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## About Me (and Linux)

### Hobbyist

- 1994 Linux/m68k on Amiga
- 1997 Linux/PPC on CHRP
- 1997 FBDev

### Sony

- 2006 Linux on PS3/Cell

### Glider bvba

- 2013 Renesas ARM-based SoCs
System-Centric Power Management

PC

- On
- Suspended
- Hibernated
- Off
System-Centric Power Management

Building: Day Time

NINE-TO-FIVE LTD
System-Centric Power Management

Building: Night Time
Runtime Power Management
Computing Device

- Parts become active when needed
- Parts become inactive when no longer needed
Hardware / SoC
Multiple Power Areas, Clock Domain

[Diagram showing a complex system with multiple power areas and clock domains, including BIG-MP, LITTLE-MP, BIG-CPU, LITTLE-CPU, CPU0, CPU1, CPU2, CPU3, L1, L2, MOD, MOD, VIDEO, AUDIO, MEDIA, SYSTEM, BUS, POWER CTRL, CLK CTRL, I/O]
Power Domains

- Devices can be Power Managed by Controlling Power
- Multiple Power Domains / Power Areas
- Power Controllers

Clock Domains

- Devices can be Power Managed by Controlling Clocks
  - Synchronous logic driven by clock
  - Gating the clock saves power
- Clock Controllers
Power/Clock Distribution
- Per-device
- Device groups

Power/Clock Topology
- Flat
- Tree
- Complex hierarchy

Dependencies!
PM Domains not Power Domains
Not limited to Power Domains / Power Areas

PM Domain = Collection of devices treated similarly w.r.t. power management
- One single power area
- One clock controller for power-managing per-device clocks
- Combination
- Firmware (e.g. ACPI)
- ...
Generic I/O PM Domains (genpd)
Generic implementations of various device PM callbacks
Supports controlling an entire PM Domain
Supports controlling a single device in a PM Domain
Supports PM Subdomains

select PM_GENERIC_DOMAINS if PM

Note: Other PM Domains (e.g. ACPI)
Allows I/O devices to be put into energy-saving states
After a specified period of inactivity
Woken up in response to a hardware-generated wake-up event or a driver’s request
Used to have its own config symbol (CONFIG_PM_RUNTIME)
Always enabled if CONFIG_PM_SLEEP is enabled since v3.19
More Linux PM?

- Cpuidle: Multiple CPU idle levels
- Cpufreq: CPU frequency and voltage scaling
  - Cfr. breathing, heartbeat, ...
- ...

⇒ Introduction to Kernel Power Management by Kevin Hilman
**Example: r8a7740/armadillo800eva**

```bash
$ cat /sys/kernel/debug/pm_genpd/pm_genpd_summary

(Config PM_DEBUG=y and CONFIG_PM_ADVANCED_DEBUG=y)
```

<table>
<thead>
<tr>
<th>domain</th>
<th>status</th>
<th>slaves</th>
<th>runtime status</th>
</tr>
</thead>
<tbody>
<tr>
<td>/device</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a4su</td>
<td>off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a3sg</td>
<td>off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a3sm</td>
<td>on</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a3sp</td>
<td>on</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e6600000.pwm</td>
<td>suspended</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e6c50000.serial</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e6850000.sd</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e6bd0000.mmc</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a4s</td>
<td>on</td>
<td>a3sp, a3sm, a3sg</td>
<td>active</td>
</tr>
<tr>
<td>/devices/platform/e6900000.irqpin</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e6900004.irqpin</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e6900008.irqpin</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e690000c.irqpin</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e9a00000.eternet</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a3rv</td>
<td>off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a4r</td>
<td>on</td>
<td>a3rv</td>
<td>suspended</td>
</tr>
<tr>
<td>/devices/platform/fff20000.i2c</td>
<td>suspended</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/fff80000.timer</td>
<td>active</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d4</td>
<td>on</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a4mp</td>
<td>off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>/devices/platform/felf0000.sound</td>
<td>suspended</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a4lc</td>
<td>off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c5</td>
<td>on</td>
<td>a4lc, a4mp, d4, a4r, a4s, a4su</td>
<td>unsupported</td>
</tr>
<tr>
<td>/devices/platform/e6050000.pfc</td>
<td></td>
<td>suspended</td>
<td></td>
</tr>
<tr>
<td>/devices/platform/e6138000.timer</td>
<td></td>
<td>suspended</td>
<td></td>
</tr>
</tbody>
</table>
/* struct dev_pm_ops - device PM callbacks */
struct dev_pm_ops {
    int (*prepare)(struct device *dev);
    void (*complete)(struct device *dev);
    int (*suspend)(struct device *dev);
    int (*resume)(struct device *dev);
    ...
    int (*runtime_suspend)(struct device *dev);
    int (*runtime_resume)(struct device *dev);
    ...
};

Can be:

- **Bus specific** (struct bus_type.pm)
- **Device driver specific** (struct device_driver.pm)
- **Device class specific** (struct class.pm)
- **Device type specific** (struct device_type.pm)
- **PM Domain specific** (struct dev_pm_domain.pm)
- Platform specific
/*
 * Power domains provide callbacks that are executed during system suspend, hibernation, system resume and during runtime PM transitions along with subsystem-level and driver-level callbacks.
 */
struct dev_pm_domain {
    struct dev_pm_ops ops;
    void (*detach)(struct device *dev, bool power_off);
};

- **Used by Devices** *(struct device.pm_domain)*
- **Provided by:**
  - **Generic PM Domain** *(struct generic_pm_domain.domain)*
  - Platform code, Legacy Clock Domains, VGA switcheroo
  - ACPI
struct dev_power_governor {
    bool (*power_down_ok)(struct dev_pm_domain *domain);
    bool (*stop_ok)(struct device *dev);
};

struct gpd_dev_ops {
    int (*start)(struct device *dev);
    int (*stop)(struct device *dev);
    int (*save_state)(struct device *dev);
    int (*restore_state)(struct device *dev);
    bool (*active_wakeup)(struct device *dev);
};
#define GENPD_FLAG_PM_CLK (1U << 0)  /* Use PM clk */

struct generic_pm_domain {
        struct dev_pm_domain domain;  /* PM domain ops */
        struct list_head gpd_list_node;  /* Global list */
        ...
        const char *name;
        ...
        enum gpd_status status;  /* Current state */
        ...
        int (*power_off)(struct generic_pm_domain *domain);
        s64 power_off_latency_ns;
        int (*power_on)(struct generic_pm_domain *domain);
        s64 power_on_latency_ns;
        struct gpd_dev_ops dev_ops;
        ...
        int (*attach_dev)(struct generic_pm_domain *domain, struct device *dev);
        void (*detach_dev)(struct generic_pm_domain *domain, struct device *dev);
        unsigned int flags;  /* Bit field of configs */
};
void pm_genpd_init(struct generic_pm_domain *genpd,
                  struct dev_power_governor *gov,
                  bool is_off);

int pm_genpd_add_subdomain(struct generic_pm_domain *genpd,
                           struct generic_pm_domain *new_subdomain);
int pm_genpd_remove_subdomain(struct generic_pm_domain *genpd,
                               struct generic_pm_domain *target);

struct genpd_onecell_data {
   struct generic_pm_domain **domains;
   unsigned int num_domains;
};

int of_genpd_add_provider_simple(struct device_node *np,
                                 struct generic_pm_domain *genpd);
int of_genpd_add_provider_onecell(struct device_node *np,
                                   struct genpd_onecell_data *data);
void of_genpd_del_provider(struct device_node *np);
struct generic_pm_domain *of_genpd_get_from_provider(
                                 struct of_phandle_args *genpdspec);
Linux API
Populating PM Domains

```c
int __pm_genpd_add_device(struct generic_pm_domain *genpd,
                         struct device *dev,
                         struct gpd_timing_data *td);
int pm_genpd_remove_device(struct generic_pm_domain *genpd,
                         struct device *dev);

int __pm_genpd_name_add_device(const char *domain_name,
                         struct device *dev,
                         struct gpd_timing_data *td);
int pm_genpd_add_subdomain_names(const char *master_name,
                         const char *subdomain_name);
```

⇒ Use DT!
Linux API

Cpuidle

int pm_genpd_attach_cpuidle(struct generic_pm_domain *genpd,
                             int state);
int pm_genpd_name_attach_cpuidle(const char *name, int state);
int pm_genpd_detach_cpuidle(struct generic_pm_domain *genpd);
int pm_genpd_name_detach_cpuidle(const char *name);

So far used only by legacy (non-DT) SH-Mobile AP4 (sh7372),
which is scheduled for removal in v4.1...
Preferred way to describe hardware PM Domains
- PM Domain Providers are registered by platform code
- PM Domain Consumers are registered by PM Domain core

Introduced last year, not that many users yet:
- Freescale i.MX6
- Renesas SH-Mobile/R-Mobile
- Samsung Exynos
- ST-Ericsson Ux500

However, more to come soon!
Device Tree

PM Domain Providers

- Required properties:

  #power-domain-cells : Number of cells in a PM domain specifier;

- 0 for nodes representing a single PM domain
- 1 for nodes providing multiple PM domains (power controllers)
- can be any value as per provider DT bindings

- Example:

```plaintext
power: power-controller@12340000 {
    compatible = "foo,power-controller";
    reg = <0x12340000 0x1000>;
    #power-domain-cells = <1>;
};
```

Documentation/devicetree/bindings/power/power_domain.txt
Required properties:

```

power-domains : A phandle and PM domain specifier as defined by bindings of the power controller specified by phandle.
```

Example:

```

leaky-device@12350000 {
    compatible = "foo,i-leak-current";
    reg = <0x12350000 0x1000>;
    power-domains = <&power 0>;
};
```

Documentation/devicetree/bindings/power/power_domain.txt
Device Tree
PM Domain Providers and Consumers Example

```
pd_lcd0: lcd0-power-domain@10023C80 {
    compatible = "samsung,exynos4210-pd";
    reg = <0x10023C80 0x20>;
    #power-domain-cells = <0>;
};

ds_i_0: dsi@11C80000 {
    compatible = "samsung,exynos4210-mipi-dsi";
    reg = <0x11C80000 0x10000>;
    interrupts = <0 79 0>;
    power-domains = <&pd_lcd0>;
    phys = <&mipi_phy 1>;
    phy-names = "dsim";
    clocks = <&clock CLK_DSIM0>, <&clock CLK_SCLK_MIPI0>;
    clock-names = "bus_clk", "pll_clk";
    status = "disabled";
    #address-cells = <1>;
    #size-cells = <0>;
};
```

arch/arm/boot/dts/exynos4.dtsi
Device Tree
Parent/Child PM Domain Providers Example

```
parent: power-controller@12340000 {
    compatible = "foo,power-controller";
    reg = <0x12340000 0x1000>;
    #power-domain-cells = <1>;
};

child: power-controller@12341000 {
    compatible = "foo,power-controller";
    reg = <0x12341000 0x1000>;
    power-domains = <&parent 0>;
    #power-domain-cells = <1>;
};
```

Documentation/devicetree/bindings/power/power_domain.txt
sysc: system-controller@e6180000 {
    compatible = "renesas,sysc-r8a7740", "renesas,sysc-rmobile";
    reg = <0xe6180000 0x8000>, <0xe6188000 0x8000>;

    pm-domains {
        pd_c5: c5 {
            #address-cells = <1>;
            #size-cells = <0>;
            #power-domain-cells = <0>;
        }
        pd_a4s: a4s@10 {
            reg = <10>;
            #address-cells = <1>;
            #size-cells = <0>;
            #power-domain-cells = <0>;
        }
        pd_a3sp: a3sp@11 {
            reg = <11>;
            #power-domain-cells = <0>;
        }
    }
    pd_a4su: a4su@20 {
        reg = <20>;
        #power-domain-cells = <0>;
    }
};
static int my_power_off(struct generic_pm_domain *genpd);
static int my_power_on(struct generic_pm_domain *genpd);

static __init int init_my_power_domain(void)
{
    struct device_node *np;

    for_each_compatible_node(np, NULL, "my-vendor,my-power") {
        struct generic_pm_domain *pd = ...;
        ...
        pd->name = np->name;
        pd->power_off = my_power_off;
        pd->power_on = my_power_on;
        pm_genpd_init(pd, NULL, false);
        of_genpd_add_provider_simple(np, pd);
    }

    return 0;
}

arch_initcall(init_my_power_domain);
static __init int init_my_power_controller(void) {
    struct device_node *np;

    for_each_compatible_node(np, NULL, "my-vendor,my-power") {
        struct genpd_onecell_data *data = ...;

        data.domains = ...;
        data.num_domains = ...;
        ...
        for (i = 0; i < data.num_domains; i++)
            pm_genpd_init(data.domains[i], NULL, false);
        of_genpd_add_provider_onecell(np, data);
    }
    return 0;
}

arch_initcall(init_my_power_controller);
static int my_attach_dev(struct generic_pm_domain *domain, struct device *dev)
{
    pm_clk_create(dev);
    pm_clk_add(dev, ...); /* Find and add module clock */
}

static void my_detach_dev(struct generic_pm_domain *domain, struct device *dev)
{
    pm_clk_destroy(dev);
}

static __init int init_my_clock_domain(void)
{
    ...
    pd->attach_dev = my_attach_dev;
    pd->detach_dev = my_detach_dev;
    /* dev_ops.{start,stop} = pm_clk_{suspend,resume}() */
    pd->flags = GENPD_FLAG_PM_CLK;
    ...
}
(Existing) Device Drivers

- Ideally, device drivers should not be aware of PM Domains
- Abstracted by Runtime PM

- Power Domains: Never accessed directly by drivers
  - Module needs to be powered when active
  - Automatic, Runtime PM

- Clock Domains: Who is in charge of the clocks(s)?
  - Functional clocks
  - Interface clocks
  - Clock-agnostic (hardware is just synchronous?)
  - Clock rate
  - …
Device Drivers
Example: Thermal and GPIO Modules

- Needs power
- Clock-agnostic
- Input may need clock
Device Drivers
Example: SPI Master Module

- Needs power, clock
- Needs to know clock rate
- Who is in charge of the clock?
Device Drivers
Example: Audio Module

- Capture at 32 kHz
- Playback at 44.1 kHz
- Audio processing
- Needs power, clock
- Driver is in charge of the clocks
Device Drivers

Runtime PM

- Runtime PM is disabled by default
- Driver needs minimal Runtime PM:

```c
#include <linux/pm_runtime.h>

...

static int my_probe(struct platform_device *pdev)
{
    ...
    pm_runtime_enable(&pdev->dev);
    pm_runtime_get_sync(&pdev->dev);
    ...
}

static int my_remove(struct platform_device *pdev)
{
    ...
    pm_runtime_put(&pdev->dev);
    pm_runtime_disable(&pdev->dev);
    ...
}
```
Better: more advanced Runtime PM

Call `pm_runtime_put()` after becoming inactive,
Call `pm_runtime_get_sync()` before becoming active.

May be subsystem-specific

E.g. SPI core handles this automatically if
`spi_master.auto_runtime_pm == true`

Provide your own `struct dev_pm_ops`
Caveats

- Unused PM Domains will be powered down by the genpd core (cfr. clocks)
- If you make a mistake, something will break, eventually
  - Incorrect description in DT
  - Driver / subsystem without / with incorrect Runtime PM
  - …
- Shared PM Domain: it may work by accident
- Wake-up
Example: Simple Power Managed Bus
Example: Simple Power Managed Bus
Original

```c
bsc: bus@fec10000 {
    compatible = "simple-bus";
    #address-cells = <1>;
    #size-cells = <1>;
    ranges = <0 0 0x20000000>;
}

ethernet@10000000 {
    compatible = "smsc,lan9220", "smsc,lan9115";
    reg = <0x10000000 0x100>;
    ...
};
};
```

- Missing BSC clock, broke when CCF was introduced
- Bad workaround: add BSC clock to ethernet node
- Even more broken with the advent of PM Domains
Example: Simple Power Managed Bus
Solution 1: Add Clock, PM Domain

```
bsc: bus@fec10000 {
    compatible = "simple-bus";
    #address-cells = <1>;
    #size-cells = <1>;
    ranges = <0 0 0x20000000>;
    clocks = <&zb_clk>;
    power-domains = <&pd_a4s>;

    ethernet@10000000 {
        compatible = "smsc,lan9220", "smsc,lan9115";
        reg = <0x10000000 0x100>;
        ...
    }
};
```

✓ Ethernet driver now has minimal Runtime PM support
✓ Runtime PM takes into account parent/child relationship
✗ Without a BSC driver, Runtime PM stays disabled, and the PM Domain is not powered on.
Example: Simple Power Managed Bus
Solution 2: Generic "simple-pm-bus" Bindings and Driver

```c
bsc: bus@fec10000 {
    compatible = "renesas,bsc-sh73a0", "renesas,bsc", "simple-pm-bus";
    ...
    clocks = <&zb_clk>;
    power-domains = <&pd_a4s>;

    ethernet@10000000 {
        compatible = "smsc,lan9220", "smsc,lan9115";
        ...
    }
};
```

- Ethernet driver now has minimal Runtime PM support
- Runtime PM takes into account parent/child relationship
- Generic "simple-pm-bus" driver calls `pm_runtime_enable()` and populates children
- PM Domain is managed correctly
DT describes the hardware, not the behavior

- This PM Domain must not be powered down
- "always-on" property in DT
- Prohibits a proper future solution

- Ask yourself: why must this PM Domain not be powered down?
- Reference PM domain from (new) device node that uses it
- Have a driver or platform code that powers up the PM domain (and keeps it powered up)
Examples: Special Devices, No Runtime PM Support

- Scan DT topology to find PM Domains containing special devices
- Handle in platform code:
  - Protect against runtime suspend:
    ```c
    pm_genpd_init(..., &pm_domain_always_on_gov, ...);
    ```
  - Protect against system suspend:
    ```c
    static int power_off_always_busy(void)
    {
        /* This domain should not be turned off */
        return -EBUSY;
    }
    
    genpd->power_off = power_off_always_busy;
    ```
- Hopefully a temporary solution!
Examples: Special Devices, No Runtime PM Support

CPUs

- Scan DT for device nodes under "/cpus"
- Avoid power down while the CPU is busy
- Optional: Handle cpuidle

Serial Console

- no_console_suspend
- /sys/module/printk/parameters/console_suspend
- chosen/stdout-path
- struct device_node *of_stdout

static int power_off_console_busy(void)
{
    /* Keep the PM Domain on if "no_console_suspend" is set */
    return console_suspend_enabled ? 0 : -EBUSY;
}

genpd->power_off = power_off_console;
Examples: Special Devices, No Runtime PM Support

ARM Coresight-ETM (Debug)

- `arch/arm/kernel/hw_breakpoint.c` accesses debug registers unconditionally
- Add minimal device node for Coresight-ETM
- Scan DT for "arm,coresight-etm3x"

Memory Controllers

- No driver for memory controller
- Add minimal device node for memory controller
- Scan DT for known memory controllers
Challenges

Interrupt controllers using `IRQCHIP_DECLARE`

- Initialized too early, not part of PM Domain
- Not a platform device, no Runtime PM

DMA and IOMMUs

- DMA mappings are typically created during device probe
- Runtime PM only knows about active devices, not about active DMA mappings
- When to suspend/resume IOMMUs?
Thanks & Acknowledgements

- **Renesas Electronics Corporation**, for contracting me to do Linux kernel work,

- The **Linux Foundation**, for organizing this conference and giving me the opportunity to present here,

- The **Renesas Linux Kernel Team**, for insights and discussions,

- The **Linux Kernel Community**, for having so much fun working together towards a common goal.
Appendix
Linux Kernel Source Tree References

Documentation/power/devices.txt
Documentation/power/runtime_pm.txt
Documentation/devicetree/bindings/power/power_domain.txt
include/linux/pm.h
include/linux/pm_domain.h
include/linux/pm_runtime.h
include/linux/pm_clock.h
drivers/base/power/domain.c
drivers/base/power/domain_governor.c
drivers/base/power/runtime.c
drivers/base/power/clock_ops.c