

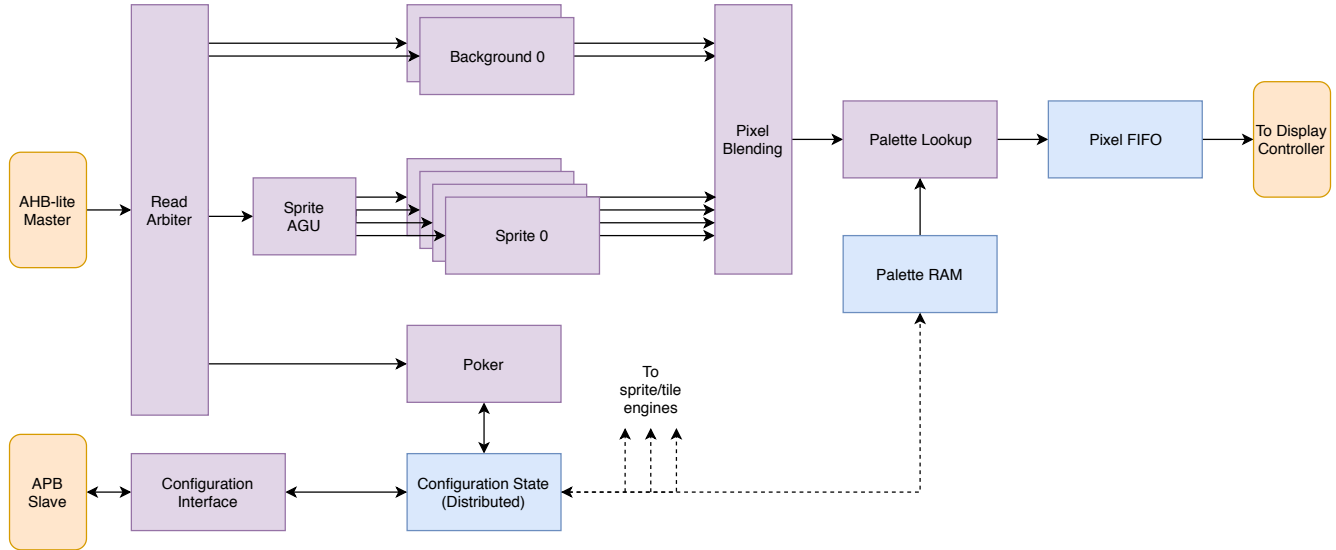


Figure 5 shows the high-level structure of the PPU. A number of independent sprite and background engines stream tile and pixel data from system memory, each producing a pixel stream which is continuous in the case of the backgrounds, and generally sparse in the case of sprites. These multiple streams are blended according to transparency and layer order. Finally, any paletted pixels are looked up in the shared palette RAM, to produce full-colour pixels for the display.

The PPU makes no assumptions about display timing: for example, RISCBoy is currently equipped with a 320×240 SPI LCD, which is driven continuously, with no horizontal or vertical blanking periods, as the SPI interface is the framerate bottleneck. The PPU continuously generates pixels at some rate which is hopefully higher than the display scan rate, and its timing is decoupled from the display via the pixel FIFO (as this is the narrowest point of the PPU, so the cheapest to buffer).

A key feature is the Poker: this is a simple raster-synchronised coprocessor that allows the PPU to modify its own configuration with pixel-perfect timing, enabling advanced rendering tricks such as in-scanline sprite multiplexing.

3.1 Pixel Formats

Internally, the PPU uses a single native pixel format, namely ARGB 1555 (see figure 6), but to save bandwidth, the PPU can stream pixels from memory in a variety of formats, and convert internally. These range down to 1 bit per pixel, for both sprites and tiles. PPU memory accesses are **always little-endian**: for performance reasons the PPU performs the widest possible fetch, yielding multiple pixels each, which are numbered least-significant-first.

Background pixel format is configured per-background; sprite pixel format is configured globally.

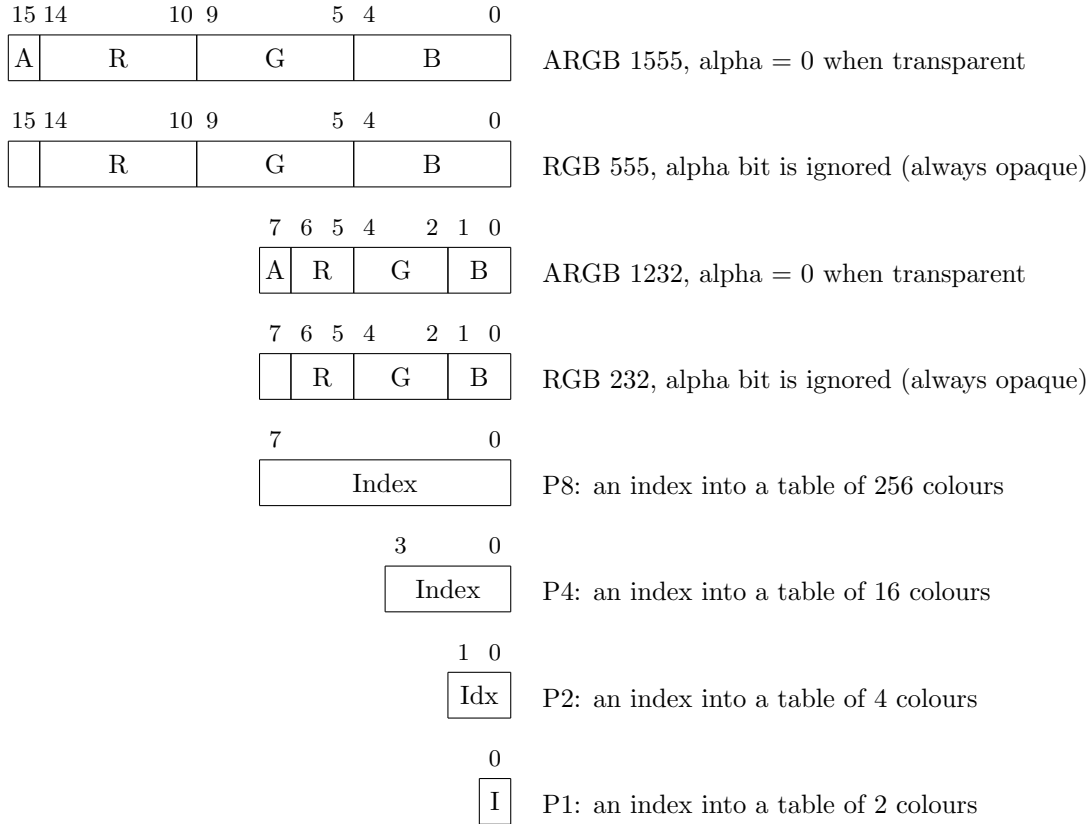
For pixels smaller than one byte, the pixel order continues to be defined in a little-endian fashion, i.e. the least-significant pixel will be the first to be displayed. There is an additional constraint that all pixels be naturally aligned in memory. That is, pixel address modulo pixel size is zero.

A paletted pixel is transparent if:

- The colour index is 0, and
- Transparency is enabled for that pixel source

So at e.g. 1 bit per pixel, it is possible to have either 2 colours, or 1 colour plus transparency. It is important

Figure 6: PPU pixel formats



that the transparency of a pixel is known as early as possible: this enables the PPU to perform layer composition before palette lookup, so only one palette lookup per *screen* pixel is required.

3.2 Palettes

The PPU contains a single hardware palette memory (PRAM). The PRAM is large enough to store 256 colours in RGB 555 format. Each pixel in a paletted image (see figure 6) consists of an index into PRAM. The PPU looks these indices up before passing pixels to the screen; wide colour range is maintained at reduced bits per pixel.

Although there is only a single hardware palette, 256 colours in size, backgrounds and sprites can index this palette at an offset. PRAM may be initialised with e.g. multiple 16-colour tables at different (potentially overlapping) locations, giving effectively independent palettes.

PRAM can be addressed through the PPU's configuration interface, for configuration by the system. The PPU has priority access to the PRAM, so attempting to access PRAM during drawing may cause a lengthy stall. As with all PPU configuration state, it can also be updated by the Poker, using a *poke* instruction; under ideal conditions the PPU can completely replace PRAM contents in 257 cycles.

3.3 Layers

Each background, and each sprite, can be individually assigned a layer number in the range $0 \leq n < N$, where N is the layer count (configurable). The number of layers is wholly independent from the number of sprites, backgrounds, etc., and may be as little as 1. For each blended pixel, the blender observes non-transparent pixels from each source (sprite or background), and applies the following rules:

- If there are no input pixels, output the display background colour.
- Else output the pixel with the lowest layer number

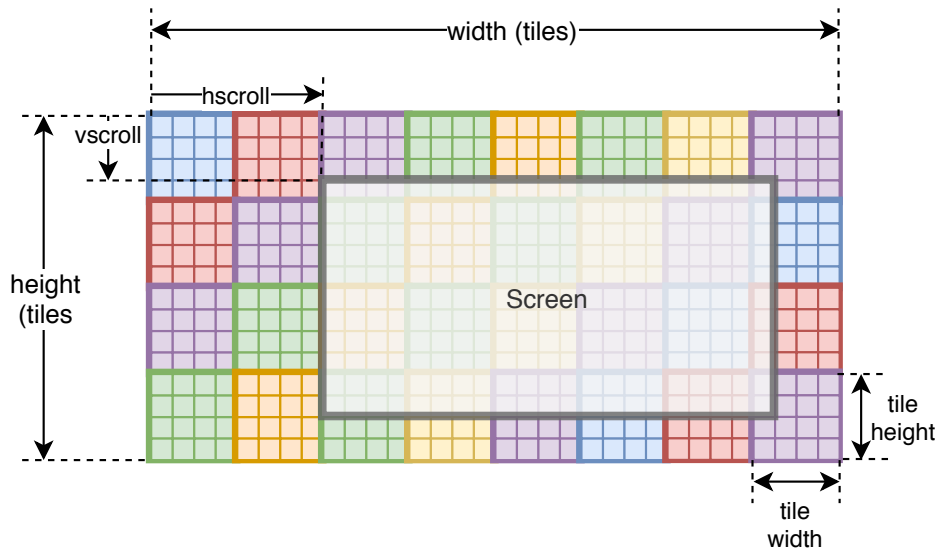
- If there are multiple pixels on the same layer:
 - Sprites beat backgrounds
 - Lower-numbered sprites beat higher-numbered
 - Lower-numbered backgrounds beat higher-numbered

Layer number can be thought of as depth into the screen. X is positive to the right, and Y is positive downward, so in a right-handed coordinate system, Z would be positive into the screen.

3.4 Backgrounds

Backgrounds are composed of tiles. Tiles are composed of pixels.

Figure 7: PPU background coordinate system



Each tile is a square image, the width and height of which (measured in pixels) is configured per-background, and is always a power of two. Tiles are stored in memory in a packed format: each tile is a sequence of pixels starting at the top left, proceeding left-to-right, then top-to-bottom. A region of memory packed with a series of tile images will be referred to as a *tileset*. All images in a *tileset* are the same dimensions, and have the same pixel format.

The background itself is defined by:

- A width and height, in tiles.
- A pointer to a *tileset*. The pointer is aligned to a one-tile boundary. The *tileset* contains up to 256 tiles.
- A pointer to a *tilemap*. The *tilemap* is $width \times height$ bytes in size, and byte-aligned.

For each pixel on the screen, the *tilemap* tells the PPU which tile should be at that location, and the corresponding tile image in the *tileset* tells the PPU the colour of each pixel in that screen tile.

The screen origin is offset into the background by configuring the horizontal and vertical scroll. This allows the game view to move smoothly over a fixed background. If the screen area overhangs the background, coordinates are wrapped. Unfortunately, the physical dimensions of the screen cannot be modified at run time.

3.5 Sprites

Sprites are small images which can be displayed at arbitrary screen coordinates; for example, the player character.

3.6 Pixel Gearboxes

One design challenge the PPU faces is the high ratio of data bus width to smallest pixel size (32:1). Another is the wide variety of pixel sizes (16 \rightarrow 1 bits). Consequently, to make efficient use of the bus, sprite and tile engines must be able to capture the result of one bus read, and parcel it out over a number of clock cycles.

A naive but effective implementation is a databus-sized register with mux taps to perform shift-by-16, shift-by-8, and so on, for each pixel size. Unfortunately, this is much too large – around 120 LUTs on iCE40, if you include the extra mux for loading bus data. Savings can be made by noting we can trash data which will not reach the end (e.g. no need to zero the top half on a shift-by-16), but it is not enough for a component which will be in every sprite and tile engine. The number of taps could be reduced, but this carries a performance cost.

To improve on this, the key observation is that the total shift count will always be 0, modulo the pixel size. Put differently, every shift starts on a bit boundary aligned to at least the size of that shift.

The hardware scheme used by the pixel gearbox is:

- There is a register the same size as the databus.
- The left half of this register can be copied to the right half
- This continues recursively, to the right:
 - The left half of the right half can instead be copied to the right half of the right half
 - The left half of *this* can instead be copied to the right half of this
 - So on, down to one bit

This is dramatically smaller, because the number of mux taps is exponentially distributed over the bits: half of the flops have no taps, a quarter have one, an eighth have two, and so on. (Ignoring the tap used for loading all flops from data bus.) On iCE40 this is 40 LUTs per gearbox, for a 32 bit databus and 1 bit minimum pixels.

Figure 8: Pixel gearbox, shift-by-8

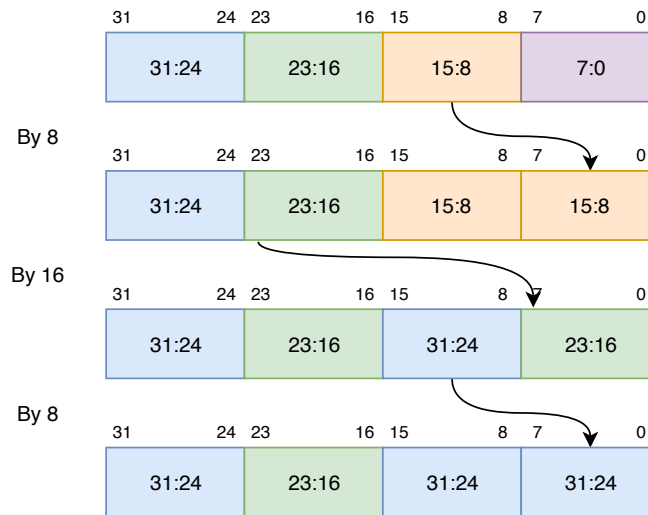


Figure 8 shows the sequence for shifting 8-bit pixels through the pixel gearbox. Note that the time-ordered sequence of pixels down the rightmost column is the same as the right-to-left sequence in the top row (recall pixel order is little-endian). All of the shift sizes are possible; proof is left as an exercise!

Based on the above observation about naturally-aligned boundaries, there is a very satisfying way of generating the control signals for the gearbox:

- Initialise a counter
- Every clock, the counter increments by the shift amount

- The next counter value will always have exactly one bit set which is not set in the current counter value (this is a property of counters)
- The weight of this bit is equal to the copy stride of the gearbox for this cycle

I.e. `shamt = ctr_next & ~ctr`. In figure 8 the counter values would be 0b00000, 0b01000, 0b10000, 0b11000, hence the strides are 8, 16, 8.

Note that this control scheme also allows rapid (log-time) seeking to arbitrary offsets, by adding first the MSB of the offset to the counter, then the next bit, and so on. This maintains the invariant that we are aligned to a shift-sized boundary, since we have sorted our shifts in descending size order.

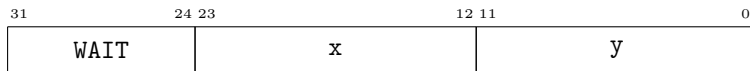
3.7 Poker

The Poker is a programmable component of the PPU, inspired by the Amiga Copper. It allows the PPU to manipulate its own controls, with pixel-perfect timing. There are no restrictions on when this takes place, or what is changed.

This enables acrobatic feats such as multiplexing a single sprite back-to-back down a scanline. However, Poker execution does have a performance cost, as Poker instructions are fetched through the same memory interface as pixel data. Reconfiguring some pieces of hardware (e.g. a background engine) mid-scanline may trigger flushing of that hardware, which is also wasteful. Overuse may cause missed pixels.

Poker instructions reside in main system memory. Instructions are documented below. The instruction set is designed to be simple to decode and simple to generate dynamically, not to have high code density!

WAIT

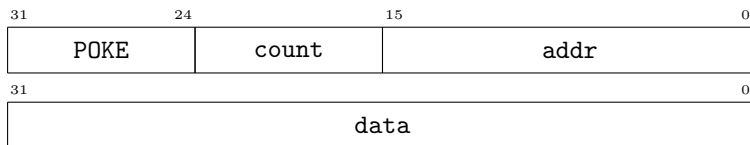


Suspend execution, resuming immediately before pixel (x, y). For example `WAIT 0, 0` will halt Poker execution until the start of the next frame. The Poker should generally spend most of its time in a suspended state, as it blocks pixel data fetches while it is executing.

Setting x or y to the all-ones bit pattern means “any”. For example, the Poker may scan a block of sprite configuration at the start of every line, or change background colour at a certain point on every scanline.

Any pixels before (x, y) are unaffected by any changes the Poker may make. Once the Poker finishes poking, and goes back into the `WAIT` state, all pixels after this point (inclusive of (x, y) take the new values into account.

POKE



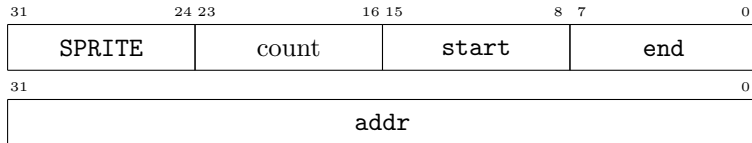
Write `data` into the PPU’s configuration address space, starting at `addr`. The `data` payload is `count + 1` words in size. Absolutely any state can be modified, but beware that each pixel engine (sprite or background) will perform a reload when relevant config is written to.

For example, a background may have its tileset `POKEd` at a certain point in each scanline, if there is a menu on the side of the screen which uses a font tilemap to draw text.

Some `POKEs` are more expensive than others: it is possible to change the vertical scroll for every single pixel along a scanline, and this will produce the expected image. However, scrolling the screen invalidates the state of all sprites and backgrounds, which may cause slowdown if done too often.

Note that the Poker’s program counter is mapped into the configuration address space; `POKE` can be used to perform jumps.

SPRITE



Scan through **count** sprite configuration words starting at **addr** and assign them to sprites in range **start...end** if they intersect the current scanline. Disable remaining sprites. Stop scanning if **end** is reached. If the display has a horizontal blanking period, this is the ideal time to perform **SPRITE** scanning. This instruction is implemented with hardware already present in the PPU, so presents little extra cost.

This mechanism is similar to GameBoy OAM search. The effect is that the user can define a large number of virtual sprites – more than are available in hardware – and the PPU can draw all of these, as long as the number of sprites on one scanline is not greater than the hardware sprite count.

Alternatively, sprite allocation can be performed by software, and the sprites updated using a **POKE** instruction. The **POKE** approach is more flexible, and makes it easier to multiplex hard sprites within a single scanline.

SKIP



Skip the following instruction, if the beam has reached some point. Full details TBD. It might be better to provide a conditional jump with a target, because not all of our instructions are the same length (especially **POKE**)

This allows Poker loops to be programmed, and makes the wait wildcard values much more useful.

4 Bus Fabric and Memory Subsystem

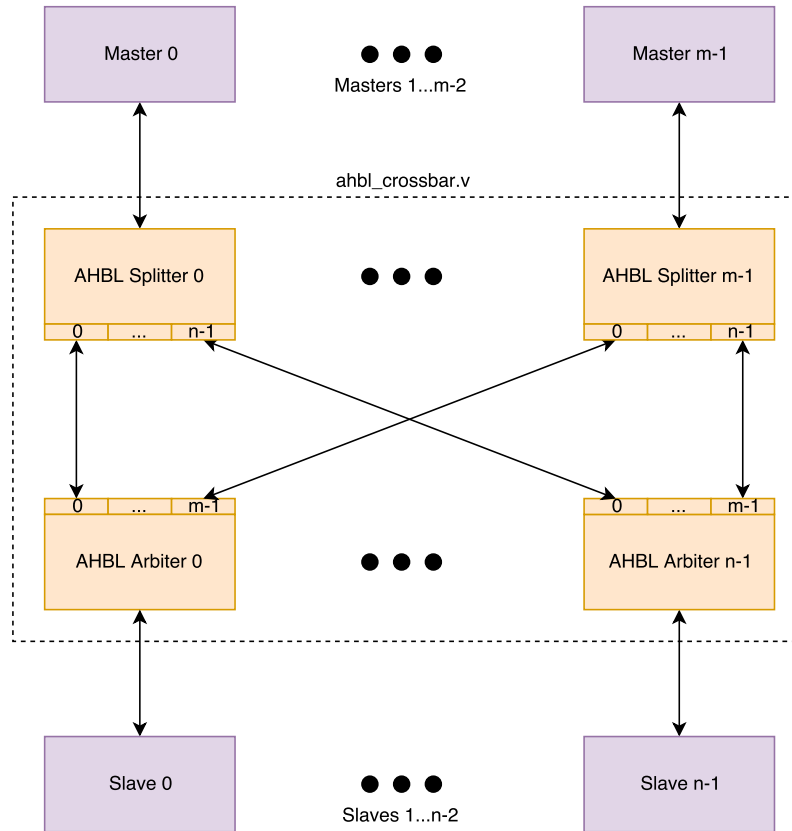
Bus fabric is digital plumbing. A master, such as a processor, requests a read or write on some address; the bus fabric routes the request to the correct slave device, and routes the response back. RISCBoy implements two bus fabric standards:

- AMBA 3 AHB-Lite connects masters to high-performance devices such as SRAM controllers
- AMBA 3 APB connects to simple devices such as a UART

Figure 9 shows the structure of the AHB-Lite crossbar (`ahbl_crossbar.v`). The crossbar is shown in context in figure 1. An independent AHB-Lite datapath connects each of m masters to each of n slaves. One master can address one slave at a time, and one slave can be in data-phase with one master at a time; subject to these constraints, up to $\min(m, n)$ independent transfers can take place in a single machine clock cycle.

Some claim AHB-Lite does not “support” multi-master arbitration. Their problem is a lack of enthusiasm: motorbikes do not “support” wheelies by design, but are excellent at it.

Figure 9: AHB-Lite crossbar, module-level block diagram



Each master is under the illusion that it is the only master in the system, but that slaves sometimes take longer to respond. During this waiting period, the slave may actually have fielded multiple transactions from higher-priority masters; this interaction is handled by the slave’s AHB-Lite arbiter, and is transparent to the masters.

One of the crossbar’s slave ports is attached to an AHBL-APB bridge. This bridge appears as a slave to the AHB portion of the bus fabric, and as a master to the APB portion. There are three main benefits to this scheme:

- APB is fundamentally simpler
 - This keeps peripheral gate count down
 - The peripherals on the APB bus do not need the full AHB-Lite bandwidth anyway

- Fewer AHB-Lite slaves
 - There is a nonlinear area scaling associated with adding slaves to the AHB-Lite fabric
 - This would also add extra gate delays to a fairly critical data path
- One APB master
 - AHB-Lite masters get arbitrated down to one inside the AHB-Lite crossbar. APB slaves do not care who is addressing them.
 - Different masters accessing different APB slaves will have to queue to use the bridge, even though they could theoretically proceed simultaneously
 - However, area/complexity vs performance tradeoff is more than worth it for slow peripherals
 - Multi-master APB is easy to implement, but never used in practice, due to the above tradeoff

The splitter and arbiter modules in the AHB-Lite crossbar can also be used on their own. Arbitrary multi-layer busfabric topologies should be possible with these two components.

Currently, the RISCBoy busfabric does not support AHB-Lite bursts (TODO), and the masters do not use them.

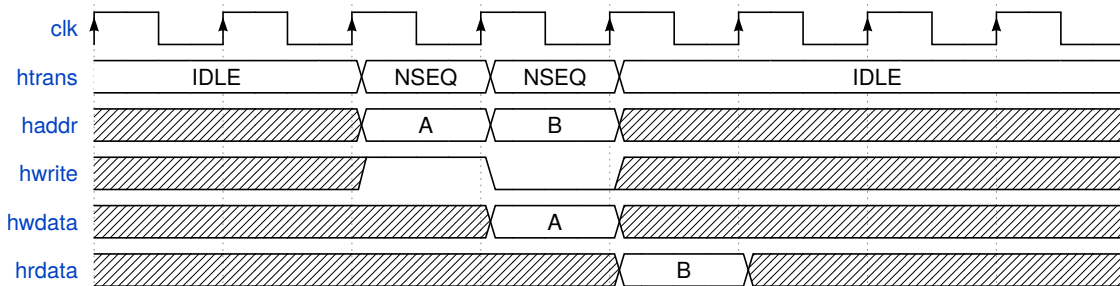
4.1 AHB-Lite Primer

For a full understanding of the bus standard used by RISCBoy, read through ARM’s AMBA 3 AHB-Lite spec. This document is mirrored in the **reference** folder in the GitHub repository, and gives a clear and comprehensive breakdown of AHB-Lite. However, the following overview should provide sufficient understanding of the standard to read through the Verilog.

Transactions take place in two phases, named the address phase and the data phase. During the address phase, the master asserts signals which control the nature of the transfer, such as the address, whether the transfer is a read or write, protection/permission information, the width of the data, and so on. During the data phase, data is asserted on either the read or write data bus (**hrdata** and **hwdata**), but never both. **hrdata** is driven by the slave, and **hwdata** by the master.

The central conceit of AHB-Lite is that these two phases are *pipelined*. Whilst the master is asserting or accepting data for an earlier transaction (currently in data phase), it concurrently asserts address and control information for a later transaction (currently in address phase). As is generally the case with pipelining, the goal is to enable higher clock frequencies with undiminished work-per-clock.

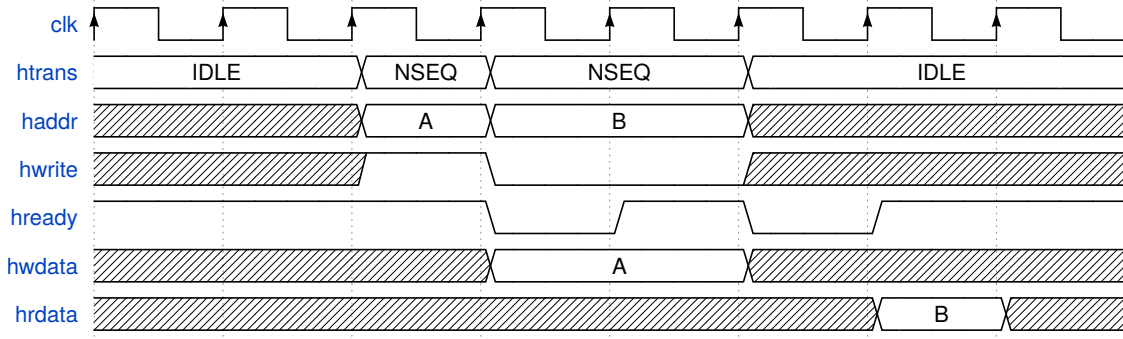
Figure 10: AHB-Lite transfers, a simple example



In figure 10, a master carries out two AHB-Lite transactions: a write to address A, followed by a read from address B. Only a subset of AHB-Lite signals are shown on the diagram. **htrans**, **haddr**, and **hwrite** are driven by the master, during the address phase; the other two are data phase signals. **htrans** indicates the type of transfer the master next wishes to perform, which is one of **IDLE**, **NSEQ** (non-sequential), **SEQ** and **BUSY**. The latter two are exclusive to burst transactions, which are not used in RISCBoy. (See the ARM spec if you do want details.)

Sometimes a slave is unable to service a request immediately, as shown in figure 11. **hready** is a data phase signal, which signifies the end of the current data phase.

Figure 11: AHB-Lite transfers, simple example with stalling



This slave needs two cycles to perform each data phase; perhaps it is an SRAM capable of running only at half the system clock speed. Therefore, **hready** is low for one cycle, and high for the second (last) cycle of each data phase. The master drives **hwddata** for the duration of A's data phase, waiting for the slave to signal completion. **hrdata**, on the other hand, is invalid until the final cycle of a read data phase.

Note that an address phase does not complete until the preceding transfer's data phase completes. In figure 11, address B (and associated address-phase signals) continue to be driven until the A data phase completes. IDLE transactions do have a data phase, which always completes immediately. Consequently, **hready** idles high while the bus is in an idle state. This is why A's address phase completes immediately in the figure.

In a practical system, there are multiple slaves. Each drives a signal called **hreadyout**, to indicate that *that slave* is ready. The bus fabric tracks which slave the master is currently accessing in the data phase, and selects that slave's **hreadyout** to be the global **hready**. To see why this is necessary, think about the situation where a master is in data phase with one slave, and address phase with a different slave.

4.2 Multi-Master Operation

In a single-master busfabric, **hready** is a global signal, which causes the entire AHB-Lite state machine (masters, slaves, fabric, the lot) to advance. Where multiple masters are concerned, **hready** is more subtle; in part it is a per-master stall signal. At this point we need to be more specific about the relationship between **hreadyout** and **hready**.

Any AHB-Lite slave port (of which there is one on the master side of the splitter, n on the master side of the arbiter, and one on each slave device) has an output called **hreadyout**, which indicates the slave's readiness. Each of these ports also has an input called **hready**, which indicates that the data phase is ending for the master who is connected to this slave (which does not mean that it is in data phase with *this* slave; it may be addressing this slave while in data phase with another). **hready** is a function of **hreadyouts** and bus state. The connections between masters, splitters, arbiters and slaves are shown in figure 9.

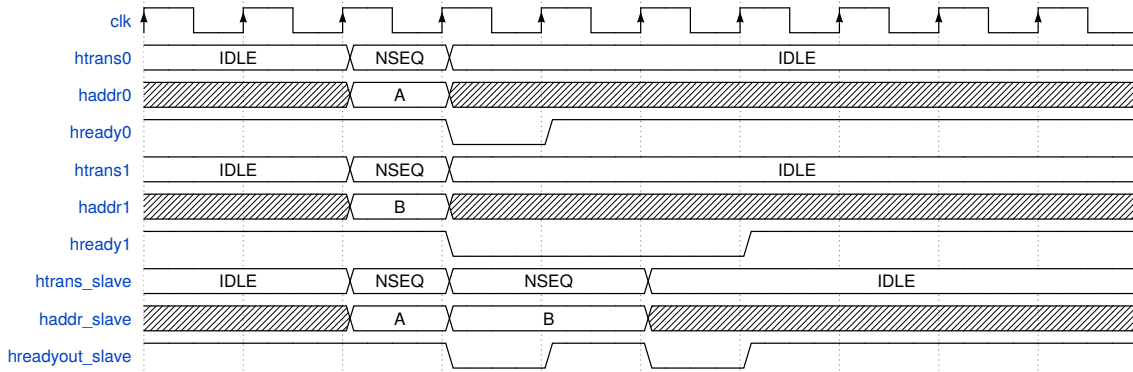
In the single-layer crossbar on RISCBoy, each system AHB-Lite slave is the slave of an arbiter, which is the slave of several splitters, each of which is the slave of a system master. As a general rule, the busfabric must filter system slaves' **hreadyouts** up to each system master, tie **hreadyouts** across to **hreadys** at the very top of the busfabric, and then distribute these **hready** signals down to the correct system slaves.

4.2.1 Multiple Masters, One Slave

The arbiters are the most complex busfabric component, so it is instructive to consider interactions between multiple masters and a single slave, which are mediated by one arbiter. There are additional complexities when we combine arbiters and splitters to build a crossbar, which are discussed in the next section.

In figure 12, two masters attempt to access a single slave simultaneously. Assume that master 0 always wins address-phase arbitration:

Figure 12: AHB-Lite transfers, two masters access one slave



Again, we assume the slave requires 2 cycles to complete each data phase.

If we look at each master's trace, there is no indication at all that there is more than one master in the system: they present an address, and subsequently the transaction completes. Likewise, the slave neither knows nor cares that there are multiple masters: it simply carries out transactions according to the address-phase signals it sees. All of the smoke, mirrors and machinery are inside of the arbiter.

One odd feature of this trace is that, when the slave sees the address B, no master is asserting this address.

1. Initially, both masters assert IDLE; IDLE data phases complete in one cycle
2. IDLE data phases are concurrent with A, B address phases, so these *also* complete immediately
3. From the master 1's point of view, transaction B proceeds immediately to data phase.
4. From both the master 0's and the slave's point of view, transaction A proceeds immediately to data phase
5. Whilst the slave is in data phase for A, it is simultaneously in address phase for B
6. When A data phase completes, master 0 is signaled, and B proceeds to data phase at the slave
7. When B data phase completes, master 1 is signaled

More concisely put, the first clock cycle of a given transaction's data phase may differ between the slave and master, but the *last* cycle of that data phase is always the same clock cycle. The slave address phase will occur some time between the master address phase starting, and the slave data phase starting. These are strong enough guarantees for correct operation.

Based on this discussion, the AHB-Lite arbiters need the facility to buffer one address-phase request, per master. A buffered request will be applied before any new requests from that master, but after any higher-priority requests. There is a nonzero hardware cost to this buffering, but there are clear engineering benefits to keeping this complexity confined to the arbiters, as they are the only component in the busfabric which is explicitly "multi master".

Figure 13: AHB-Lite transfers, two masters access one slave, with low-priority back-to-back

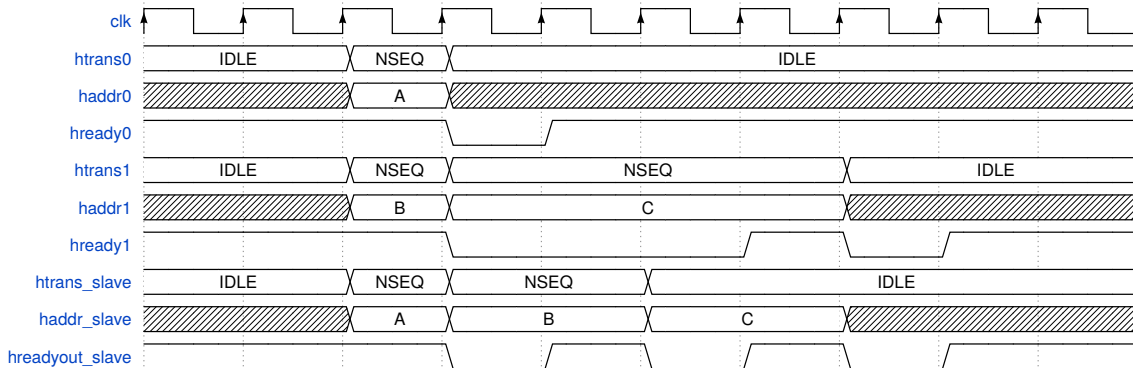
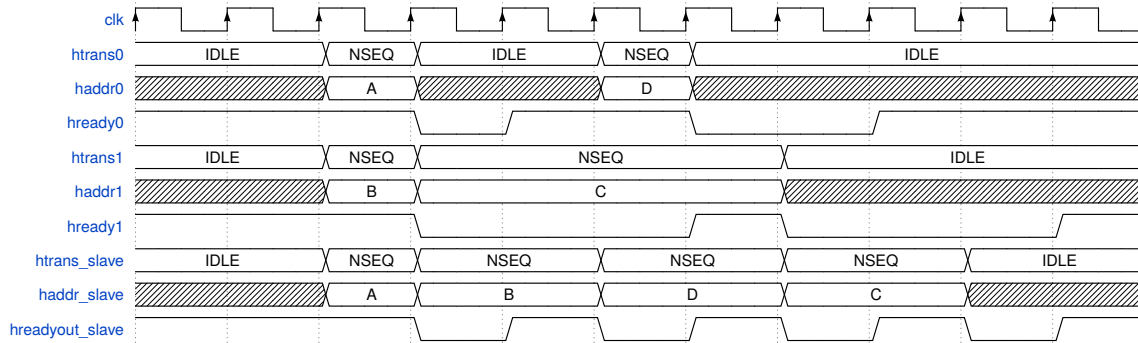


Figure 13 shows the same sequence of events as figure 12, except master 1 now performs two back-to-back transactions. Once B's slave address phase completes, the arbiter's request buffer is cleared, and the C request passes transparently through the arbiter to the slave. Again, the only indication to master 1 of any master 0 activity is increased latency.

There is a different case which requires the arbiter's request buffer, shown in figure 14.

Figure 14: AHB-Lite arbiter: simultaneous request buffer writes

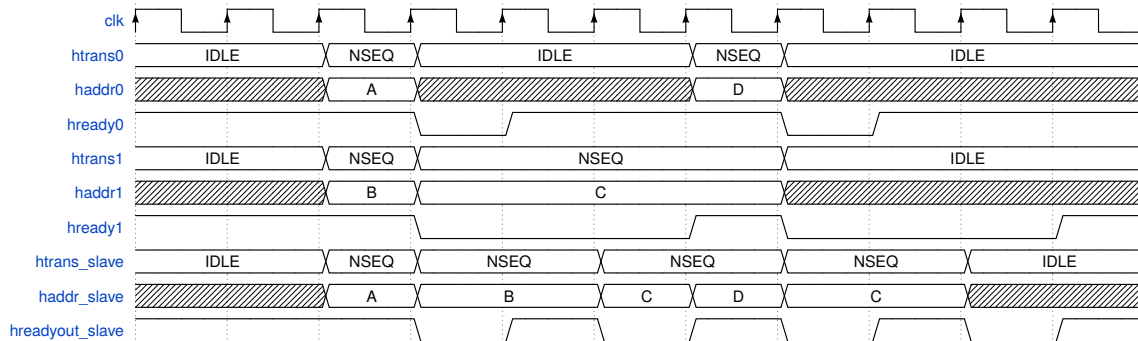


At the instant where D address phase is asserted, **hready0** is high, because master 0 previously asserted an IDLE transfer. However, the slave is not ready. In this case, the arbiter needs to buffer master 0's request, even though it is the highest-priority master. The buffered request is cleared once its slave address phase completes, as usual.

On the next cycle, B's data phase completes, and master 1 also considers this to be the end of the C address phase. The arbiter must write the C request into master 1's request buffer. Master 0's buffered request will continue to take priority over master 1's buffered request, until the first buffer is cleared.

There is one final case, for two masters accessing one slave, which is worth being aware of (figure 15).

Figure 15: AHB-Lite arbiter: late arrival of high priority request



Whilst **hreadyout** is low, the C address briefly appears on the slave bus, before being replaced by the higher-priority D request. **This is a departure from the AHB-Lite standard**, which stipulates the address must be constant during this time. This is deliberate, and easily amended. Slaves are generally insensitive to address-phase request during this time (as there is no performance benefit to latching APR before **hreadyout**, due to the way the bus operates), and this avoids a priority inversion, reducing average latency for higher-priority masters. If you find something that this breaks, write me an angry email! I would be interested to see such a slave.

The D request causes the low-priority C request to be buffered; the B data phase completes on this cycle, hence, from master 0's point of view, the C address phase does too.

4.2.2 Full Crossbar

The previous section discussed some cases where multiple masters access a single slave, and showed how the arbiter safely navigates them. There are yet more issues to consider when multiple masters and multiple slaves are involved,

which must be handled without added latency cycles, and with minimal extra gate delay.

For example, a master may be engaged in address phase with one arbiter and data phase with another arbiter simultaneously, via a splitter, and these two arbiters will not necessarily signal **hreadyout** at the same time. Consequently, a master may have a positive **hready**, filtered from its data phase arbiter, when its address phase arbiter has a negative **hreadyout**, which requires action on the arbiter's part.

There is also the issue that being in data phase with an arbiter does not mean you are genuinely in data phase with the arbitrated slave; in fact, a very simple sequence of events (all masters **IDLE** → all masters **NSEQ**) will put all masters simultaneously in data phase with the same arbiter. The arbiter behaviour described in the previous section should allow us to abstract this away, provided we can deal with the first issue safely.

Splitters will filter their slaves' **hreadyouts** based on which is currently in data phase, and present it on their own slave port. Arbiters will present their slave's **hreadyout** on any master-facing ports which are in data phase with the arbiter, and will present **hreadyout** = 1 on any idle ports.

Splitters will fan their **hready** signal out to all of their slaves; a low **hready** directed at a slave you are not engaged with is harmless.

4.3 Memories

RISCBoy possesses two memory areas for data and code: an external SRAM (512 kiB, 16 b wide, asynchronous), and internal RAM (8 kiB, 32 b wide, synchronous), assembled from FPGA block RAMs. The former is the main system memory, which most games will simply load into as a flat image; the latter is intended to be used for processor stack, and some critical code sections, including ISRs. Internal RAM also contains the first-stage bootloader, as it can be initialised during FPGA configuration, so is a convenient place to put the first few thousand instructions the processor will execute at start-of-day. SRAM was chosen for the external memory due to the low initial access latency – this permits reasonable performance without building complex cache hierarchies into the system bus masters. On a larger FPGA we could consider something like HyperRAM, or even DDRx SDRAM.

Both memories need to be interfaced to the AHB-lite system bus. SRAMs aren't too complex, but they can be a little fiddly to use efficiently due to the timing of AHB-lite – in particular, the alignment of **haddr** and **hdata** is more or less the opposite of what you want for a synchronous SRAM.

The internal SRAM can perform one 32-bit read or write per cycle. The external SRAM can also service a 32-bit AHB-lite read every cycle, because it is double-pumped; the controller performs two back-to-back 16 bit SRAM reads in one clock cycle. However, writes to external SRAM are limited to 16 bits per clock cycle, due to the timing of the **WE** pin, which is deasserted part way through each access. This is reasonable – reads are more common than writes, for almost any workload. However, special cases like the processor stack will benefit from the improved write performance of IRAM.

4.3.1 Internal RAM

Synchronous single-port SRAMs typically behave as follows:

- Address, write data and write enable are presented on one clock
- Read data is available on the next clock (and the whole process is pipelined)
- Byte-enables allow narrow writes to be performed without a read-modify-write sequence.

This is shown in figure 16. However, in AHB-lite, read and write data are both presented during the data phase, which begins on the cycle after the address phase completes. The timing of this is shown in figure 17. Note the difference in timing between **wdata** in figure 16 and **hdata** in figure 17.

Figure 16: Timing of synchronous SRAM interface

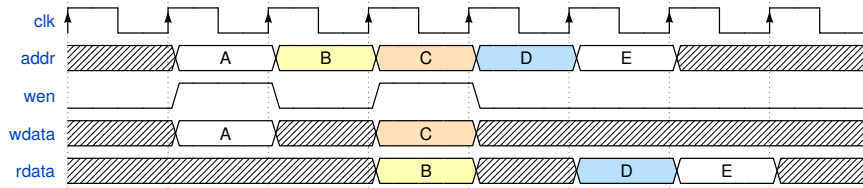
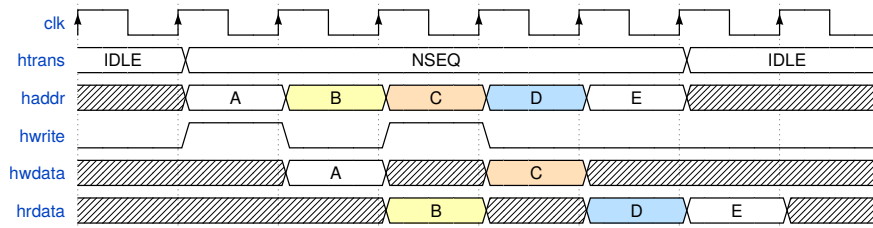
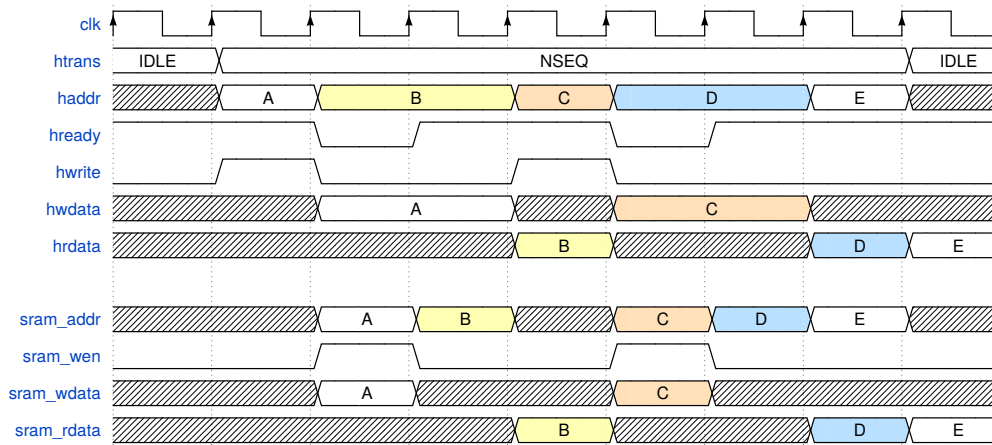


Figure 17: Timing of AHB-lite SRAM accesses, showing write data misalignment



The issue is that, as we can't source signals from the future, the SRAM write cycle must be delayed so that write address is aligned with write data. However, if the next transfer is a read, there is a collision: the delayed write address would need to be presented on the same cycle as the read address, which is impossible for a single-port SRAM. One way to resolve this is to simply insert wait states on write access, shown in figure 18.

Figure 18: AHB-lite SRAM access: resolving address collision with wait states

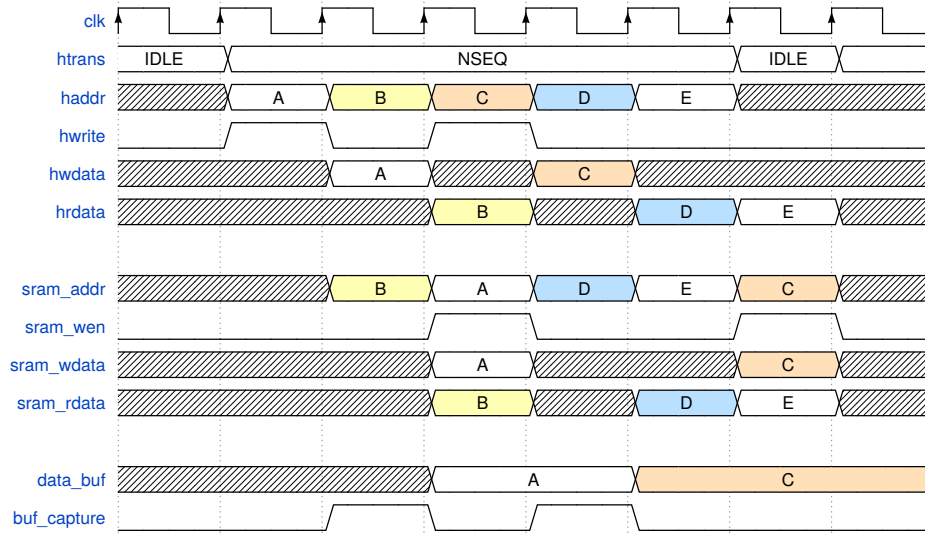


This works, but the performance cost is significant if you are constantly swapping back and forth between reads and writes (like, say, a processor!). This needn't be so. Noting that:

- Multiple consecutive writes are fine; all addresses are delayed equally, so do not collide
- Write-to-read has a single collision, and no more
- A run of consecutive reads is always followed by either an idle cycle or a write cycle (by definition)
- Read-to-write leaves the SRAM idle for one cycle; this is seen in figure 18

If we are able to buffer a single write, and hold onto it until the SRAM is idle (either AHB idle or read-to-write), we never need wait states. The only additional wrinkle is that, if a read is issued to an address we are currently holding a buffered write to, we will need to merge the buffered write data into the read data on-the-fly. As the write may be narrower than the SRAM, this needs to be done on a byte-by-byte basis. Use of a write buffer is shown in figure 19.

Figure 19: AHB-lite SRAM access: resolving address collision with a write buffer



It's probably worth staring at for a short while. Key observations for figure 19:

- SRAM reads are always aligned with AHB-lite reads, to avoid adding latency
- SRAM writes are in-order with respect to other SRAM writes (otherwise we'd need more buffering)
- An SRAM write can be deferred for any number of read cycles, after which the SRAM address bus will be free
- The data buffer is only needed for write-to-read, not write-to-write or write-to-idle.

4.3.2 Main Memory

Main memory consists of a 16-bit-wide, 512 kiB asynchronous SRAM. The rough timing of read and write cycles is shown below (just signal alignment, no timing parameters):

(TODO)

Currently the controller requires a single cycle for each 16-bit access, and services 32-bit accesses from the busfabric as two back-to-back external access cycles; a single wait state is inserted via `hready`. At RISCBoy's target clock frequency of 36 MHz, this cuts the available bandwidth down to 72 MiB/s.

The part used has a 10 ns access time, and RISCBoy is targeting around a 36 MHz system clock period (~28 ns), so with some care we may be able to perform two reads in the same clock cycle, using a DDR output on the least-significant address bit, and an optional negedge capture fed into the lower half of the AHB-lite data bus. This means we can service one 32-bit AHB-lite read each cycle, which is ideal for a 32-bit processor with up to 32-bit instructions!

Writes are more problematic: due to the timing of the `WE` pin, we need a full cycle for each 16-bit write cycle, so 32-bit writes will stall for one cycle. Write-intensive memory regions such as the processor stack should be located in IRAM if possible, to avoid this performance penalty.