PRU Guide

by Brian Fraser
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Guide has been tested on

BeagleBone (Target):	**Debian 11.4**
PC OS (host):	**Debian 11.5**

Tested on Linux Kernel 5.10

This document guides the user through

1. Compiling code for the PRU
2. GPIO read/write for the PRU
3. Using shared memory to transfer data between PRU and Linux app

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Formatting

1. Commands for the host Linux's console are show as:
   `(host)$ echo "Hello PC world!"`
2. Commands for the target (BeagleBone) Linux's console are shown as:
   `(bbg)$ echo "Hello embedded world!"`
3. Almost all commands are case sensitive.

Revision History

- Nov 20, 2022: Initial release
- Nov 21, 2022: Added troubleshooting info
- Nov 22, 2022: Added command to start PRU if `make install_PRU0` fails

1. PRU

The Programmable Real-time Unit (PRU) is a pair of small 32-bit microprocessor which are integrated into the AM335x system-on-chip (SoC), as found on the BeagleBone Black/Green/.... It allows us to run code bare-metal (without Linux getting in the way) to give us deterministic and fast timing.

1. Linux uses the Remote Processor framework to communicate with the PRU:
   ```
   (bbg)$ ls /sys/class/remoteproc/
   ```
   - `remoteproc0` is for power management, not related to the PRU
   - `remoteproc1`/ is for PRU0, `remoteproc2`/ is for PRU2.
2. We can control if a PRU is running using:
   ```
   (bbg)$ cd /sys/class/remoteproc/remoteproc1/
   (bbg)$ echo 'stop'  | sudo tee ./state
   (bbg)$ echo 'start' | sudo tee ./state
   (bbg)$ cat ./state
   ```

1.1 Running Code on the PRU

1. Configure the BBG so the compiler can find `pru_cfg.h`:
   ```
   (bbg)$ cd /usr/lib/ti
   (bbg)$ sudo ln pru-software-support-package-v6.0 pru-software-support-package -s
   ```
   This command links the -v6.0 package to the base name.
2. From the GitHub repo for Derek Molloy's Exploring BeagleBone book, clone or download the code for chapter 15: https://github.com/derekmolloy/exploringBB/tree/version2/chp15

   Git command to clone:
   ```
   (host)$ git clone https://github.com/derekmolloy/exploringBB.git
   ```
3. Create new PRU projects folder for your code. It's suggested you put it in your own Git repo; or create it here:
   ```
   (host)$ mkdir -p ~/cmpt433/work/pru/hello/
   ```
4. From the Ch15 folder, copy into this project folder (`~/cmpt433/work/pru/hello/`) the following files:
   - `Makefile`: Used to build and install our PRU code
   - `resource_table_empty.h`: Used for interacting with the Linux `remoteproc` framework.
   - `AM335x_PRU.cmd`: Linker command file for layout of resources in PRU processor

   You can copy them from the repo (above), or directly from:
   https://github.com/derekmolloy/exploringBB/tree/version2/chp15/pru/ledFlashC

5. In `~/cmpt433/work/pru/hello/` (or your project folder) create the file `ledFun.c`:

```
// By TI; modified by Brian Fraser
#include <stdint.h>
#include <pru_cfg.h>
#include "resource_table_empty.h"

// PRU runs at 200Mhz
#define DELAY_250_MS 50000000

volatile register uint32_t __R30;   // output GPIO register
volatile register uint32_t __R31;   // input GPIO register

// Pin P9_27 = pru0_pru_r30_5 as an output LED (bit 5 = 0b0010 0000)
#define LED_MASK (1 << 5)

// Pin P9_28 = pru0_pru_r31_3 as a button (bit 3 = 0b0000 1000)
#define BUTTON_MASK (1 << 3)

void main(void)
{
    // Toggle LED until button pressed
    while (!(__R31 & BUTTON_MASK)) {
        __R30 ^= LED_MASK;
        __delay_cycles(DELAY_250_MS);
    }

    // End program
    __halt();
}
```

6. In `~/cmpt433/work/pru/` create a project `makefile` for the host (1 level above the above code!):

```
# RUN THIS ON THE HOST!
all: pru-copy

pru-copy:
	mkdir -p $(HOME)/cmpt433/public/pru/
	cp -r * $(HOME)/cmpt433/public/pru/
	@echo "COPY ONLY" > $(HOME)/cmpt433/public/pru/_COPY_ONLY_
	@echo ""
	@echo "You must build the PRU code on the target, then install it:"
	@echo "(bbg)$$ cd /mount/remote/pru/<your-folder>/"
	@echo "(bbg)$$ make"
	@echo "(bbg)$$ sudo make install_PRU0"
```

7. Your folder should now look like the following:

```
(host)$ cd ~/cmpt433/work/pru
(host)$ tree
.
├── ledFun
│   ├── AM335x_PRU.cmd
│   ├── ledFun.c
│   ├── Makefile
│   └── resource_table_empty.h
└── makefile

1 directory, 5 files
```

8. Build process
   - Run `make` on the <u>host</u> to copy PRU code to `~/cmpt433/public/pru`

     ```
     (host)$ cd ~/cmpt433/work/pru
     (host)$ make
     ```
   - On the <u>target</u>, run `make` (in `/mnt/remote/cmpt433/pru/<folder>`) to natively build the PRU code into ./`gen/<foldername>.out`

     ```
     (bbg)$ cd /mnt/remote/pru/hello/
     (bbg)$ make
     ```

     Building on the target uses PRU Code Generation Tool (CGT); it is preinstalled on our Debian 11.x Bullseye images.
9. Configure target pins for PRU use (depending on your GPIO needs). Must be done each boot of the BBG:

   ```
   (bbg)$ config-pin p9_27 pruout
   (bbg)$ config-pin p9_28 pruin
   ```
10. Run PRU code (change “PRU0” to “PRU1” to target other microprocessor.

    ```
    (bbg)$ cd /mnt/remote/pru/hello/
    (bbg)$ make install_PRU0
    ```

    If you see “`write error: Invalid argument`” then read troubleshooting below.
11. Troubleshooting:
    - If the `make install_PRU0` fails with an error:

      ```
      write error: Invalid argument
      ```

      Then you likely need to start the PRU before running the make command:

      ```
      (bbg)$ echo start | sudo tee /sys/class/remoteproc/remoteproc1/state
      ```
    - When writing to `/sys/class/remoteproc/remoteproc1/state` if you get an error “`write error: Invalid argument`” or “`write error: Device or resource busy`” it likely means that the device was already stopped (or started) and could not execute the command again.
    - If your code seems not to run, or when you run `make` on the target it finds no changes, then wait a couple seconds between running `make` on the host, and `make` on the target.
    - When compiling the program, if you see the error:

      ```
      fatal error #1965: cannot open source file "pru_cfg.h"
      ```

      Then double check that you have run the command above which creates the link to `/usr/lib/ti/pru-software-support-package/`
    - When compiling the program, if you see the error:

      ```
      make: warning: Clock skew detected. Your build may be incomplete.
      ```

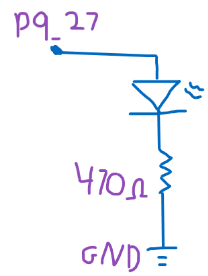
      It means that your BBG’s clock is not in sync with your host. Get your BBG access to the internet (see previous guides; test with `ping google.com`) and the network time protocol (NTP) on the BBG should then automatically update your BBG’s time.

2. GPIO

1. PRUs can easily and quickly access special Enhance GPIO pins.
   For example, pin P9_27 can used by the PRU as an output(pr1_pru0_pru_r31_5) or an input(pr1_pru0_pru_r30_5)

   Look up the P8 and P9 header pinouts (see course website) for which P8 & P9 pins can be mapped to the PRU (look for names like those above).

2.1 Output (drive an LED)



2. Wire an LED on pin P9_27.
   - Connect the LED to the pin
   - Connect a 470 ohm resistor (or the like) between the LED and ground.
3. PRU pin naming:

```
        pr1_pru<N>_pru_r3<D>_<B>
```

   `N`: 0 or 1, for PRU0 or PRU
   `D`: 0 for output, 1 for input (Direction)
   `B`: 0-31 for Bit number

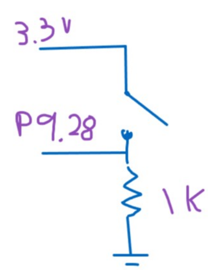
   Ex: `pr1_pru0_pru_r31_3` = PRU0, Direction out, Pin #3; maps to P9_28
4. Configure the pin to be used by the PRU for output.

```
(bbg)$ config-pin p9_27 pruout
```

5. Write the C code to drive the LED (see `ledFun.c`)

```
while(true) {
        __R30 ^= 1 << 5;
    __delay_cycles(DELAY_500_MS);
}
```

2.2 Input (read a button)



6. Read input from a button by wiring it with a pull down resistor to ground:
   - Button one input connected to 3.3V
   - Button other input connected to both a pull-down resistor (1K ohm+), and sense wire to pin P9.28.
7. Configure the pin to be used by the PRU for output.

```
(bbg)$ config-pin p9_28 pruin
```

8. Read the pin with C code such as the following:

```
if (!(__R31 & (1 << 3))) {
    ...
}
```

9. Trouble shooting
   - If your program seems to load correctly, but have problems reading/writing from/to a single pin, then
     - ensure you have the correct GPIO pin (check P8 & P9 headers)
     - ensure you have run the `config-pin`, and run correctly.

3. Transfer data between Linux and GPIO

See notes on PRU for more detailed explanation on topics.

Create a folder for your combined project.

- Have a sub folder for PRU code (including the code, `makefile`, and other necessary PRU related files discussed above
- Have a sub folder for the Linux code, including a `makefile` as normal (`sharedMem-Linux/` in the `makefile` below)
- In the root of the project, have the following makefile:

```
# RUN THIS ON THE HOST!

all: nested-sharedMem pru-copy

nested-sharedMem:
	make --directory=sharedMem-Linux

pru-copy:
	mkdir -p $(HOME)/cmpt433/public/pru/
	cp -r * $(HOME)/cmpt433/public/pru/
	@echo "DO NOT MODIFY THIS FOLDER: COPY ONLY" >
$(HOME)/cmpt433/public/pru/COPY_ONLY___DO_NOT_MODIFY
	@echo ""
	@echo "You must build the PRU code on the target, then install it:"
	@echo "(bbg)$$ cd /mount/remote/pru/<your-folder>/"
	@echo "(bbg)$$ make"
	@echo "(bbg)$$ sudo make install_PRU0"
```

3.1 Shared Struct

Have the following `struct` declared in one .h file, and both the PRU and Linux code #include it.

File: `sharedMem-Linux/sharedDataStruct.h`

```
#ifndef _SHARED_DATA_STRUCT_H_
#define _SHARED_DATA_STRUCT_H_

#include <stdbool.h>
#include <stdint.h>

// WARNING:
// Fields in the struct must be aligned to match ARM's alignment
//    bool/char, uint8_t:   byte aligned
//    int/long,  uint32_t:  word (4 byte) aligned
//    double,    uint64_t:  dword (8 byte) aligned
// Add padding fields (char _p1) to pad out to alignment.

// My Shared Memory Structure
// ----------------------------------------------------------------
typedef struct {
    bool isLedOn;
    bool isButtonPressed;
} sharedMemStruct_t;

#endif
```

3.2 PRU Code

File: `sharedMem-PRU/sharedMem-PRU.c`

```
#include <stdint.h>
#include <stdbool.h>
#include <pru_cfg.h>
#include "resource_table_empty.h"
#include "../sharedMem-Linux/sharedDataStruct.h"

// Reference for shared RAM:
// https://markayoder.github.io/PRUCookbook/05blocks/blocks.html#_controlling_the_pwm_frequency

// GPIO Configuration
// ----------------------------------------------------------
volatile register uint32_t __R30;   // output GPIO register
volatile register uint32_t __R31;   // input GPIO register

// Use pru0_rpu_r30_5 as an output (bit 5 = 0b0010 0000)
#define LED_MASK (1 << 5)

// Use pru0_pru_r31_3 as a button (bit 3 = 0b0000 1000)
#define BUTTON_MASK (1 << 3)


// Shared Memory Configuration
// -----------------------------------------------------------
#define THIS_PRU_DRAM       0x00000         // Address of DRAM
#define OFFSET              0x200           // Skip 0x100 for Stack, 0x100 for
Heap (from makefile)
#define THIS_PRU_DRAM_USABLE (THIS_PRU_DRAM + OFFSET)

// This works for both PRU0 and PRU1 as both map their own memory to 0x0000000
volatile sharedMemStruct_t *pSharedMemStruct = (volatile void
*)THIS_PRU_DRAM_USABLE;

void main(void)
{
    // Initialize:
    pSharedMemStruct->isLedOn = true;
    pSharedMemStruct->isButtonPressed = false;

    while (true) {

        // Drive LED from shared memory
        if (pSharedMemStruct->isLedOn) {
            __R30 |= LED_MASK;
        } else {
            __R30 &= ~LED_MASK;
        }

        // Sample button state to shared memory
        pSharedMemStruct->isButtonPressed = (__R31 & BUTTON_MASK) != 0;
    }
}
```

3.3 Linux Code

File: `sharedMem-Linux/sharedMem-Linux.c`

```
#include <fcntl.h>
#include <unistd.h>
#include <stdio.h>
#include <stdbool.h>
#include <stdlib.h>
#include <sys/mman.h>

#include "sharedDataStruct.h"

// General PRU Memomry Sharing Routine
// ----------------------------------------------------------------
#define PRU_ADDR      0x4A300000   // Start of PRU memory Page 184 am335x TRM
#define PRU_LEN       0x80000      // Length of PRU memory
#define PRU0_DRAM     0x00000      // Offset to DRAM
#define PRU1_DRAM     0x02000
#define PRU_SHAREDMEM 0x10000      // Offset to shared memory
#define PRU_MEM_RESERVED 0x200     // Amount used by stack and heap

// Convert base address to each memory section
#define PRU0_MEM_FROM_BASE(base) ( (base) + PRU0_DRAM + PRU_MEM_RESERVED)
#define PRU1_MEM_FROM_BASE(base) ( (base) + PRU1_DRAM + PRU_MEM_RESERVED)
#define PRUSHARED_MEM_FROM_BASE(base) ( (base) + PRU_SHAREDMEM)

// Return the address of the PRU's base memory
volatile void* getPruMmapAddr(void) {
    int fd = open("/dev/mem", O_RDWR | O_SYNC);
    if (fd == -1) {
        perror("ERROR: could not open /dev/mem");
        exit(EXIT_FAILURE);
    }

    // Points to start of PRU memory.
    volatile void* pPruBase = mmap(0, PRU_LEN, PROT_READ | PROT_WRITE,
            MAP_SHARED, fd, PRU_ADDR);
    if (pPruBase == MAP_FAILED) {
        perror("ERROR: could not map memory");
        exit(EXIT_FAILURE);
    }
    close(fd);
    return pPruBase;
}

void freePruMmapAddr(volatile void* pPruBase){
    if (munmap((void*) pPruBase, PRU_LEN)) {
        perror("PRU munmap failed");
        exit(EXIT_FAILURE);
    }
}
```

(continued on next page for `main()`)

```
int main(void) {
    printf("Sharing memory with PRU\n");
    printf("  LED should toggle each second\n");
    printf("  Press the button to see its state here.\n");

    // Get access to shared memory for my uses
    volatile void *pPruBase = getPruMmapAddr();
    volatile sharedMemStruct_t *pSharedPru0 = PRU0_MEM_FROM_BASE(pPruBase);

    // Drive it
    for (int i = 0; i < 20; i++) {
        // Drive LED
        pSharedPru0->isLedOn = (i % 2 == 0);

        // Print button
        printf("Button: %d\n",
            pSharedPru0->isButtonPressed);

        // Timing
        sleep(1);
    }

    // Cleanup
    freePruMmapAddr(pPruBase);
}
```

3.4 Padding Structs

A C `struct` is a convenient way to pass structured data between the PRU and a Linux program. However, on the ARM Cortex A8 (Linux) a `struct` is word aligned (for `int/float/uint32_t`) or double-word aligned (for `double`, `uint64_t`). However, on the RISC processor of the PRU, a `struct` is byte aligned. Therefore, the same C `struct` may end up looking different in the PRU and Linux, which is a problem because they are both looking at the same area of memory to exchange meaningful structured data.

The solution is to manually pad the `struct` so that both the Linux and PRP code expect the same memory layout.

- Single byte values are byte aligned on both, and can be put anywhere in the `struct`
- 4 byte values (`int`, `uint32_t`, `float`) should be word aligned (4 bytes)
- 8 byte values (`double`, `uint64_t`) should be double-word aligned (8 bytes)

For example, the `struct` below uses 2 padding bytes before the field `second` because it must be 4-byte aligned.

```
typedef struct {
    int first;
    bool isLedOn;
    bool isButtonPressed;
    uint8_t _pad1;
    uint8_t _pad2;
    int second;
} myStruct_t;
```

4. PRU Troubleshooting

Programming on the PRU has very low visibility into its internal state. Therefore, you should:

1. Write a small bit of PRU code.
2. Test the code works (say by flashing an LED...)

Here are some common issues:

- In VS Code, if you see error-bars under the #include statements for the PRU, those can be ignored because it does not know were to find the include files.
- When writing to `/sys/class/remoteproc/remoteproc1/state` if you get an error "`write error: Invalid argument`" or "`write error: Device or resource busy`" it likely means that the device was already stopped (or started) and could not execute the command again.
  - You may get this error when trying to run make install_PRU0 because it first stops the PRU. If so, you'll first need to run:
    ```
    (bbg)$ echo 'stop'  | sudo tee /sys/class/remoteproc/remoteproc1/state
    ```
- If your code seems not to run, or when you run `make` on the target it finds no changes, then wait a couple seconds between running `make` on the host, and `make` on the target.
- When running your Linux program which tries to use shared memory (`mmap()`), if you get a permission denied on /dev/mem error, then run your app using `sudo`.
- If the GPIO input (a button) or output (an LED) is not working, ensure you have run config-pin on the correct pins, such as:
  ```
  (bbg)$ sudo config-pin P9_28 pruout
  ```
  Check the mode with:
  ```
  (bbg)$ sudo config-pin -q P9_28
  ```
- If you are using a struct and shared memory to exchange data between your Linux app and the PRU, but the data seems to get corrupted:
  - check your data structure is word/dword aligned
  - check that you don't have any race cases where one processor is reading the data while the other is writing it. Primitives (like `char`, `int`, `uint32_t`) can be assumed to be written in one clock-cycle (no race case). For larger data structures (copying an array, ...), you should build in a signaling mechanism for one processor to indicate that the data is ready (a flag).
- Changes to code not running:
  - Try waiting a moment before compiling on the target to allow NFS to read the changed state of your source code files.
  - Add compile-time error to check if correct code is compiling.

5. TI License

Any code in this document which says “By TI” would include the following copyright notice