A New AMD CPU Performance Scaling Proposal on Linux®

Huang Rui

Background

- VKD3D-Pronton Tuning on AMD APU (CPU + GPU) Platforms
  - The original problems are found by Valve Software (Link)
    - Incorrect CPU maximum frequency
      - https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/commit/?id=3743d55b289c203d8f77b7cd47c24926b9d186ae
    - Slow slow-motion on Horizon Zero Dawn
      - Horizon Zero Dawn is Direct3D games which is using vkd3d-pronton to implement DirectX® games cross-platform on Steam Linux®
      - Issue is caused from the incorrect use with CPUFreq sysfs call on Wine
- Kernel CPUFreq on AMD Processors
  - By co-working with Valve software engineers on two issues, we found the original CPU performance scaling module was still based on the legacy kernel common ACPI cpufreq driver on AMD processors
  - This ACPI cpufreq driver is not very performance/power efficiency for modern AMD platforms right now

Legacy CPU Freq Design and Potential Conflict

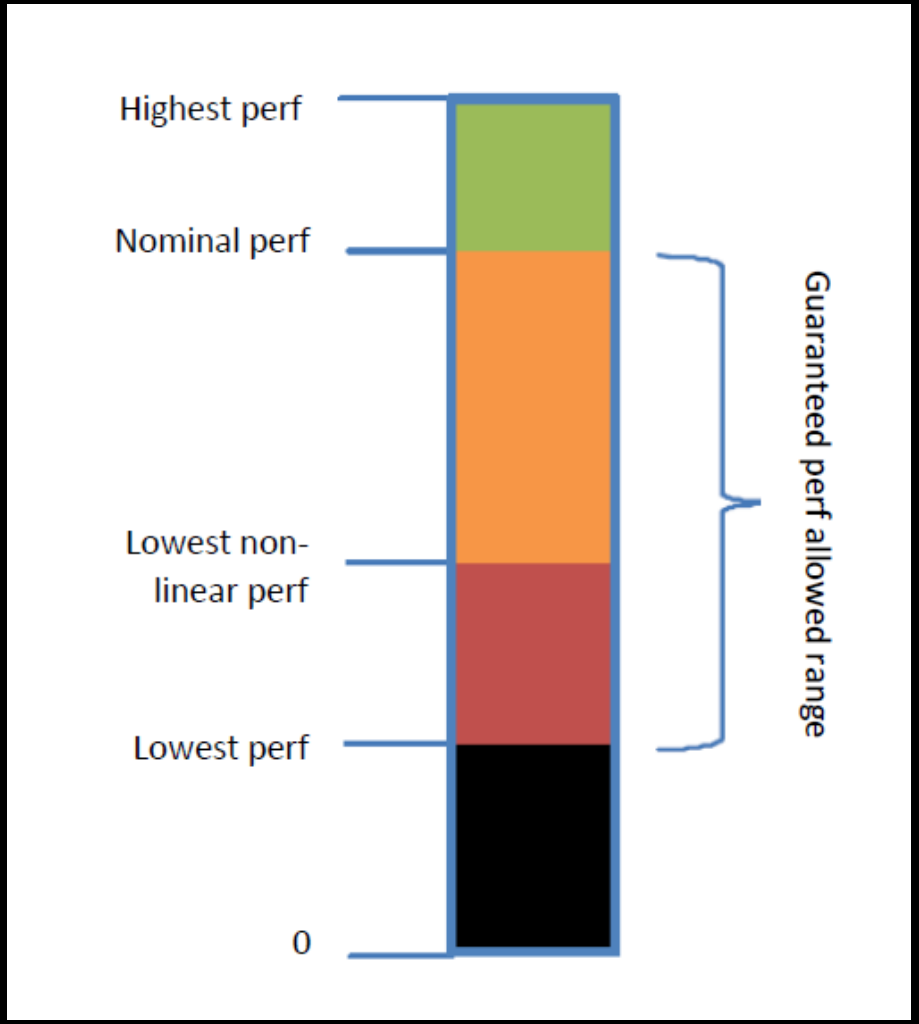
- Legacy CPU Freq Design
  - Linux Kernel provides existing CPU Freq framework to use software governor (Ondemand) policy to control CPU frequency and clocks
  - Intel implemented ACPI based CPU frequency driver which is using on legacy Intel CPU (before Sandy Bridge) then switch to Intel specific Pstate driver in recent CPU series
  - Current AMD CPU platforms are still using ACPI based CPU frequency driver to manage CPU frequency and clocks with switching only in **3 P-states**
  - ACPI based CPU frequency driver develops on Intel platforms and might bring some potential issues on AMD processors
- Potential Conflict with SMU Cclk (CPU Clock) Dynamic Power Management (DPM)
  - Cclk DPM provides the firmware-based method to control the CPU frequency as well
  - The Cclk DPM and ACPI CPU Freq driver control would have the conflict to impact the target frequency

New AMD CPU Freq Design Proposal

- CPU Hardware Dependencies
  - SMU Cclk DPM - Sampling C0 residency (CPU Idle)
  - SBIOS ACPI CPPC Tables
  - CPU MSR is the backend
    - The reliability and accuracy of MSR APIs should be the same with CPPC
    - MSR is the low-latency register model that is faster than ACPI AML code interpreter
- **Design a new CPPC Based CPU Freq Driver for AMD Processors**
  - Implement a new amd-pstate driver instead of acpi-cpufreq driver on AMD platform
  - Use fine grain CPPC frequency range instead of ACPI 3 P-States to control CPU frequency
  - “schedutil” governor can predict the workload to calculate more reasonable desired performance value via Linux® CPU CFS scheduler
  - Use “schedutil” governor to optimize the solution, and manage the hints to SMU Cclk DPM Arbiter and then calculate the target frequency

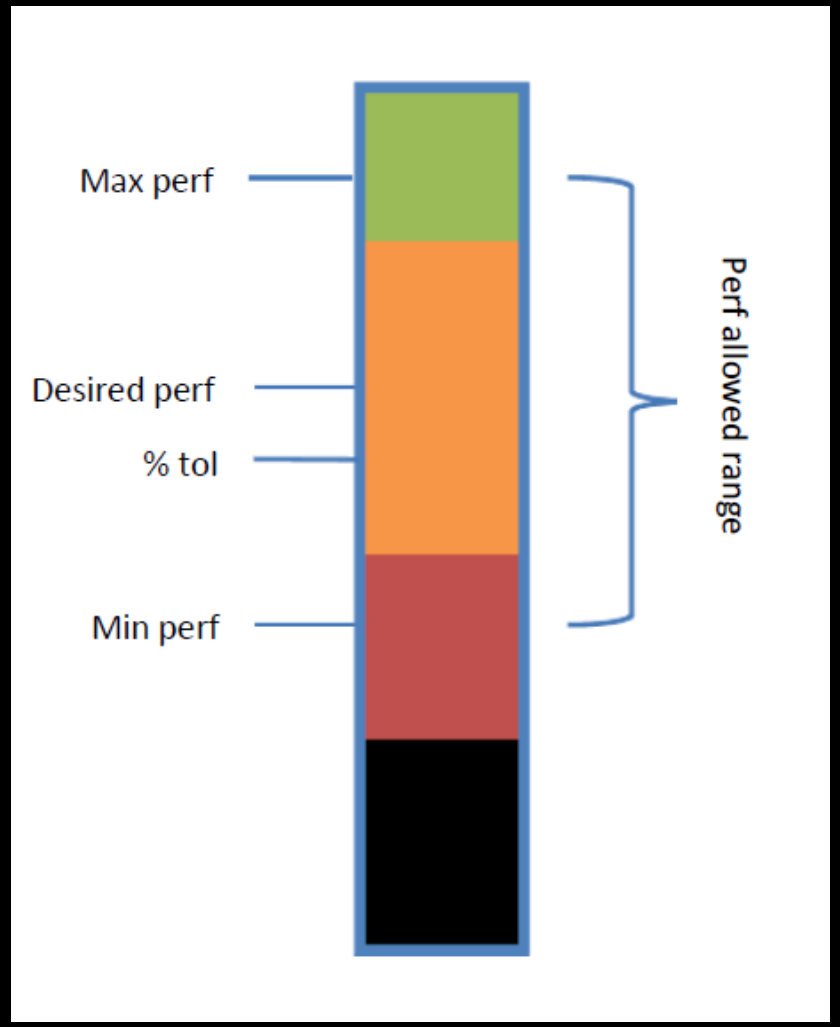
AMD P-States Performance Capability

- Highest Performance (RO)
  - It is the absolute maximum performance an individual processor may reach, assuming ideal conditions
- Nominal (Guaranteed) Performance (RO)
  - It is the maximum sustained performance level of the processor, assuming ideal operating conditions
- Lowest non-linear Performance (RO)
  - It is the lowest performance level at which nonlinear power savings are achieved, for example, due to the combined effects of voltage and frequency scaling
- Lowest Performance (RO)
  - It is the absolute lowest performance level of the processor



AMD P-States Performance Control

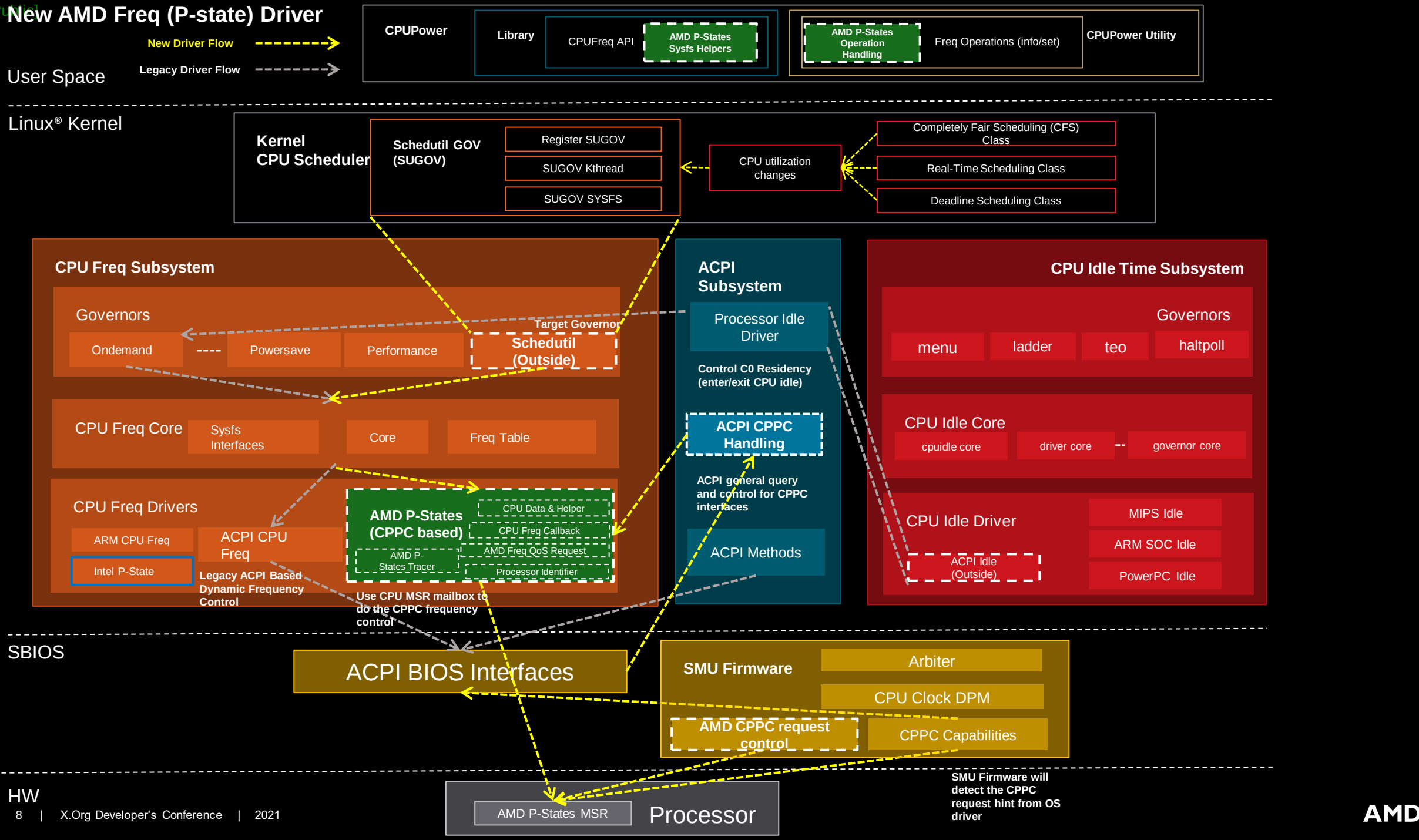
- Minimum Requested Performance (RW)
  - Software specifies the minimum allowed performance level
- Maximum Requested Performance (RW)
  - Software specifies a limit the maximum performance that is expected to be supplied by the hardware
- Desired performance target (RW)
  - Software specifies a desired QoS target in the performance scale as a relative number
- Energy Performance Preference (EPP) (RW)
  - Provides a hint to the hardware if software wants to bias toward performance (0x0) or energy efficiency (0xff)



Frequency Control Governors in Linux Kernel

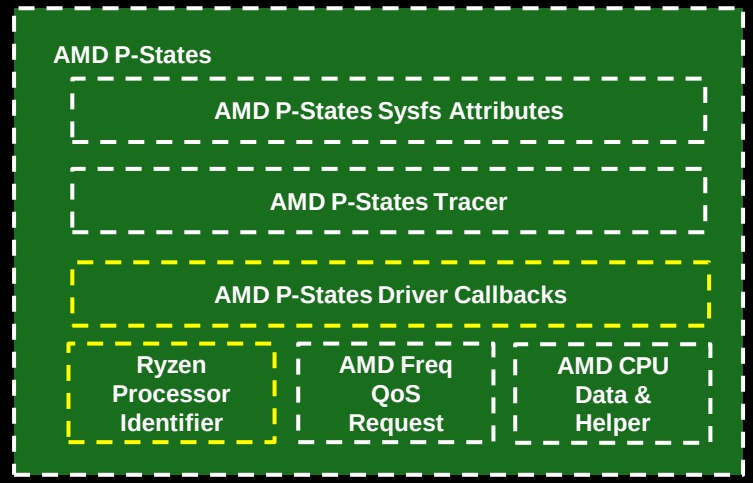
- Traditional Max/Min Governor: Performance/Powersave
  - Performance
    - Set the minimum performance as the nominal performance value
    - Set the maximum performance as the highest performance value
  - Powersave
    - Set the minimum performance as the lowest nonlinear performance value
    - Set the maximum performance as the lowest nonlinear performance value
- Legacy Dynamic Control Governor: Ondemand
  - This governor sets the CPU frequency depending on the current system load
- CPU CFS Scheduler Governor: Schedutil
  - This "schedutil" governor uses PELT-based next frequency formula
  - Per-Entity Load Tracking (PELT) mechanism in the Linux® kernel scheduler

New AMD Freq (P-state) Driver



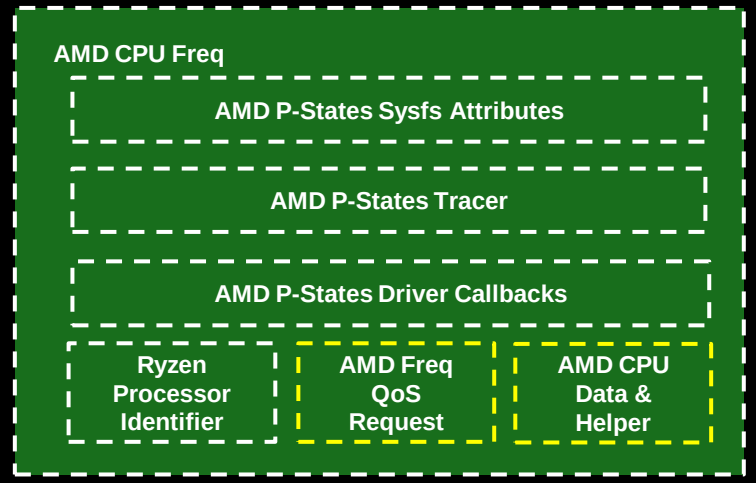
New AMD-PSTATE Core Design and Implementation (1)

- **Introduce a new CPU Freq Kernel Module: “AMD_PSTATE”**
  - Manage the CPU frequency and performance via AMD P-States API with multiple Linux® kernel governors.
  - Ryzen Processor Identifier
    - Identify the AMD P-States with _CPC check.
    - Identify the AMD P-States for full MSR support with bit 27 of *CPUID Fn80000008_EBX*
  - AMD CPU Freq Driver Callbacks
    - *amd_pstate_driver* instance
    - Callback functions of *struct cpufreq_driver*
    - *target* and *adjust_perf* method to support Ondemand and Schedutil governors
  - AMD CPU P-State reStructuredText (kernel documentation)
    - Implement amd-pstate CPU performance scaling driver RST documentation



New AMD-PSTATE Core Design and Implementation (2)

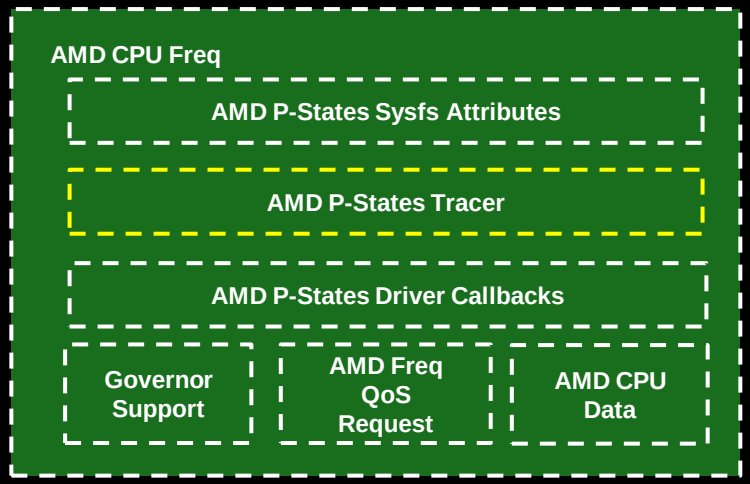
- **Introduce a new CPU Freq Kernel Module: “AMD_PSTATE”**
  - AMD CPU Data & Helper
    - Implement a *struct amd_cpudata* to store private AMD specific information and function callbacks
    - Implement MSR register write/read helpers
      - AMD P-States Capability
      - AMD P-States Request
  - AMD Freq QoS (Quality of Service) Request
    - *struct freq_qos_request*
  - Future Design Work (under planning)
    - Kernel parameters to switch different frequency management policies
    - Customization for the different management policy for specific product
    - EPP (Energy Performance Preference)
    - Preferred Core



AMD-PSTATE Tracer Design and Implementation

- **Two Trace Events for Diagnostics and Tunning**
  - *cpu_frequency* trace event from CPUFreq core
  - *amd_pstate_perf* trace event specific to amd-pstate

```
root@hr-test1:/home/ray# cd /sys/kernel/tracing/
root@hr-test1:/sys/kernel/tracing# echo 1 > events/amd_cpu/enable
root@hr-test1:/sys/kernel/tracing# cat trace
# tracer: nop
#
# entries-in-buffer/entries-written: 47827/42233061   #P:2
#
#                                _-----=> irqs-off
#                               / _----=> need-resched
#                              | / _---=> hardirq/softirq
#                              || / _--=> preempt-depth
#                              ||| /     delay
#           TASK-PID     CPU#  ||||   TIMESTAMP  FUNCTION
#              | |         |   ||||      |         |
          <idle>-0       [000] d.s. 244057.464842: amd_pstate_perf: amd_min_perf=39 amd_des_perf=39 amd_max_perf=166 cpu_id=0 prev=0x2727a6 value=0x2727a6
          <idle>-0       [000] d.h. 244057.475436: amd_pstate_perf: amd_min_perf=39 amd_des_perf=39 amd_max_perf=166 cpu_id=0 prev=0x2727a6 value=0x2727a6
          <idle>-0       [000] d.h. 244057.476629: amd_pstate_perf: amd_min_perf=39 amd_des_perf=39 amd_max_perf=166 cpu_id=0 prev=0x2727a6 value=0x2727a6
          <idle>-0       [000] d.s. 244057.484847: amd_pstate_perf: amd_min_perf=39 amd_des_perf=39 amd_max_perf=166 cpu_id=0 prev=0x2727a6 value=0x2727a6
          <idle>-0       [000] d.h. 244057.499821: amd_pstate_perf: amd_min_perf=39 amd_des_perf=39 amd_max_perf=166 cpu_id=0 prev=0x2727a6 value=0x2727a6
    avahi-daemon-528     [000] d... 244057.513568: amd_pstate_perf: amd_min_perf=39 amd_des_perf=39 amd_max_perf=166 cpu_id=0 prev=0x2727a6 value=0x2727a6
```



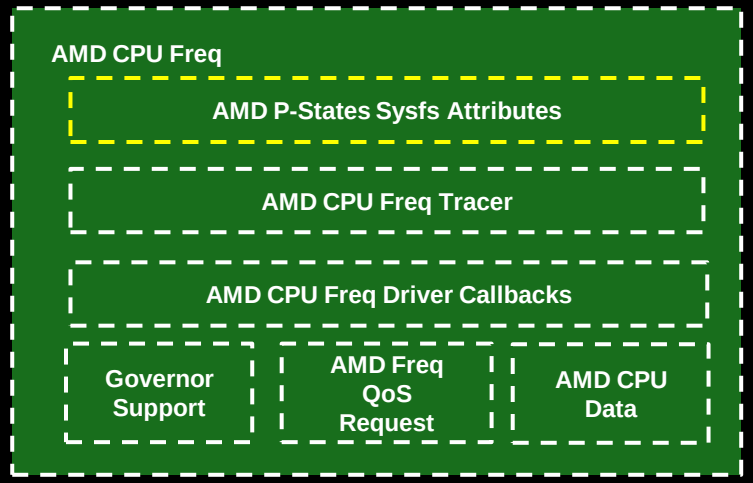
AMD-PSTATE Sysfs Attributes Design and Implementation

Global Kernel Sysfs Attributes For User Mode Library Query

- amd-pstate exposes several global attributes (files) in sysfs to control its functionality at the system level. They located in the /sys/devices/system/cpu/cpufreq/policyX/ directory and affect all CPUs

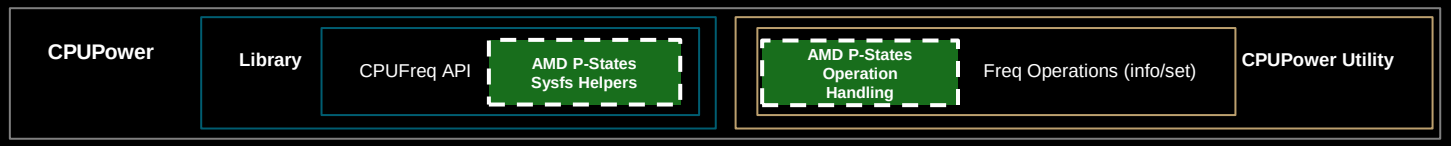
```
root@hr-test1:/home/ray# ls /sys/devices/system/cpu/cpufreq/policy0/*amd*
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_highest_perf
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_lowest_nonlinear_freq
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_lowest_nonlinear_perf
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_lowest_perf
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_max_freq
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_min_freq
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_nominal_freq
/sys/devices/system/cpu/cpufreq/policy0/amd_pstate_nominal_perf
/sys/devices/system/cpu/cpufreq/policy0/is_amd_pstate_enabled
```

- *is_amd_pstate_enabled*
- *amd_pstate_highest_perf / amd_pstate_max_freq*
- *amd_pstate_nominal_perf / amd_pstate_nominal_freq*
- *amd_pstate_lowest_nonlinear_perf / amd_pstate_lowest_nonlinear_freq*
- *amd_pstate_lowest_perf / amd_pstate_min_freq*



CPU Power Library and Tool Support

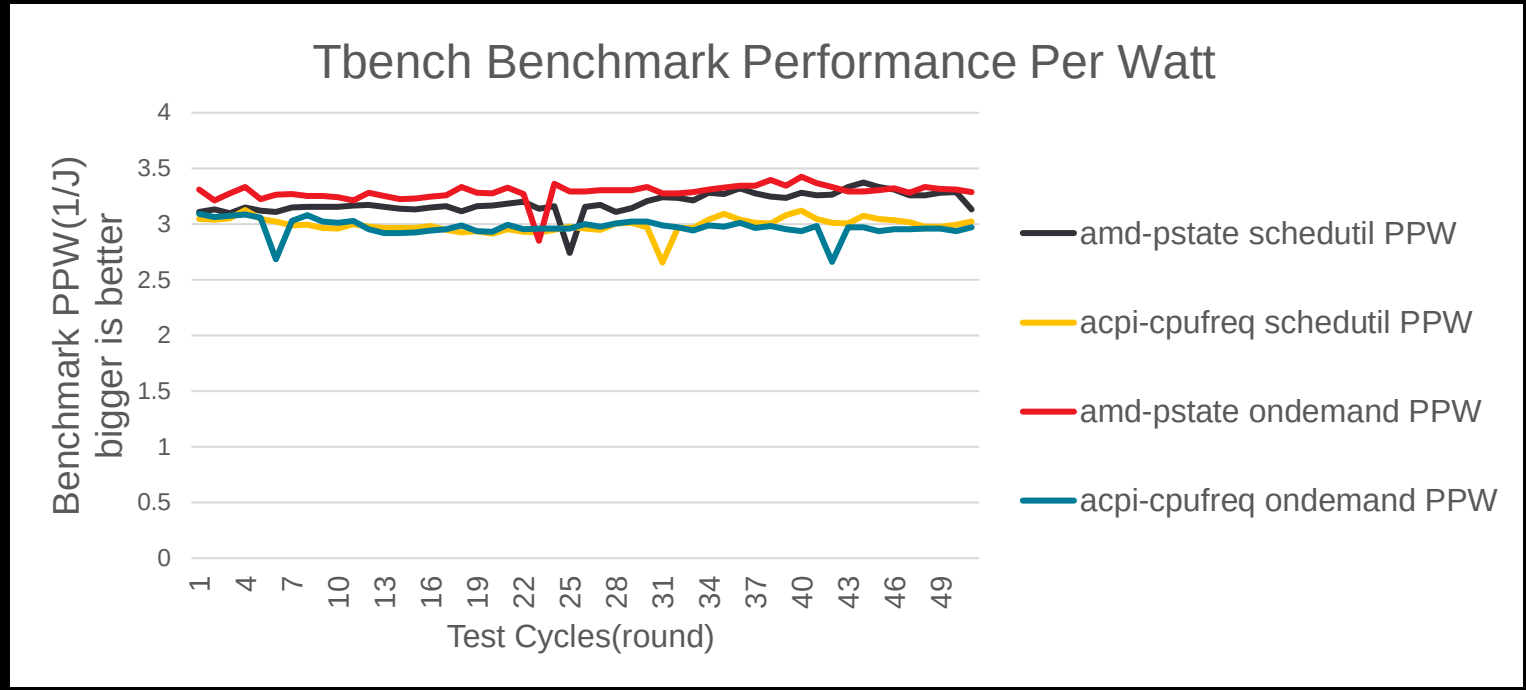
- CPUPower
  - cpupower is a set of user space utilities designed to assist with CPU frequency scaling
    - Implement the support for new amd-pstate module which expose the sysfs API from kernel to use space
      - Expose AMD P-States performance capability into the library of cpupower
      - Implement the frequency operation control into cpupower utilities for AMD P-States




```
root@hr-test1:/home/ray# cpupower frequency-info
analyzing CPU 0:
  driver: amd-pstate
  CPUs which run at the same hardware frequency: 0
  CPUs which need to have their frequency coordinated by software: 0
  maximum transition latency: 131 us
  hardware limits: 400 MHz - 4.68 GHz
  available cpufreq governors: ondemand conservative powersave userspace performance schedutil
  current policy: frequency should be within 400 MHz and 4.68 GHz.
                  The governor "schedutil" may decide which speed to use
                  within this range.
  current CPU frequency: Unable to call hardware
  current CPU frequency: 4.02 GHz (asserted by call to kernel)
  boost state support:
    Supported: yes
    Active: yes
    AMD PSTATE Highest Performance: 166. Maximum Frequency: 4.68 GHz.
    AMD PSTATE Nominal Performance: 117. Nominal Frequency: 3.30 GHz.
    AMD PSTATE Lowest Non-linear Performance: 39. Lowest Non-linear Frequency: 1.10 GHz.
    AMD PSTATE Lowest Performance: 15. Lowest Frequency: 400 MHz.
```

TBench Benchmark for AMD-PSTATE vs ACPI-CPUFREQ

- AMD-PSTATE vs ACPI-CPUFREQ on AMD Cezanne APU
  - TBench Benchmark
    - CPU: "Cezanne" Ryzen 7 5750G, 8C16T, disabled iGPU
    - MEM: DDR4 2666/8G*2/two channel
    - GPU: dGPU Radeon VII
    - Storage: NVME SSD, PCI-e x4, Samsung 980 512GB
    - OS: ubuntu 20.04.2 LTS
    - Kernel: test kernel, 5.12.0-rc5
    - Filesystem: ext4
    - BIOS: WA21407N 04/06/2021
    - Motherboard: Artic, known as B550
    - TBench Client number: 128
    - TBench Link: https://dbench.samba.org/web/download.html

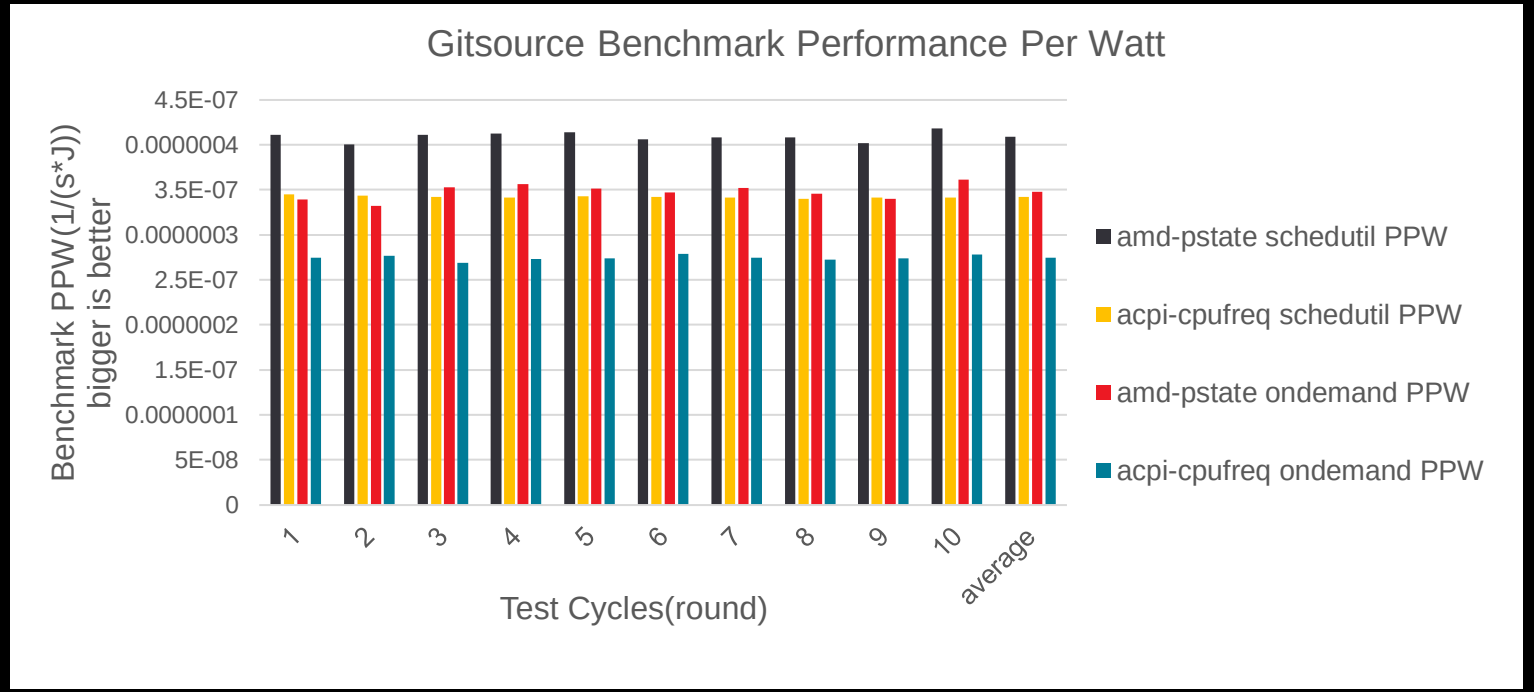


TBench

Formula	Kernel Module	Performance Per Watt (Schedutil) Unit: MB/(s*Joules)	Performance Per Watt (Ondemand) Unit: MB/(s*Joules)
Performance Per Watts (PPW) = F/E (F as Throughput MB/s, E as Energy Joules, the result unit is MB/(s*Joules))	acpi-cpufreq (legacy)	3.022	2.969
	amd-pstate	3.131 (+ 3.6%)	3.284 (+ 10.6%)

Gitsource Benchmark for AMD-PSTATE vs ACPI-CPUFREQ

- AMD-PSTATE vs ACPI-CPUFREQ on AMD Cezanne APU
  - Gitsource Benchmark
    - CPU: "Cezanne" Ryzen 7 5750G, 8C16T, disabled iGPU
    - MEM: DDR4 2666/8G*2/two channel
    - GPU: dGPU Radeon VII
    - Storage: NVME SSD, PCI-e x4, Samsung 980 512GB
    - OS: ubuntu 20.04.2 LTS
    - Kernel: test kernel, 5.12.0-rc5
    - Filesystem: ext4
    - BIOS: WA21407N 04/06/2021
    - Motherboard: Artic, known as B550
    - git version: 2.15.1
    - Benchmark Link: https://github.com/git/git

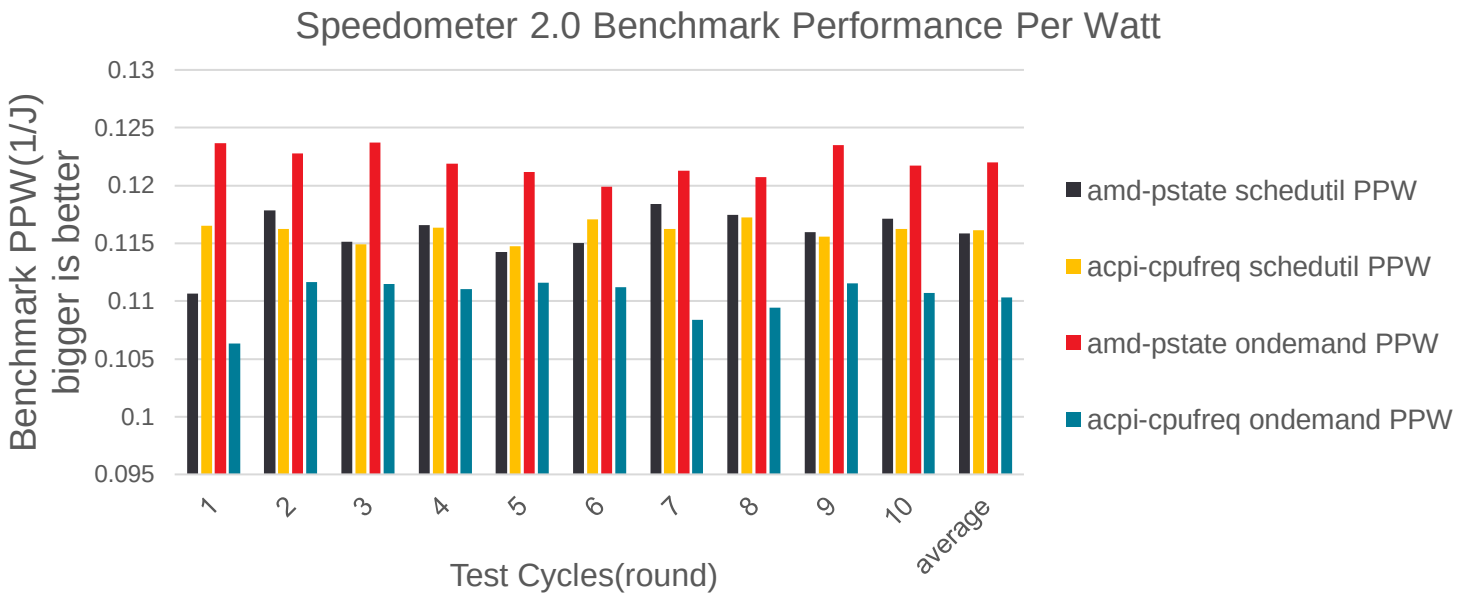


Gitsource

Formula	Kernel Module	Performance Per Watt (Schedutil) Unit: 1/(s*Joules)	Performance Per Watt (Ondemand) Unit: 1/(s*Joules)
Performance Per Watts (PPW) = F/E (F as the reciprocal of time 1/s, E as Energy Joules, the result unit is 1/(s*Joules))	acpi-cpufreq (legacy)	3.42E-07	2.74508E-07
	amd-pstate	4.09E-07 (+ 19.5%)	3.4761E-07 (+ 26.6%)

Speedometer 2.0 Benchmark for AMD-PSTATE vs ACPI-CPUFREQ

- AMD-PSTATE vs ACPI-CPUFREQ on AMD Cezanne APU
  - Speedometer 2.0 (For Chrome Book)
    - CPU: "Cezanne" Ryzen 7 5750G, 8C16T, disabled iGPU
    - MEM: DDR4 2666/8G*2/two channel
    - GPU: dGPU Radeon VII
    - Storage: NVME SSD, PCI-e x4, Samsung 980 512GB
    - OS: ubuntu 20.04.2 LTS
    - Kernel: test kernel, 5.12.0-rc5
    - Filesystem: ext4
    - BIOS: WA21407N 04/06/2021
    - Motherboard: Artic, known as B550
    - Speedometer 2.0 link: https://browserbench.org/Speedometer2.0/



Speedometer 2.0

Formula	Kernel Module	Performance Per Watt (Schedutil) Unit: 1/Joules	Performance Per Watt (Ondemand) Unit: 1/Joules
Performance Per Watts (PPW) = F/E (F as benchmark goal, E as Energy Joules, the result unit is 1/Joules)	acpi-cpufreq (legacy)	0.116111767	0.110321664
	amd-pstate	0.115825281 (-0.25%)	0.122024299 (+ 10.6%)

Horizon Zero Dawn for AMD-PSTATE vs ACPI-CPUFREQ

- AMD-PSTATE vs ACPI-CPUFREQ on AMD Cezanne APU
  - Horizon Zero Dawn (Provided by Valve)
    - APU/CPU: Cezanne, Ryzen 7 pro 5750g, disabled iGPU (make sure no GPU bottleneck)
    - dGPU: VEGA20, Radeon VII
    - Memory: DDR4 8+8GB, double channel
    - Game config, HZD on steam with VKD3D Proton, @1080P, 60Hz, same graphics configuration
  - It is easy to observe the right platform with amd-pstate module faster and lower average power consumption

Challenges and Future

- Improvement from legacy acpi-cpufreq to amd-pstate solution
  - We have tested many CPU benchmarks and get positive improvement (please refer TBench/Gitsource/Speedometer/Horizon Zero Dawn comparison result)
    - These Benchmarks covered generic Linux and Chrome platforms
- Linux® Kernel Upstream
  - We are in progress to upstream the whole solution into official Linux® kernel (https://www.kernel.org/)
    - Below is our working git repo for upstream
    - https://git.kernel.org/pub/scm/linux/kernel/git/rui/linux.git/
- Challenges
  - AMD P-States MSR based APIs are the first time (new) for Linux® solution, it may have potential stability issues that need more testing and verification
  - Hope this solution to be accepted by Linux® community

Reference

- Linux® amd-pstate driver source
  - https://lore.kernel.org/linux-pm/20210908150001.3702552-1-ray.huang@amd.com/
- CPUFreq and The Scheduler
  - http://events17.linuxfoundation.org/sites/events/files/slides/cpufreq_and_scheduler_0.pdf
- Linux® cpufreq governor
  - https://www.kernel.org/doc/Documentation/cpu-freq/governors.txt
- Prior Work
  - https://lkml.org/lkml/2019/7/10/682
- Windows® Server CPPC
  - https://docs.microsoft.com/en-us/windows-server/administration/performance-tuning/hardware/power/power-performance-tuning

Thank You and Q&A

Contributors:

- Paul Blinzer <paul.blinzer@amd.com>
- Alex Deucher <alexander.deucher@amd.com>
- Deepak Sharma <deepak.sharma@amd.com>
- Jinzhou Su <Jinzhou.Su@amd.com>
- Xiaojian Du <Xiaojian.Du@amd.com>
- Mario Limonciello <mario.limonciello@amd.com>
- Nathan Fontenot <nathan.fontenot@amd.com>

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