PAWS a Risc-V RV32IMCB CPU – Programming Guide

About

PAWS is a project to occupy my time in retirement, with the aim of teaching myself about FPGA programming. It is based upon the idea of the 8-bit computers and consoles from the 1980s, but using a modern CPU.

It is a development from the work I did on the J1 CPU, which is a 16-bit CPU designed to run Forth natively, to which I added a display via HDMI, plus various input/out facilities such as a UART, button input, LED output and basic audio.

The J1 CPU has been swapped out for a Risc-V RV32 processor, as this can easily be programmed via C using GCC, in addition to being relatively straightforward to being implemented on an FPGA.

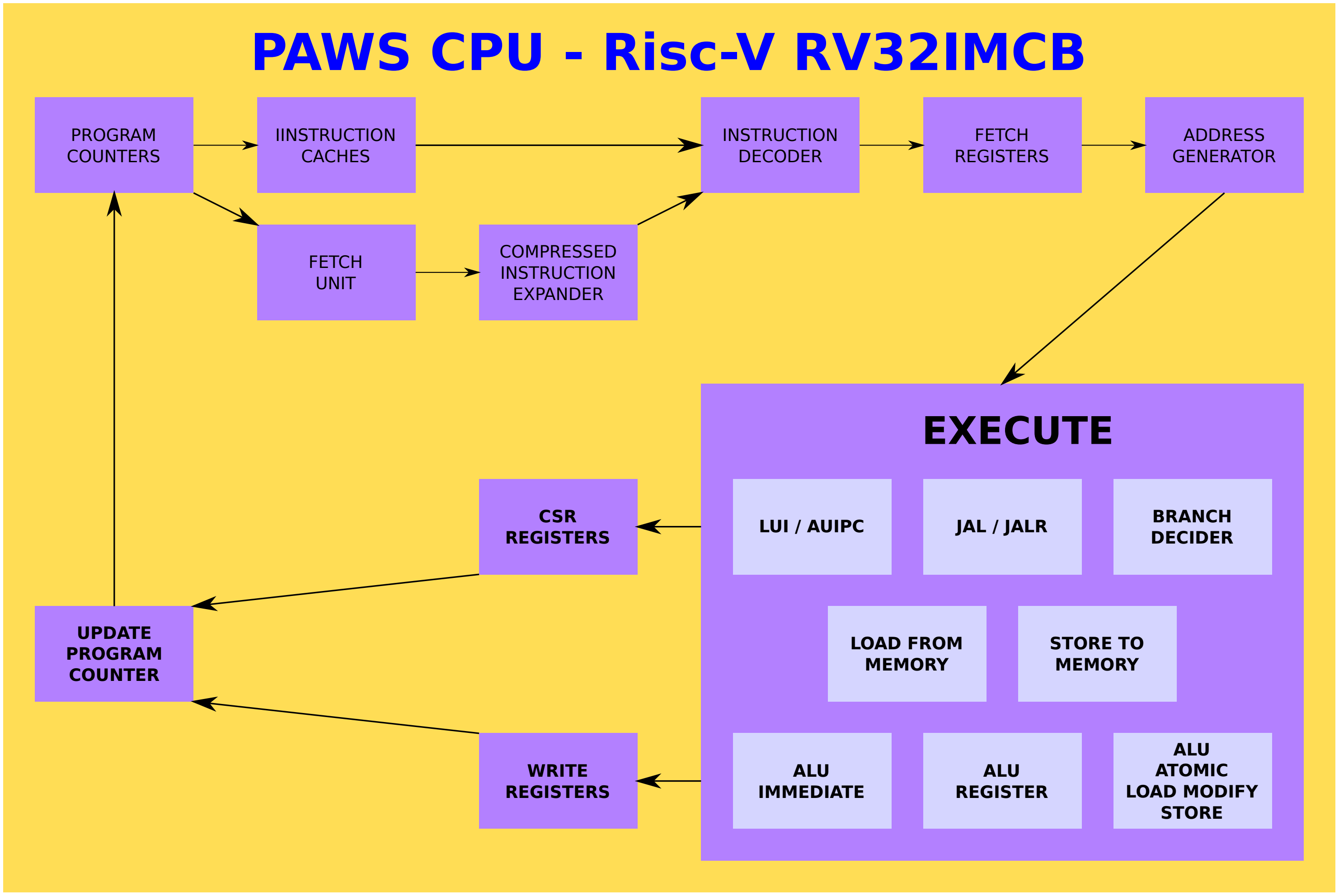
A support library, libPAWS, for easy access to the hardware is provided. This documentation details libPAWS and describes the hardware.

Silice

PAWS is coded in Silice, a hardware description language developed by @sylefeb. Details can be found here GitHub (https://github.com/sylefeb/Silice).

My coding style may not result in the *best* design, the aim was to create a design that could be easily understood.

PAWS CPU and SOC



The PAWS CPU is a Risc-V RV32IMCB that implements only the features needed to run GCC compiled code.

- No interrupts.
- Machine mode only.

The PAWS CPU has two modes:

- Single thread – all available cycles.
- Dual thread
  - Execute an instruction on each thread alternatively.
  - Second thread can be stopped/started as required.

Instruction and SDRAM Caches

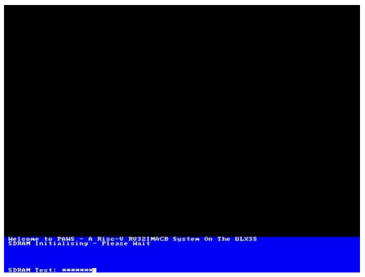
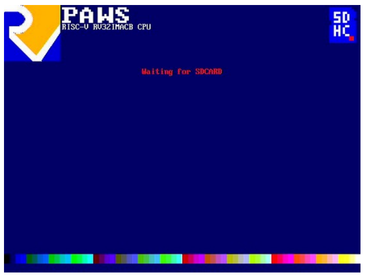
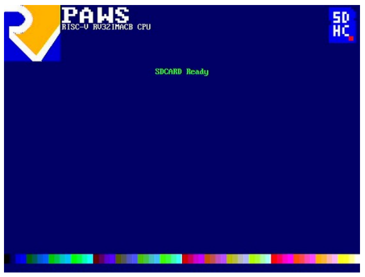
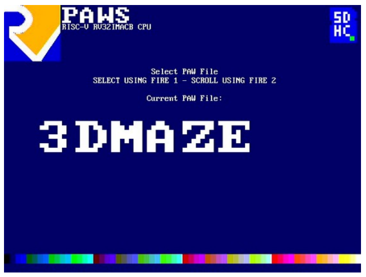
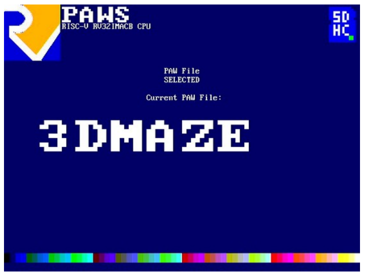
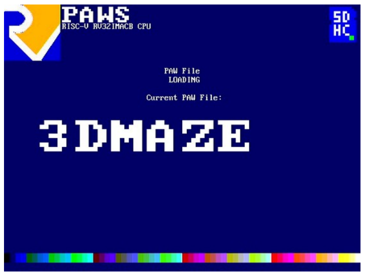
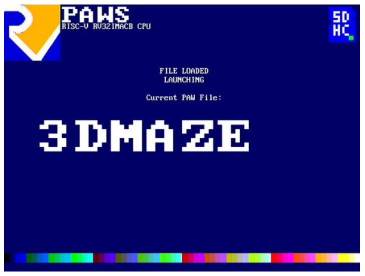
There are 3 types of cache in PAWS. Each CPU thread, referred to as “MAIN” and “SMT”, has a 32 instruction cache, of the most recently fetched instructions. These are specifically designed to assist in the execution of small loops.

The SDRAM has separate instruction (8k) and data (4k) directly mapped caches. Memory accesses to memory are marked by the CPU as being to fetch instructions or data so that the appropriate cache is used.

Memory access are organised as 16 bit, the bus width of the SDRAM chip on the ULX3S. 16-bit compressed instructions are preferred as due to latency during instruction fetching these will be fetched, decoded and executed quicker than 32-bit instructions.

The bit manipulation extension was implemented to increase code density, as when output by GCC they will replace multiple RV32I instructions, again leading to quicker code execution due to reduced memory access. Presently maintained to draft 0.94 from October 2020.

Using PAWS

 Welcome to PAWS - A Risc-V RV32IMACB System On The ULX3S SDRAM Initialising - Please Wait SDRAM Test: ******** BIOS SDRAM Initialisation	 PAWS RISC-V RV32IMACB CPU Waiting for SDCARD BIOS SDCARD Initialisation	 PAWS RISC-V RV32IMACB CPU SDCARD Ready BIOS Reading SDCARD	 PAWS RISC-V RV32IMACB CPU Select PAW File SELECT USING FIRE 1 - SCROLL USING FIRE 2 Current PAW File: 3DMAZE BIOS PAW File Selection
 PAWS RISC-V RV32IMACB CPU PAW File SELECTED Current PAW File: 3DMAZE BIOS PAW File Selected	 PAWS RISC-V RV32IMACB CPU PAW File LOADING Current PAW File: 3DMAZE BIOS PAW File Loading	 PAWS RISC-V RV32IMACB CPU FILE LOADED LAUNCHING Current PAW File: 3DMAZE BIOS PAW File Loaded	

Upon startup PAWS runs the BIOS, initialises the display, tests and clears the SDRAM, clears the input/output buffers, and reads the ROOT DIRECTORY from PARTITION 0 of a FAT16 formatted SDCARD.

PAW (compiled programs) files are display for selection. Scroll through the available files using “LEFT” and “RIGHT”, then select a file for loading and executing using “FIRE 1”.

Upon selection, the BIOS will load the selected PAW into SDRAM, reset the display, and launch the selected PAW program.

Compiling Programs For PAWS

The default language for PAWS is C, specifically GCC.

To create a program for PAWS, create a C file in the SOFTWARE/c directory. It is advised to use the SOFTWARE/template.c as a starting point.

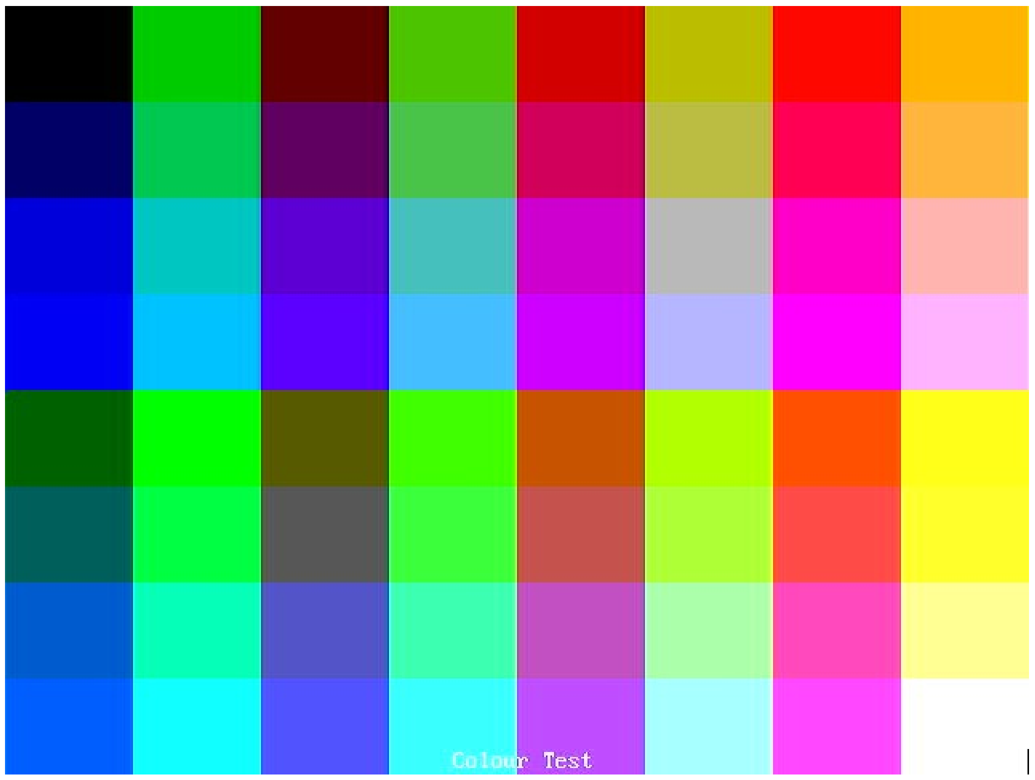
Contents of template.c	Explanation
`#include "PAWSlibrary.h"`	Use libPAWS for definitions and helper functions.
`void main( void ) {`	MAIN program loop
`    INITIALISEMEMORY();`	Setup the memory map
`    while(1) {`	Main loop.
`    }`	
`}`	

Compile your code using the helper shell script. For example, to compile the included asteroids style arcade game, `./compile.sh c/asteroids.c PAWS/ASTROIDS.PAW` . This will compile the program to PAWS/ASTROIDS.PAW, which can be copied to the SDCARD for loading via the BIOS.

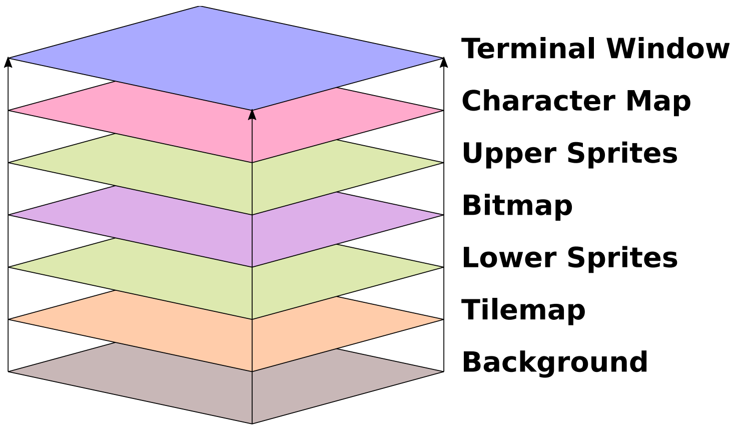
Colours

PAWS uses a 6-bit colour attribute, given as RRGGBB. This gives 64 colours, specified in decimal as per the table below. Names defined in libPAWS are given below the decimal representation.

0	1	2	3	4	5	6	7
BLACK		DKBLUE	BLUE				
8	9	10	11	12	13	14	15
DKGREEN			DKCYAN	GREEN			CYAN
16	17	18	19	20	21	22	23
			PURPLE		GREY1		
24	25	26	27	28	29	30	31
32	33	34	35	36	37	38	39
DKRED		DKMAGENTA					
40	41	42	43	44	45	46	47
DKYELLOW		GREY2					
48	49	50	51	52	53	54	55
RED			MAGENTA				
56	57	58	59	60	61	62	63
ORANGE				YELLOW			WHITE



Display Structure



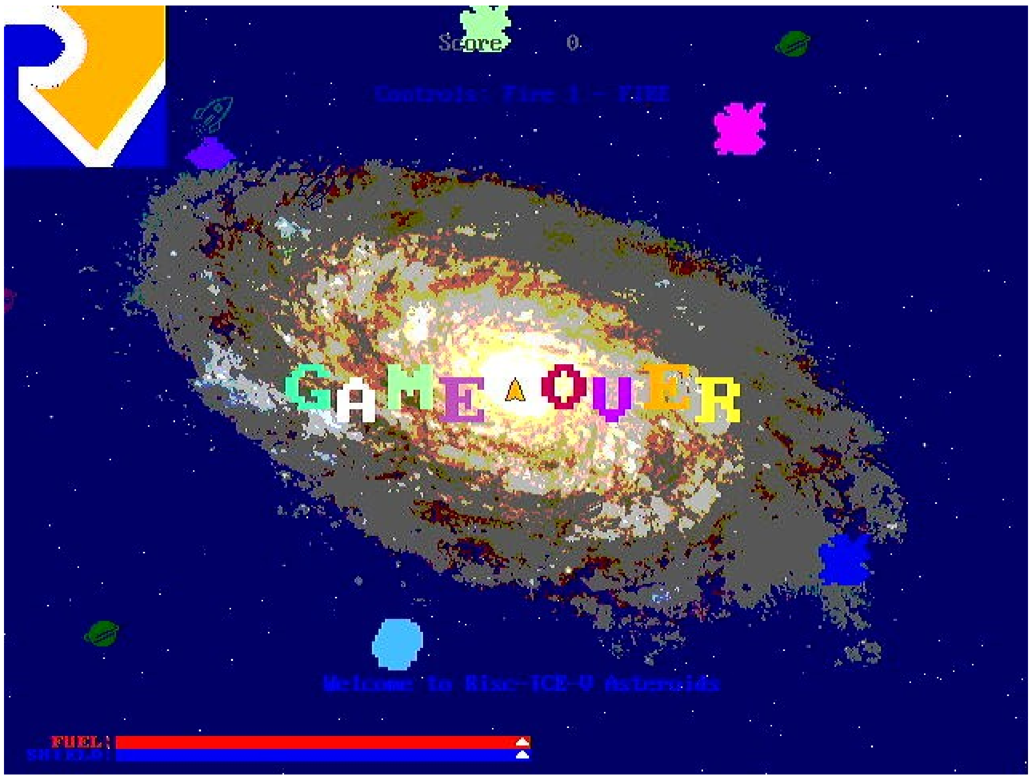
Default Display Layer Ordering

The display, 640 x 480 pixels in 64 colours, is output via HDMI.

It is formed of layers, starting with the terminal window at the top, down to the Background.

The terminal window can be switched off, otherwise it displays as an 80 x 8 character window at the bottom of the display.

All other layers, have transparency so that if no pixel is showing in that layer, the layer below shows.



PAWS running Asteroids, showing the background layer (dark blue with falling stars), the bitmap layer (Risc-V logo, galaxy image, “GAME OVER” message and the fuel bars), the tilemap (the small planets and rocket ships), the sprite layers (asteroids, UFO and player ship), and the character map layer (the player score and instructions).

PAW Asteroids runs in screen mode 2, where the bitmap is displayed below the lower sprites and the tilemap.

libPAWS Variables and Functions

`void await_vblank( void )`	Waits for the screen vertical blank to start.
`void screen_mode( unsigned char screenmode )`	Changes the display layer order. 0 = default, as above. 1 = bitmap between lower sprites and the tilemap. 2 = bitmap between the tilemap and the background. 3 = bitmap between the upper sprites and the character map.

Memory Management

The BIOS will initialise the memory, and allocates space at the top of fast BRAM memory for the CPU STACK, and space at the top the SDRAM for SDCARD buffers.

Address Range	Memory Type	Usage
0x00000000 – 0x00004000	Fast BRAM	0x00000000 – 0x00001000 BIOS 0x00004000 – 0x00002000 Main Stack 0x00002000 – 0x00001000 SMT Stack
0x00008000 – 0x0000ffff	I/O Registers	Commuincation with the PAWS hardware. No direct hardware access is required, as libPAWS provides functions for all aspects of the PAWS hardware.
0x1000000 -0x1fffffff	SDRAM	Program and data storage. Accessed via instruction and data caches. SDCARD buffers and structures are allocated at the top of this address range.

libPAWS variables and functions

`unsigned char *MEMORYTOP`	Points to the top of unallocated memory.
`void INITIALISEMEMORY( void )`	Sets up the memory map using parameters passed from the BIOS. Allocates the buffers used for SDCARD access, and correctly sets MEMORYTOP.
`unsigned char *memoryspace( unsigned int size )`	Returns a pointer to a buffer of at least size bytes, allocated from the top of the free memory space. Aligned to 16-bit address.
`unsigned char *filememoryspace( unsigned int size )`	Returns a pointer to buffer of at least size bytes, allocated from the top of the free memory space. Aligned to 16-bit address. This should be used for preference when allocating memory in which to read a file, as the buffer will contain sufficient space to account for the minimum block size of the SDCARD.

NOTE: memoryspace and filememoryspace are similar to the standard C function malloc. There is no mechanism for freeing memory in libPAWS.

File Management

libPAWS has the ability to load files from the SDCARD directly into memory.

libPAWS variables and functions

`unsigned short sdcard_findfilenumber( unsigned char *filename, unsigned char *ext )`	Returns the number of the file in the root directory on the SDCARD, or 0xffff if the file is not found.
`unsigned int sdcard_findfilesize( unsigned short filenumber )`	Returns the size of the file, in bytes.
`void sdcard_readfile( unsigned short filenumber, unsigned char * copyAddress )`	Reads the file into memory.

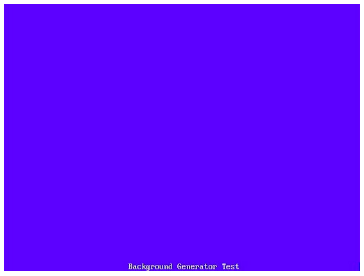
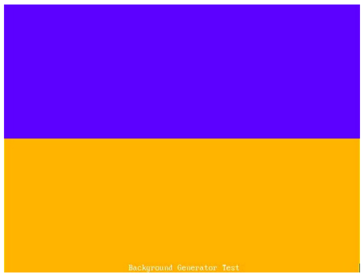
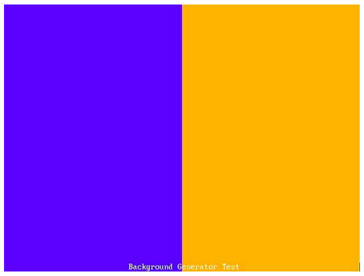
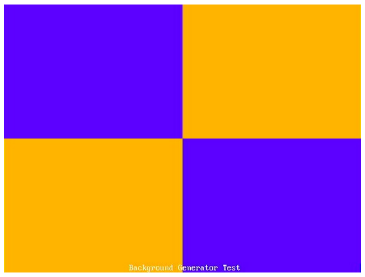
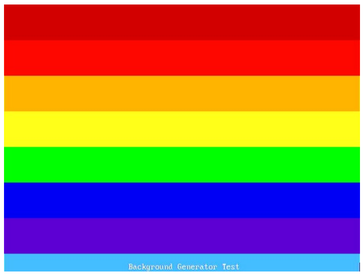
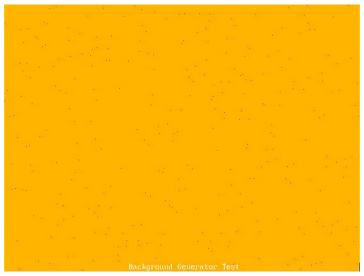
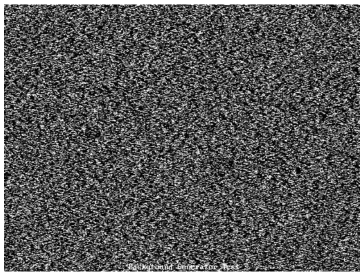
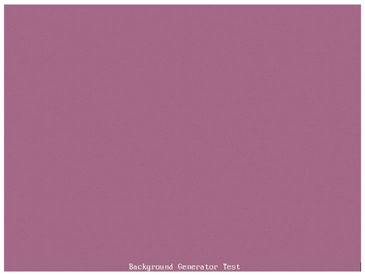
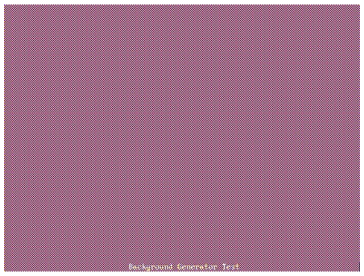
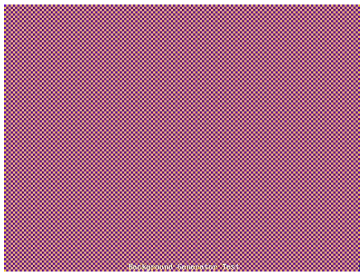
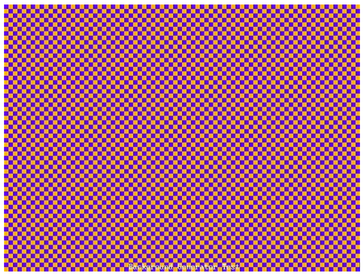
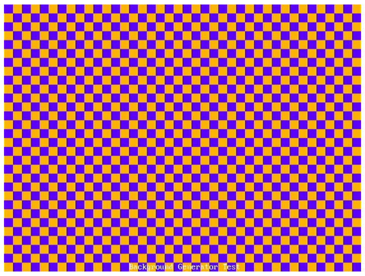
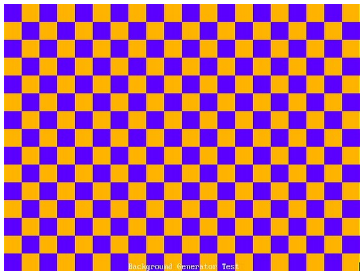
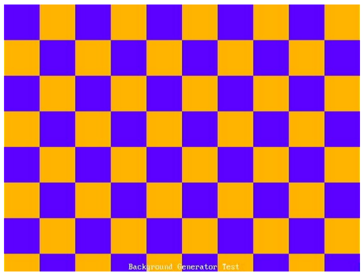
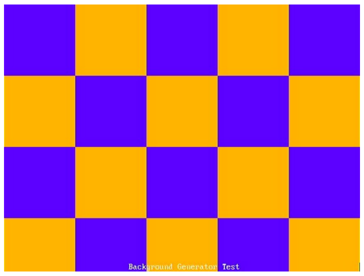
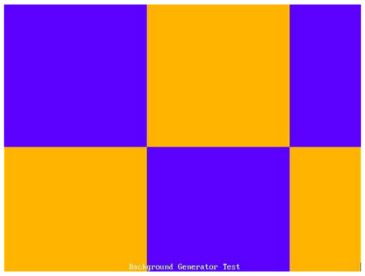
NOTE: memoryspace and filememoryspace are similar to the standard C function malloc. There is no mechanism for freeing memory in libPAWS.

Example code for loading a file (GALAXY.JPG) into memory

```
#include "PAWSlibrary.h"

void main( void ) {
    INITIALISEMEMORY();

    unsigned char *galaxyfilebuffer;
    unsigned short filenumber;

    while(1) {
        outputstring( "Finding File GALAXY.JPG");
        filenumber = sdcard_findfilenumber( "GALAXY", "JPG" );
        if( filenumber == 0xffff ) {
            outputstring( "FILE NOT FOUND" );
        } else {
            galaxyfilebuffer = filememoryspace( sdcard_findfilesize( filenumber ) );
            sdcard_readfile( filenumber, galaxybuffer );

        (void)inputcharacter();    }
}
```

Background Generator

The background layer shows when there is nothing to display from the layers above. There are 11 named generators in libPAWS. The result of the individual background generators are shown in the table below.

Result of `set_background( PURPLE, ORANGE, ` *`value from table`* ` );`			
			
BKG_SOLID	BKG_5050_V	BKG_5050_H	BKG_CHKBRD_5
			
BKG_RAINBOW	BKG_SNOW	BKG_STATIC	BKG_CHKBRD_1
			
BKG_CHKBRD_2	BKG_CHKBRD_3	BKG_CHKBRD_4	11
			
12	13	14	15

Single Thread or Dual Thread Mode

On startup PAWS runs in single thread mode. The BIOS will switch back to single thread mode when returning to the BIOS from a program running in dual thread mode.

When dual thread mode is activated PAWS will execute one instruction from each thread alternatively. All memory is shared, with no memory protection.

The Risc-V A Extension (Atomic Instructions) are decoded and executed, but ignoring the *aq* and *rl* flags. The whole of the fetch-modify-write cycle will complete before allowing the other thread to execute. FENCE instructions from the Risc-V base are treated as no-ops.

libPAWS variables and functions

`void SMTSTOP( void )void SMTSTART( unsigned int code )`	Stops the SMT thread.
`void SMTSTART( unsigned int code )`	Starts the SMT thread, jumping immediately to the address of the function provided.

Due to the way that all of the I/O operations are memory mapped there are considerations to make when writing dual threaded code. Some suggestions for best practice are listed below:

- Only one thread should access the GPU, tilemap, character map or audio. If both threads attempt to do so they will be overwriting the control registers leading to an unknown outcome.
- All timers are duplicated. The suggestion is that the main thread uses timer set 0, and the smt thread uses timer set 1. Alternatively for synchronisation, the main thread can set a timer, and BOTH threads can wait for that same timer.
- The sprite layers have duplicated control registers to allow both threads to control the sprites (only the one thread should set the sprite bitmaps as that uses a register from the main set to select the current sprite). See the SMT version of asteroids for an example.

Example code for a simple dual thread program

```
#include "PAWSlibrary.h"

void smtthread( void ) {
    // SETUP STACKPOINTER FOR THE SMT THREAD
    asm volatile ("li sp ,0x2000");
    while(1) {
        gpu_rectangle( rng( 64 ), rng( 640 ), rng( 432 ), rng( 640 ), rng( 432 ) );
        sleep( 500, 1 );
    }
}

void main( void ) {
    INITIALISEMEMORY();

    tpu_outputstringcentre( 27, TRANSPARENT, GREEN, "SMT Test" );
    tpu_outputstringcentre( 28, TRANSPARENT, YELLOW, "I'm Just Sitting Here Doing
Nothing" );
    tpu_outputstringcentre( 29, TRANSPARENT, BLUE, "The SMT Thread Is Drawing
Rectangles!" );
```

```
    SMTSTART( (unsigned int )smtthread );

    while(1) {
        tpu_set( 1, 1, TRANSPARENT, WHITE );
        tpu_outputstring( "Main Thread Counting Away: " );
        tpu_outputnumber_short( systemclock() );
        sleep( 1000, 0 );
    }
}
```

NOTE: The first line of code in the smtthread function **must** set the stack pointer to the reserved memory in the fast BRAM.