# Improvisation and demonstration of Linux thermal framework for multiple temperature sensors

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# Agenda

- Need of Thermal Management Unit
- Overview of TMU
- Overview on Thermal framework
- Thermal Management in Linux Kernel
- Thermal device structure and functions
- Pseudocode of Conventional TMU driver
- Demo of interface from user space for Thermal Framework
- TMU in Complex SoC
- Limitation in Conventional driver for TMU in Complex SoC
- Pseudocode of Complex SoC TMU driver
- Scope for improvisation in thermal framework

# Need of Thermal Management Unit

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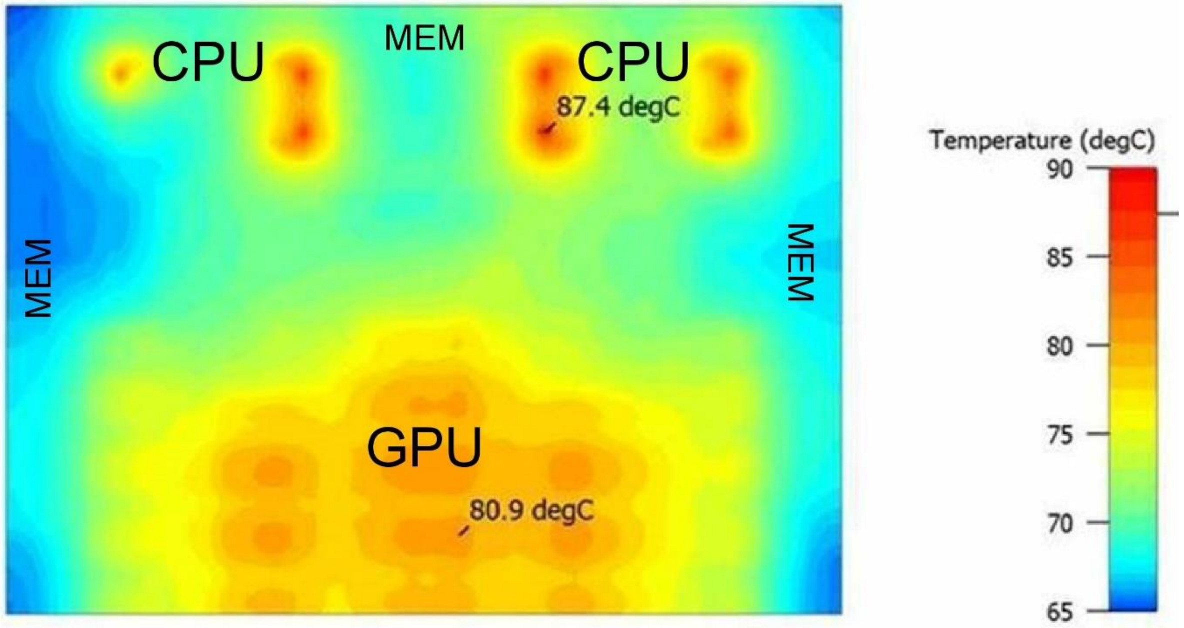
- SoC temperature increases during High computation and High frequency operation or during High Load
- High temperature of SoC results in:
  - SoC poor performance
  - SoC malfunction
  - SoC permanent damage
- Solution:
  - **Thermal throttling**: Clock speed will be reduced and performance will be limited to reduce the heat buildup
  - **Thermal cooling**: Switch on the fan or any other cooling device
  - **Thermal tripping**: Indicate PMU or voltage regulator to cut-off the power supply to SoC
- Above mentioned solutions can be achieved using Thermal Management Unit (TMU)

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# Overview of TMU

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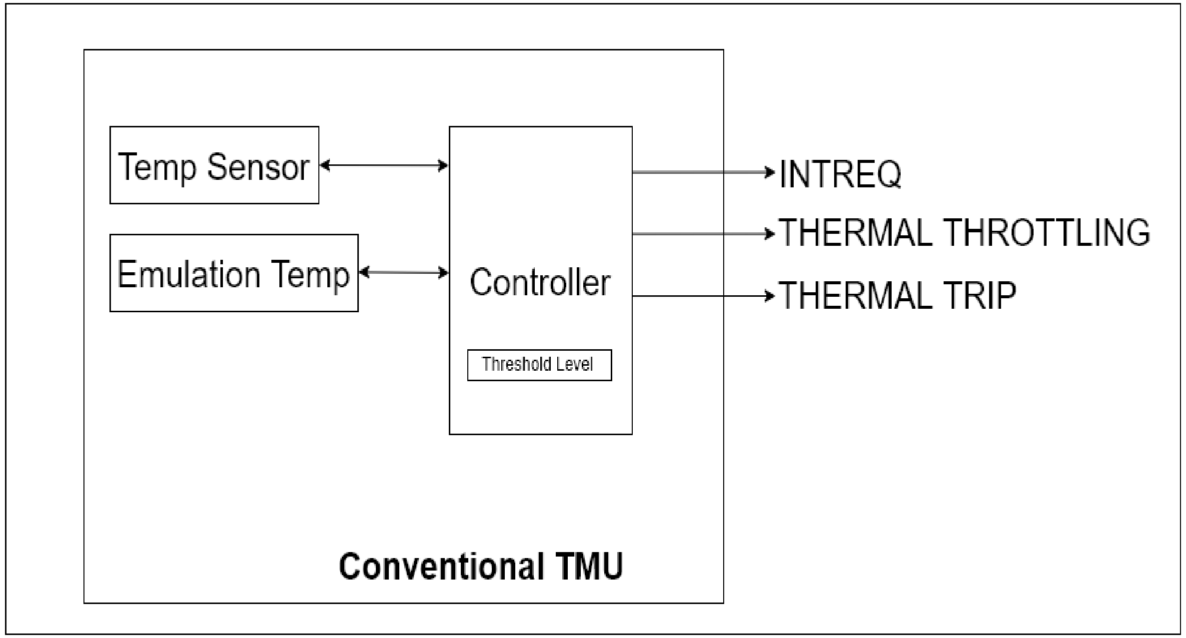
Thermal Management Unit (TMU)

- ❑ TMU have a Controller and a Sensor integrated with in.
- ❑ Each block of SoC can have separate TMU placed in it, if temperature need to be monitored.
- ❑ Controller configures the temperature sensor and initiates sensing of temperature.
- ❑ TMU can be configured with different Temperature Threshold Levels.
- ❑ TMU generates Interrupt when sensed temperature crosses these Threshold Levels.
- ❑ TMU will have separate Threshold level and Interrupts for Thermal throttling and Thermal tripping.
- ❑ Some of vendors provide Emulation Mode support in their TMU.



# Overview on Thermal framework



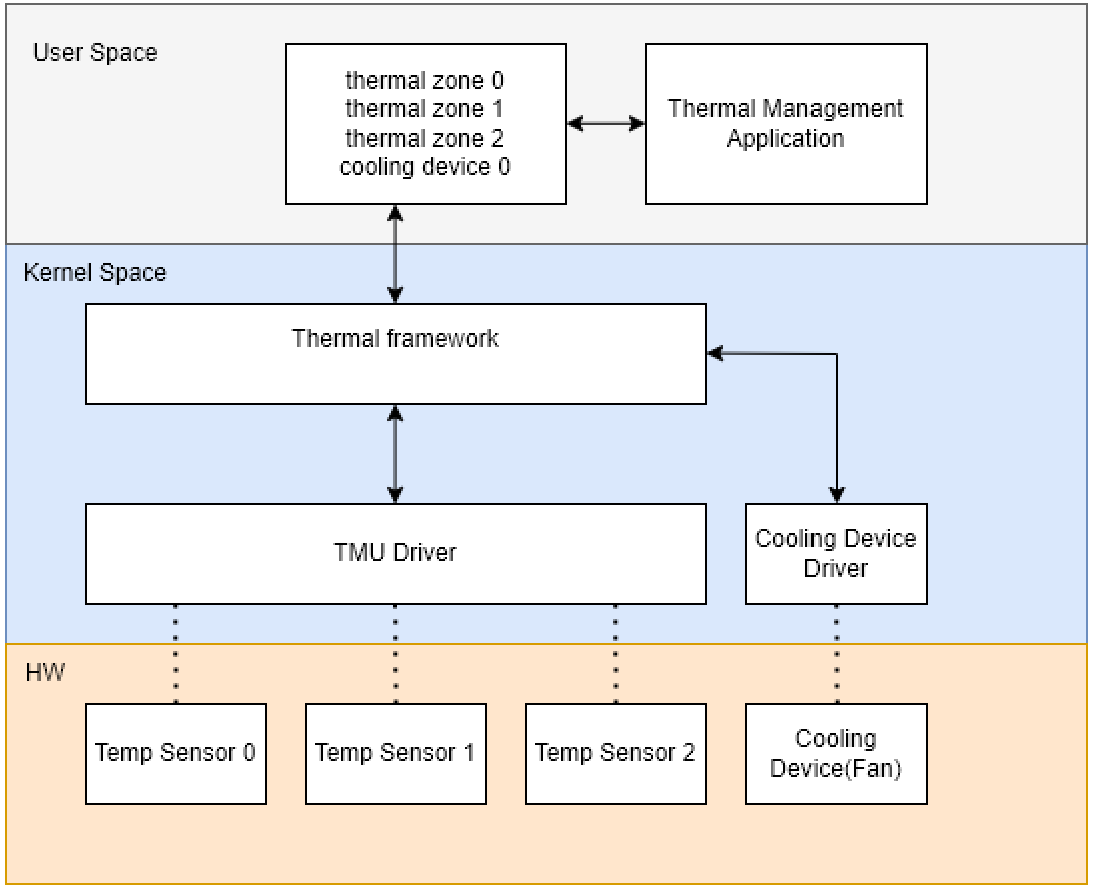
- Thermal zone device -> TMU + Temperature Sensor
- Cooling devices -> Fan or any other device

- Exposes thermal zone devices and cooling devices to the user space.

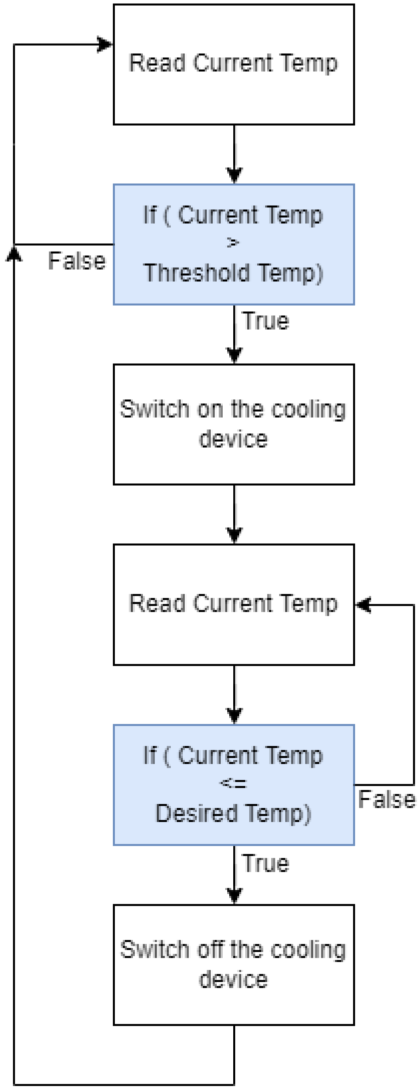
- These devices has to be registered with thermal framework.

- Registered devices becomes part of thermal management and made available to the user space

- User space application can make decisions based on current temperature and threshold temperatures



# Thermal Management in Linux Kernel



# Thermal device ops Structures

- struct **thermal_zone_device_ops**

<u>Commonly used function pointers</u>

- **bind**: binds the thermal zone device with a thermal cooling device.
- **unbind**: unbinds thermal zones from thermal cooling device.
- **get_temp**: reads the sensor temperature.
- **set_trips**: sets the trip temperature window.
- **change_mode**: switches thermal management between kernel and user space.
- **get_trip_temp**: get trip temp threshold above which trip interrupt will be triggered.
- **set_trip_temp**: change trip temp threshold.
- **set_emul_temp**: set the emulation temperature

```
struct thermal_zone_device_ops {
	int (*bind) (struct thermal_zone_device *,
		     struct thermal_cooling_device *);
	int (*unbind) (struct thermal_zone_device *,
		       struct thermal_cooling_device *);
	int (*get_temp) (struct thermal_zone_device *, int *);
	int (*set_trips) (struct thermal_zone_device *, int, int);
	int (*change_mode) (struct thermal_zone_device *,
		enum thermal_device_mode);
	int (*get_trip_type) (struct thermal_zone_device *, int,
		enum thermal_trip_type *);
	int (*get_trip_temp) (struct thermal_zone_device *, int, int *);
	int (*set_trip_temp) (struct thermal_zone_device *, int, int);
	int (*get_trip_hyst) (struct thermal_zone_device *, int, int *);
	int (*set_trip_hyst) (struct thermal_zone_device *, int, int);
	int (*get_crit_temp) (struct thermal_zone_device *, int *);
	int (*set_emul_temp) (struct thermal_zone_device *, int);
	int (*get_trend) (struct thermal_zone_device *, int,
			  enum thermal_trend *);
	void (*hot)(struct thermal_zone_device *);
	void (*critical)(struct thermal_zone_device *);
};
```

# Thermal device ops Structures



- struct **thermal_zone_of_device_ops** (device tree)

<u>Below are basic function pointers</u>

- **get_temp**: reads the sensor temperature.
- **get_trend**: calculates rate of change of temperature.
- **set_trips**: sets the trip temperature window.
- **set_emul_temp**: set the emulation temperature.
- **set_trip_temp**: change trip temp threshold.

```
struct thermal_zone_of_device_ops {
        int (*get_temp)(void *, int *);
        int (*get_trend)(void *, int, enum thermal_trend *);
        int (*set_trips)(void *, int, int);
        int (*set_emul_temp)(void *, int);
        int (*set_trip_temp)(void *, int, int);
};
```

# Cooling device ops Structures

- struct **thermal_cooling_device_ops**

Below are basic function pointers

- **get_max_state**: Max possible state of cooling devices
- **get_cur_state**: read current state of cooling device.
- **set_cur_state**: sets current state of cooling device.
- **get_requested_power**: calculates the power requested by cooling device.
- **state2power**: Calculate the power consumption based on cooling device state.
- **power2state**: Calculate the stage based on power consumption.

```
struct thermal_cooling_device_ops {
        int (*get_max_state) (struct thermal_cooling_device *, unsigned long *);
        int (*get_cur_state) (struct thermal_cooling_device *, unsigned long *);
        int (*set_cur_state) (struct thermal_cooling_device *, unsigned long);
        int (*get_requested_power)(struct thermal_cooling_device *, u32 *);
        int (*state2power)(struct thermal_cooling_device *, unsigned long, u32 *);
        int (*power2state)(struct thermal_cooling_device *, u32, unsigned long *);
};
```

# Thermal device register function



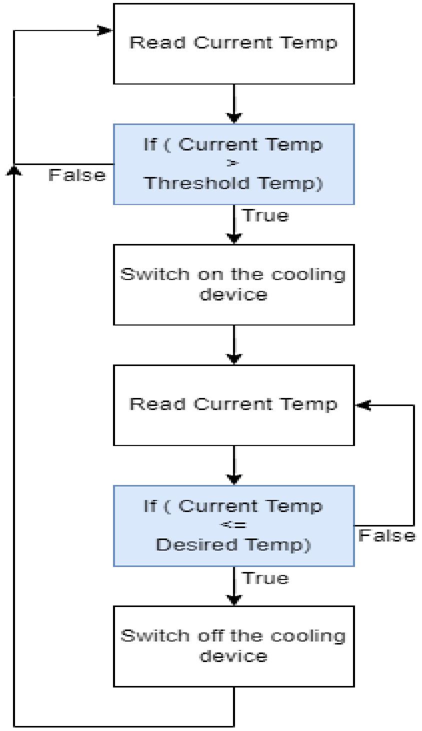
thermal_zone_device_register

- This function adds a new thermal zone device in the folder /sys/class/thermal.
- Bind all the thermal cooling devices registered at the same time.
- thermal_zone_device_unregister() must be called if device is no longer needed.

```
struct thermal_zone_device *
thermal_zone_device_register(const char *type, int trips, int mask,
                             void *devdata, struct thermal_zone_device_ops *ops,
                             struct thermal_zone_params *tzp, int passive_delay,
                             int polling_delay)
```

```
[redacted]:~$ ls /sys/class/thermal/
cooling_device0/  cooling_device1/  cooling_device2/  cooling_device3/
thermal_zone0/    thermal_zone1/
```

- **type**: thermal zone type
- **trips**: the number of trip points the thermal zone support
- **mask**: trip points are writeable or not
- **devdata**: device data
- **ops**: standard thermal zone device callbacks
- **tzp**: thermal zone platform parameters
- **passive_delay**: delay to wait between polls when performing cooling
- **polling_delay**: delay to wait between polls when checking whether threshold points have been crossed or not



# Thermal device register function

thermal_zone_of_sensor_register (device tree) :

- This function will search the thermal zones in device tree and adds new sensor to DT thermal zone.

```
struct thermal_zone_device *
thermal_zone_of_sensor_register(struct device *dev, int sensor_id, void *data,
                                const struct thermal_zone_of_device_ops *ops)
```

- **dev**: device node of the sensor
- **sensor_id**: sensor identifier
- **data**: a private pointer that will be passed back, when a temperature reading is needed.
- **ops**: struct thermal_zone_of_device_ops

# Cooling device register function



<u>thermal_cooling_device_register</u>

- This function registers and creates ***cooling_device*** file in the folder ***/sys/class/thermal/***
- It checks and binds to the thermal zone.

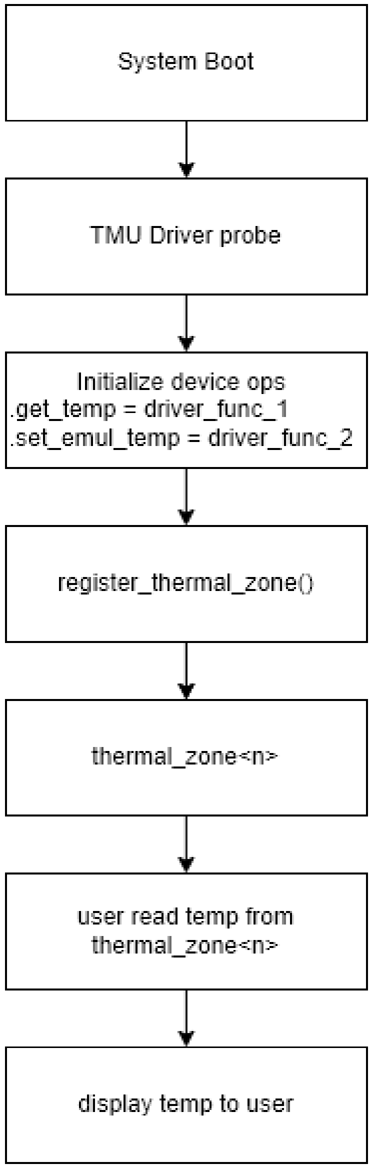
```
struct thermal_cooling_device *
thermal_cooling_device_register(const char *type, void *devdata,
                                const struct thermal_cooling_device_ops *ops)
```

```
[redacted]:~$ ls /sys/class/thermal/
cooling_device0/  cooling_device1/  cooling_device2/  cooling_device3/
thermal_zone0/    thermal_zone1/
```

- **type**: the cooling device name.
- **devdata**: device private data.
- **ops**: struct thermal_cooling_device_ops

# Flow diagram of register thermal zone

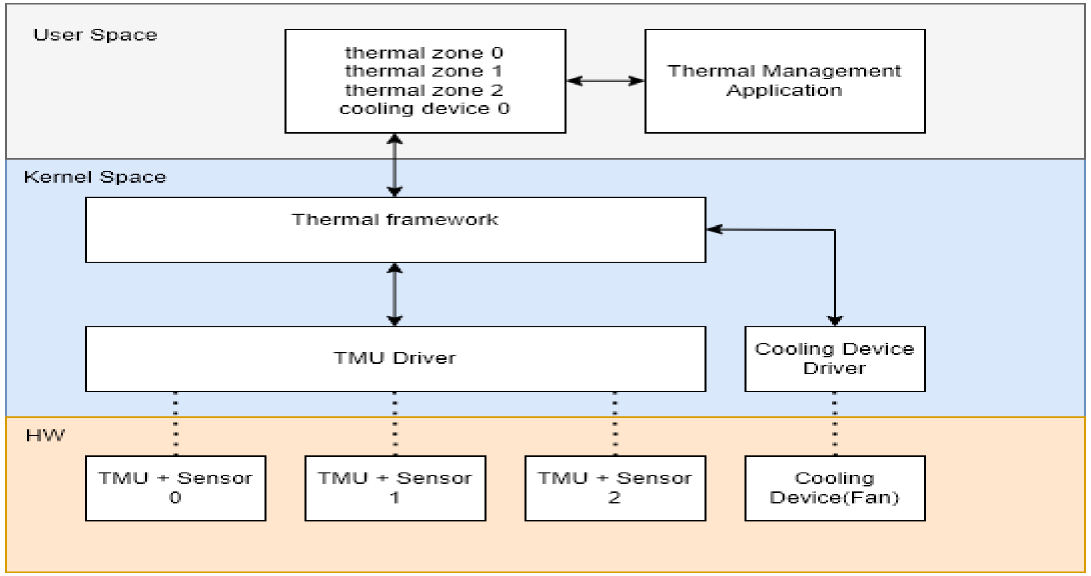




# Pseudocode of Conventional TMU driver

- Define device_ops and initialize “get_temp” pointer to the function which reads sensor temperature.
- Call function to register thermal zone in probe function of tmu driver.
- Pass device_ops which is already initialized.
- Driver might have init_func to initialize TMU.

- <tmu_driver_probe> happens multiple times.
- Each instance of TMU will be probed separately.
- Consumes additional memory and time to probe.




```
/*******************************/
/*Driver instance for TMU-0 ***/
/*******************************/
static int <driver_probe_for_tmu_0>(struct platform_device *pdev)
{
        thermal_zone_device_register(<tmu_0>);
        tmu_init_func(<tmu_0>);
}

struct thermal_zone_device_ops <tmu_0> = {
        .get_temp = read_sensor_temperature_func();
}

/*******************************/
/*Driver instance for TMU-1 ***/
/*******************************/
static int <driver_probe_for_tmu_1>(struct platform_device *pdev)
{
        thermal_zone_device_register(<tmu_1>);
        tmu_init_func(<tmu_1>);
}

struct thermal_zone_device_ops <tmu_1> = {
        .get_temp = read_sensor_temperature_func();
}
.
.
.
.
.
/*******************************/
/*Driver instance for TMU-n ***/
/*******************************/
static int <driver_probe_for_tmu_n>(struct platform_device *pdev)
{
        thermal_zone_device_register(<tmu_n>);
        tmu_init_func(<tmu_n>);
}

struct thermal_zone_device_ops <tmu_n> = {
        .get_temp = read_sensor_temperature_func();
}
```

# Demo of get temp and set emulation

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```
# ls /sys/class/thermal/
thermal_zone0  thermal_zone1  thermal_zone2
thermal_zone3  thermal_zone4

# ls /sys/class/thermal/thermal_zone0/
temp                  sustainable_power
available_policies    uevent
emul_temp             trip_point_0_hyst
integral_cutoff       trip_point_0_temp
k_d                   trip_point_0_type
k_i                   trip_point_1_hyst
k_po                  trip_point_1_temp
k_pu                  trip_point_1_type
mode                  type
offset
power
slope
subsystem

# cat /sys/class/thermal/thermal_zone0/temp
34000

# cat /sys/class/thermal/thermal_zone?/temp
34000
35000
36000
34000
35000
```

```
# cat /sys/class/thermal/thermal_zone?/temp
34000
35000
36000
34000
34000

# ls /sys/class/thermal/thermal_zone0/
temp                  sustainable_power
available_policies    uevent
emul_temp             trip_point_0_hyst
integral_cutoff       trip_point_0_temp
k_d                   trip_point_0_type
k_i                   trip_point_1_hyst
k_po                  trip_point_1_temp
k_pu                  trip_point_1_type
mode                  type
offset
power
slope

# echo 1000 > /sys/class/thermal/thermal_zone0/emul_temp
# echo 1000 > /sys/class/thermal/thermal_zone1/emul_temp
# echo 1000 > /sys/class/thermal/thermal_zone2/emul_temp
# cat /sys/class/thermal/thermal_zone?/temp
1000
1000
1000
34000
34000
```

# Demo of on policies

```
# ls /sys/class/thermal/thermal_zone0/
temp                sustainable_power
available_policies  uevent
emul_temp           trip_point_0_hyst
integral_cutoff     trip_point_0_temp
k_d                 trip_point_0_type
k_i                 trip_point_1_hyst
k_po                trip_point_1_temp
k_pu                trip_point_1_type
mode                type
offset
policy
power
slope
subsystem

# cat /sys/class/thermal/thermal_zone0/available_policies
power_allocator step_wise

# cat /sys/class/thermal/thermal_zone0/policy
step_wise
```

- Policies : Thermal governor to manage over all thermal functionality

<u>Power allocator</u>

- Closed loop control.
- Based on power budget, temperature and current power consumption
- Implements PID controller with temperature as control input and power as control output.
- k_d, k_i, k_po, k_pu constants for PID controller.
- integral_cutoff : cooling devices cant bring down temperature to the exact value the governor has requested. This field represents max offset allowed.

- <u>Step Wise</u>
- Open loop control.
- Based on temperature threshold and rate of change
- Walk through each cooling state of each cooling device

# Demo of on trip points

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```
ls /sys/class/thermal/thermal_zone0/trip_point_
trip_point_0_hyst   trip_point_2_hyst   trip_point_4_hyst   trip_point_6_hyst
trip_point_0_temp   trip_point_2_temp   trip_point_4_temp   trip_point_6_temp
trip_point_0_type   trip_point_2_type   trip_point_4_type   trip_point_6_type
trip_point_1_hyst   trip_point_3_hyst   trip_point_5_hyst   trip_point_7_hyst
trip_point_1_temp   trip_point_3_temp   trip_point_5_temp   trip_point_7_temp
trip_point_1_type   trip_point_3_type   trip_point_5_type   trip_point_7_type

# cat /sys/class/thermal/thermal_zone0/trip_point_?_type
passive
passive
passive
passive
passive
passive
passive
critical

# cat /sys/class/thermal/thermal_zone0/trip_point_?_temp
92000
95000
97000
100000
102000
105000
107000
112000

# cat /sys/class/thermal/thermal_zone0/trip_point_?_hyst
1000
1000
1000
1000
1000
1000
1000
0
```



- 0 ~ 7 threshold levels. Total 8 points
- Based on this threshold points, governor loop switch on the cooling devices and operate the cooling device in different state.

- 0 ~ 6 are passive trip points.
- 7$^{th}$ is critical trip point upon which power to the should be cut-off

- Trip temperature is displayed to user in milli-celsius range

- Hysteresis is the minimum change needed for thermal governed to take the next action

# Demo of on mode and type

```
# ls /sys/class/thermal/
thermal_zone0  thermal_zone1  thermal_zone2
thermal_zone3  thermal_zone4

# cat /sys/class/thermal/thermal_zone?/mode
enabled
enabled
enabled
enabled
disabled

cat /sys/class/thermal/thermal_zone?/type
cpu0-block-temp
cpu1-block-temp
cpu2-block-temp
cpu3-block-temp
gpu0-block-temp
```



mode

- Current mode of thermal zone
- Enabled : kernel thermal management is enabled
- Disabled: kernel thermal management doesn't take action upon trip points. User space application take charge of thermal management

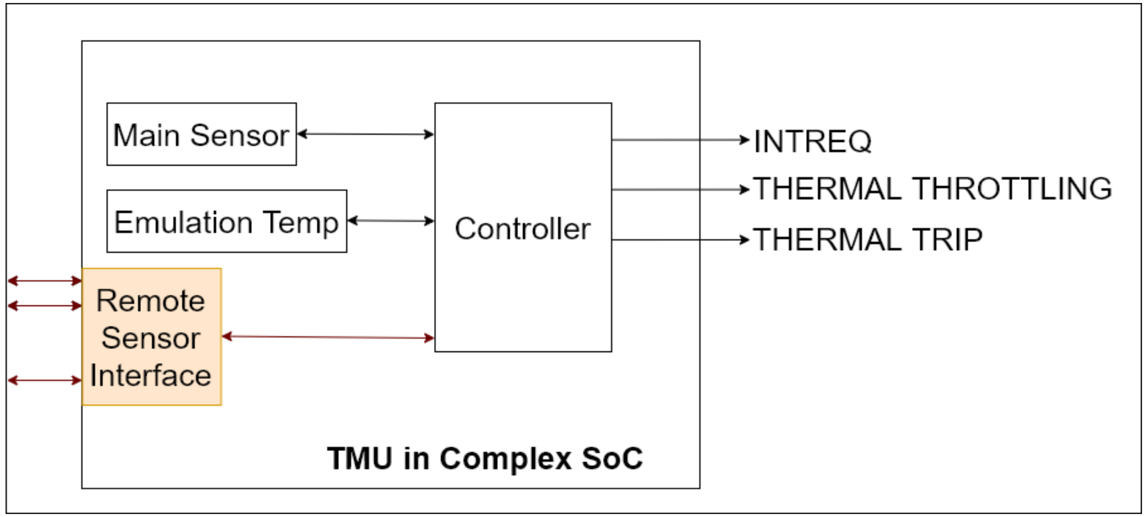
type

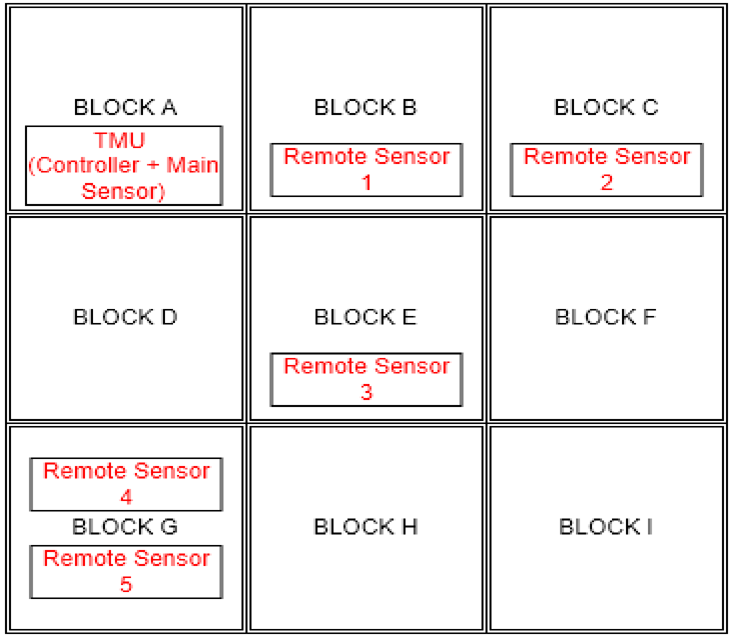
- Name of the thermal zone

# TMU in Complex SoC



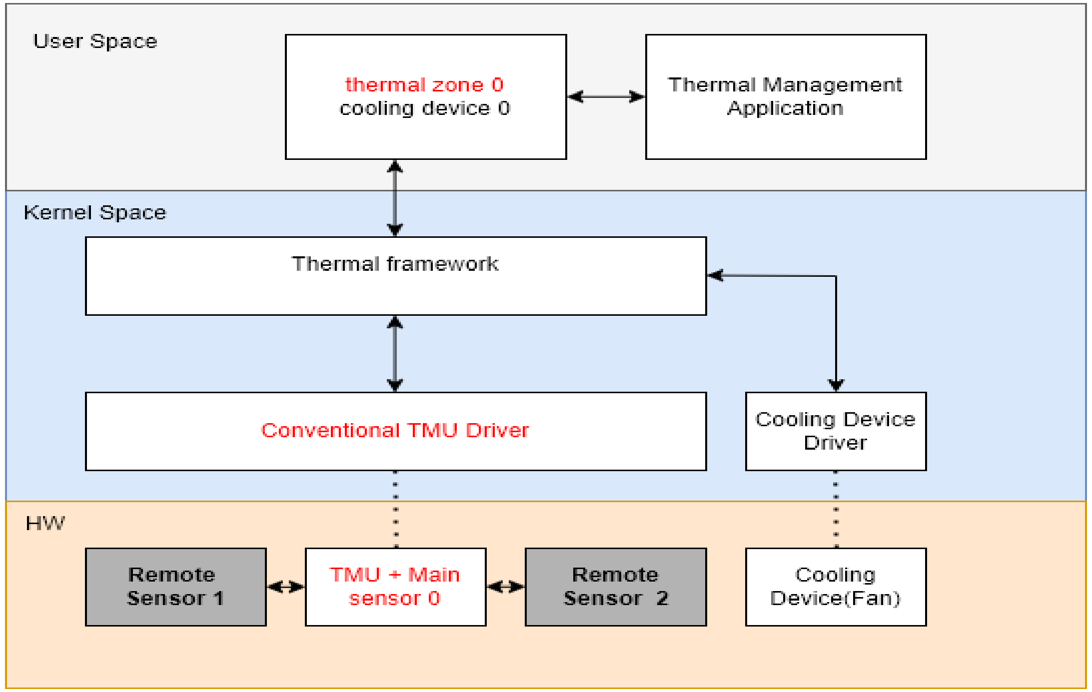
- TMU in complex SoC may have Remote Sensor Interface additionally to Conventional TMU.
- Entire SoC can have a single TMU controller.
- If any block of SoC need to be monitored, then only Remote sensor has to be placed in that block.
- Sensor placed at different blocks of SoC is controlled and monitored by single TMU controller .
- Size and Cost can be reduced.



# Limitation in Conventional driver for TMU in Complex SoC

- In Complex SoC, TMU Controller, Main Sensor and Remote sensors are represented as single unit.
- Remote Sensors are connected to TMU controllers via Remote Sensor Interface.
- Using Conventional TMU driver, can expose only Main Sensor to the user space.
- User will not be able to read temperatures from Remote Sensors.



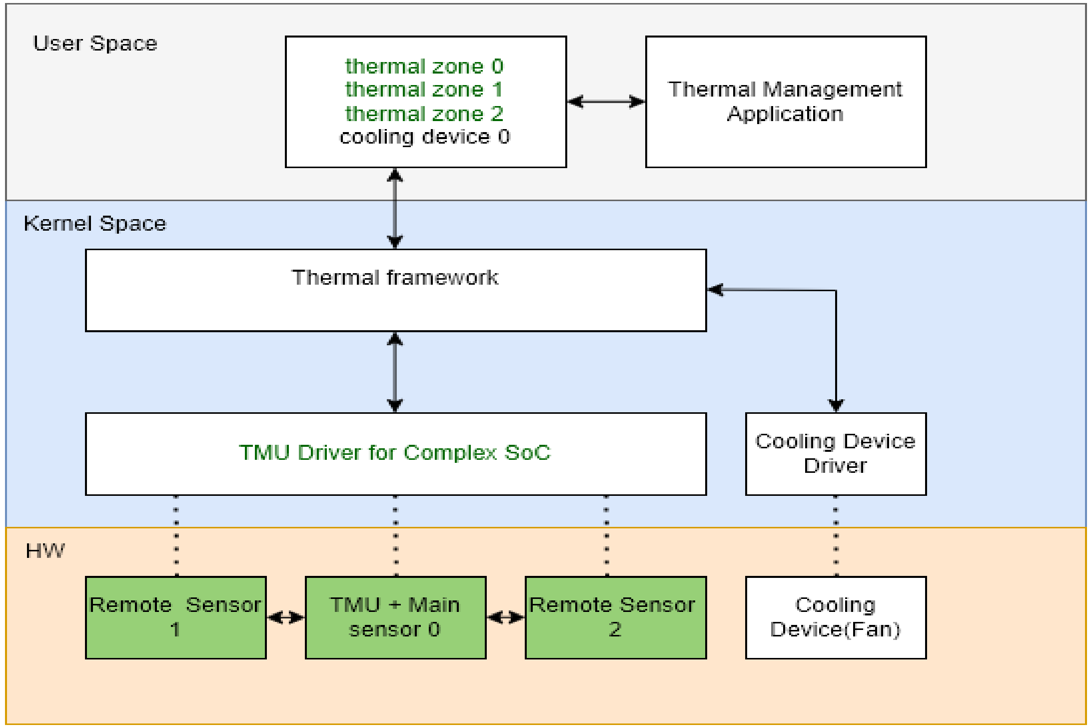

```
/******************************/
/*Driver instance for TMU-0 ***/
/******************************/
static int <driver_probe_for_tmu_0>(struct platform_device *pdev)
{
        thermal_zone_device_register(<tmu_0>);
        tmu_init_func(<tmu_0>);
}

struct thermal_zone_device_ops <tmu_0> = {
        .get_temp = read_sensor_temperature_func();
}
```

# Pseudocode of Complex SoC TMU driver



- Define separate device_ops for each sensor and initialize "get_temp" to driver function to read temp.
- In driver probe, register thermal zone for each sensor and pass respective device_ops.

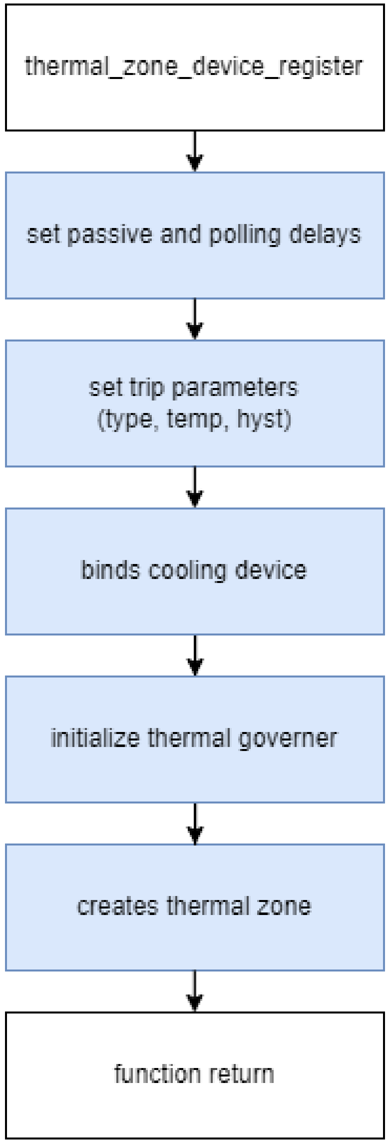
- <tmu_driver_probe> happens only once.



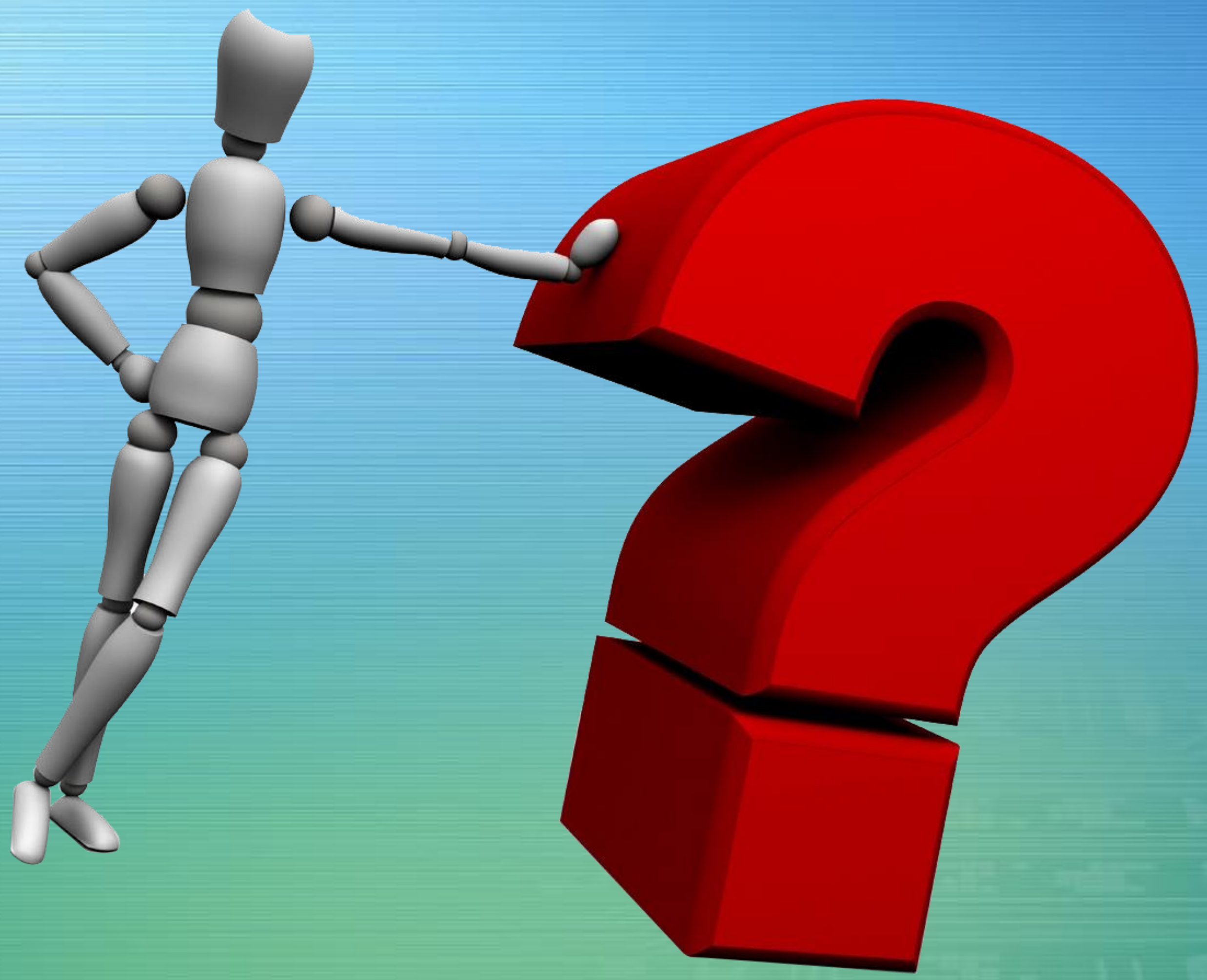

```
/**************************************************/
/*Single Driver instance for TMU in Complex SoC ***/
/**************************************************/
static int <driver_probe_for_tmu>(struct platform_device *pdev)
{
        thermal_zone_device_register(<main_sensor>);
        thermal_zone_device_register(<remote_sensor_1>);
        thermal_zone_device_register(<remote_sensor_2>);
        .
        .
        thermal_zone_device_register(<remote_sensor_n>);

        tmu_init_func(<tmu_controller>);
}

struct thermal_zone_device_ops <main_sensor> = {
        .get_temp = read_main_sensor_func();
}

struct thermal_zone_device_ops <remote_sensor_1> = {
        .get_temp = read_remote_sensor_1_func();
}

struct thermal_zone_device_ops <remote_sensor_2> = {
        .get_temp = read_remote_sensor_2_func();
}
.
.
.
struct thermal_zone_device_ops <remote_sensor_n> = {
        .get_temp = read_remote_sensor_n_func();
}
```

# Current Thermal zone device register function





# Any Questions ?



# THANK YOU