Parallized State Estimation

ME 766: HPSC

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Model Equations

$$\frac{dC_m}{dt} = \frac{F(C_{min} - C_m)}{V} - (k_p + k_{fm})C_m P_0$$

$$\frac{dC_I}{dt} = \frac{(F_I C_{Iin} - FC_I)}{V} - k_I C_I$$

$$\frac{dD_0}{dt} = (0.5k_{tc} + k_{td})P_0^2 + k_{fm}C_m P_0 - \frac{FD_0}{V}$$

$$\frac{dD_1}{dt} = M_m(k_p + k_{fm})C_m P_0 - \frac{FD_1}{V}$$

$$\frac{dT}{dt} = \frac{F(T_{in} - T)}{V} + \frac{(-\Delta H)k_p C_m P_0}{\rho C_p} - \frac{UA(T - T_j)}{\rho C_p V}$$

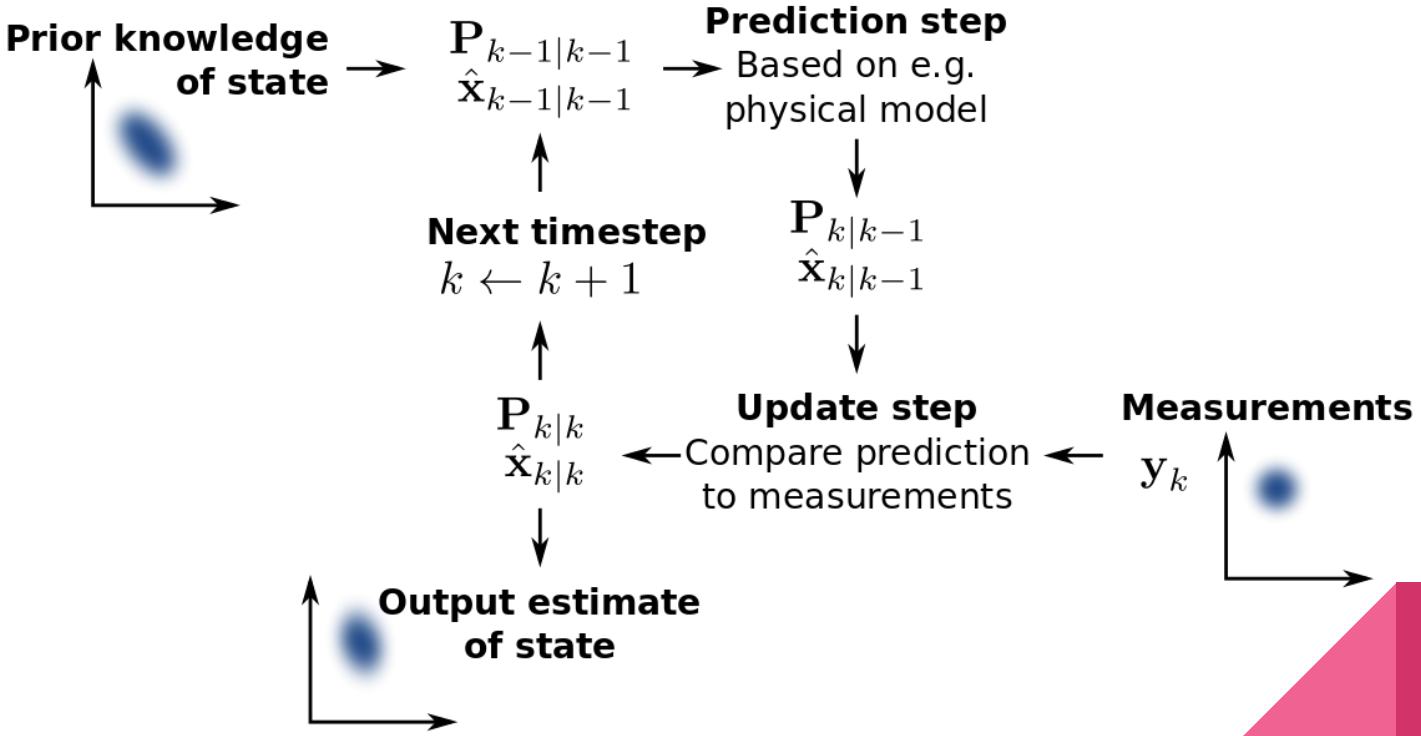
$$\frac{dT_j}{dt} = \frac{F_{cw}(T_{w0} - T_j)}{V_0} + \frac{UA(T - T_j)}{\rho_w C_{pw} V_0}$$

Non-linearities

$$k_s = A_s e^{-E_s/RT}$$
$$p, fm, I, td, tc$$

$$P_0 = (2f' C_I k_I/(k_{td} + k_{tc}))^{1/2}$$

Kalman Filtering



Wikipedia

Kalman Filtering: Model Linearization

$$\frac{d\mathbf{X}}{dt} = \mathbf{f}(\mathbf{X}, \mathbf{U}, \mathbf{D}) \tag{1}$$

$$\frac{d\mathbf{X}}{dt} \approx \mathbf{f}(\mathbf{X}^*, \mathbf{U}^*, \mathbf{D}^*) + \mathbf{A}(\mathbf{X} - \mathbf{X}^*) + \mathbf{B}(\mathbf{U} - \mathbf{U}^*) + \mathbf{H}(\mathbf{D} - \mathbf{D}^*) \tag{2}$$

$$\mathbf{x} = \mathbf{X} - \mathbf{X}^* \quad , \mathbf{u} = \mathbf{U} - \mathbf{U}^*, \quad \mathbf{d} = \mathbf{D} - \mathbf{D}^* \tag{3}$$

$$\frac{d\mathbf{x}}{dt} \approx \mathbf{f}(\mathbf{X}^*, \mathbf{U}^*, \mathbf{D}^*) + \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{H}\mathbf{d} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{H}\mathbf{d} \tag{4}$$

$$\mathbf{x}(k+1) = \mathbf{\Phi}\mathbf{x}(k) + \mathbf{\Gamma}_u\mathbf{u}(k) + \mathbf{\Gamma}_d\mathbf{d}(k)$$

Kalman Filtering

- **Prediction step**

$$\hat{\mathbf{x}}(k \mid k-1) = \Phi \hat{\mathbf{x}}(k-1 \mid k-1) + \Gamma \mathbf{u}(k-1)$$

$$\mathbf{P}(k \mid k-1) = \Phi \mathbf{P}(k-1 \mid k-1)\Phi^T + \Gamma_d \mathbf{Q}_d \Gamma_d^T$$

- **Kalman Gain Computation**

$$\mathbf{L}^*(k) = \mathbf{P}(k \mid k-1)\mathbf{C}^T \left[\mathbf{C}\mathbf{P}(k \mid k-1)\mathbf{C}^T + \mathbf{R}\right]^{-1}$$

- **Update step**

$$\mathbf{e}(k) = \left[\mathbf{y}(k) - \mathbf{C}\hat{\mathbf{x}}(k \mid k-1)\right]$$

$$\hat{\mathbf{x}}(k \mid k) = \hat{\mathbf{x}}(k \mid k-1) + \mathbf{L}^*(k)\mathbf{e}(k)$$

$$\mathbf{P}(k \mid k) = \left[\mathbf{I} - \mathbf{L}^*(k)\mathbf{C}\right]\mathbf{P}(k \mid k-1)$$

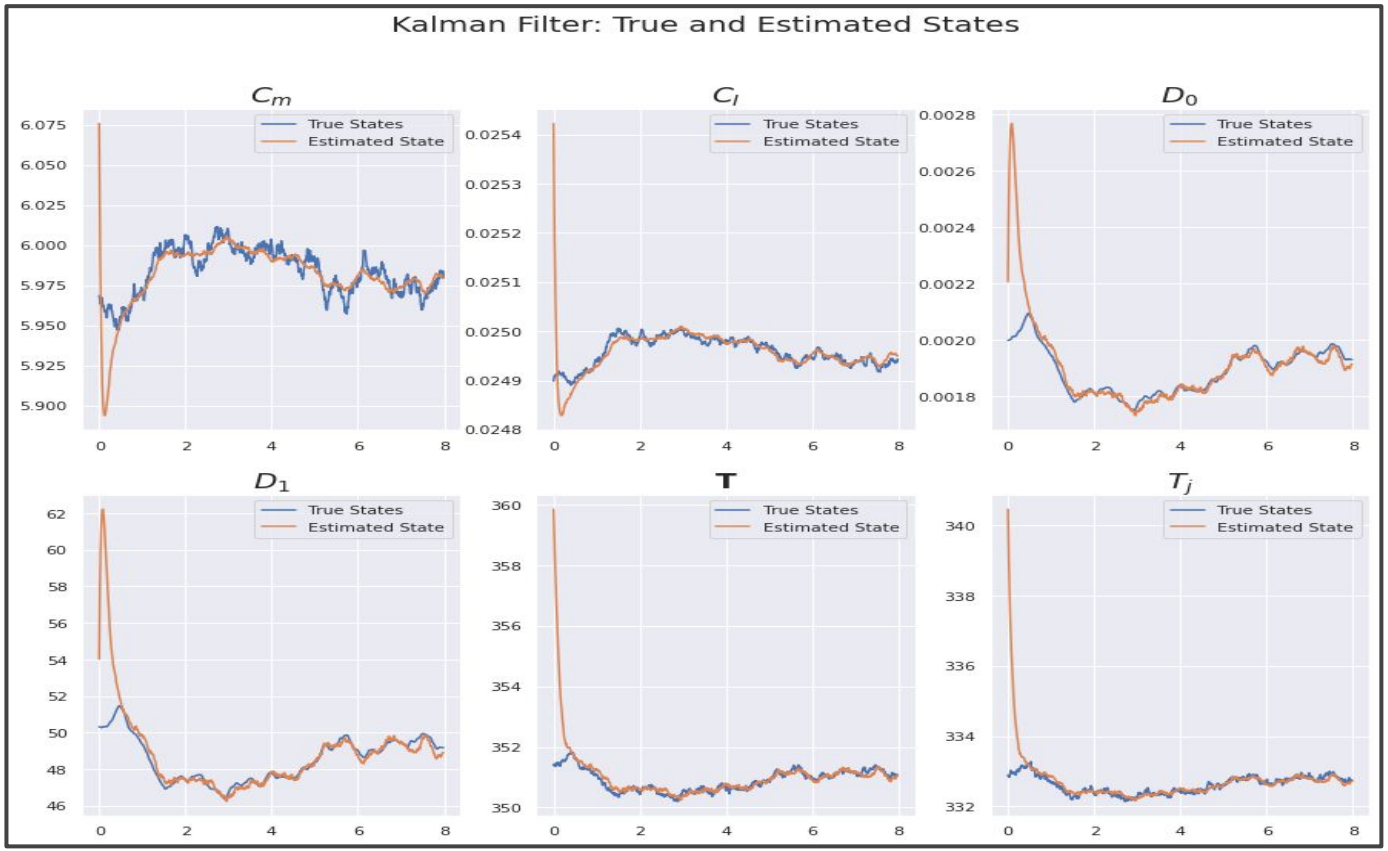
Generating States & Measurements

- Measurements are available for T and Tj
- Sampling interval of 28.8 seconds (=0.008 hrs)
- Expected simulation time: 1000 instants = 8 hrs
- Simulation parameters[1]

$$\mathbf{x}(0) = [5.9655 \;\; 0.0249 \;\; 0.0020 \;\; 50.3287 \;\; 351.4013 \;\; 332.90774]^T$$
$$Q = diag\{3.2028 \times 10^{-6}; 6.2 \times 10^{-12}; 25 \times 10^{-14}; 25.28 \times 10^{-6}; 12.34 \times 10^{-4}; 11.08 \times 10^{-4}\}$$
$$R = diag\{2.5 \times 10^{-1} \;\; 2.5 \times 10^{-1}\} \quad \hat{\mathbf{x}}_{0|0} = 1.025 \times \mathbf{x}_{0|0} \quad P_{0|0} = 10 \times Q$$

[1]Effect of Process Design/Operation on the Steady-State Operability of a Methyl Methacrylate Polymerization Reactor,Andrea Silva-Beard and Antonio Ind. Eng. Chem. Res. 1999, 38, 4790-4804

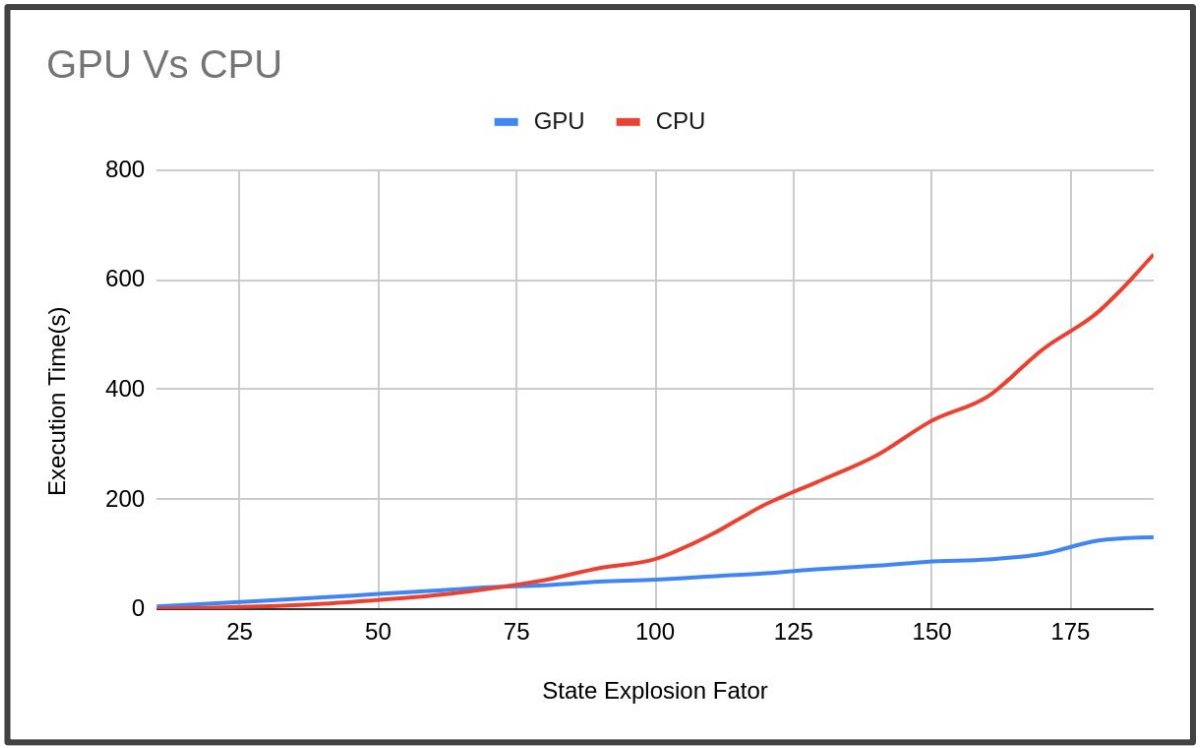
Results - Kalman Filter Performance



X axis: Time in hours

State	RMSE
1	0.012
2	0.00003
3	0.0001
4	1.744
5	0.847
6	0.687

Results - Effect of Parallelization



State Explosion Factor	GPU Time(s)	CPU Time(s)
10	4.96	0.9
20	10.17	2.45
30	15.59	5.28
40	21.27	9.48
50	27.48	16.53
60	33.4	24.72
70	39.74	37.05
80	43.41	52.75
90	49.89	74.61

State Explosion Factor= 1, Number of states=6

GPU: 1.013s CPU: 0.33s

Work Division

- Problem Selection, System Selection: Siddhesh , Chitrangna
- Modelling the System dynamics: Siddhesh
- Understanding Kalman filter: Chitrangna
- True State (data) Generation: Aryan
- KF implementation: Aryan and Siddhesh
- Experiments and Plotting Code: Chitrangna
- Report, PPT: All 3

Conclusion and Future Work

- For small matrices, CPU should be used over GPU and for applications where state space is high dimensional use a GPU
- Using the state estimation algorithm to aid the online Model Predictive Control (MPC) algorithm to control the process
- Predicting adverse phenomena such as Trommsdorff–Norrish effect that occur due to local variations in the viscosity, using a more complicated state space model

Thank you

Supplementary: Meaning of states

C_m concentration of monomer inside the reactor (kg mol/m^3)

C_i concentration of monomer inside the reactor

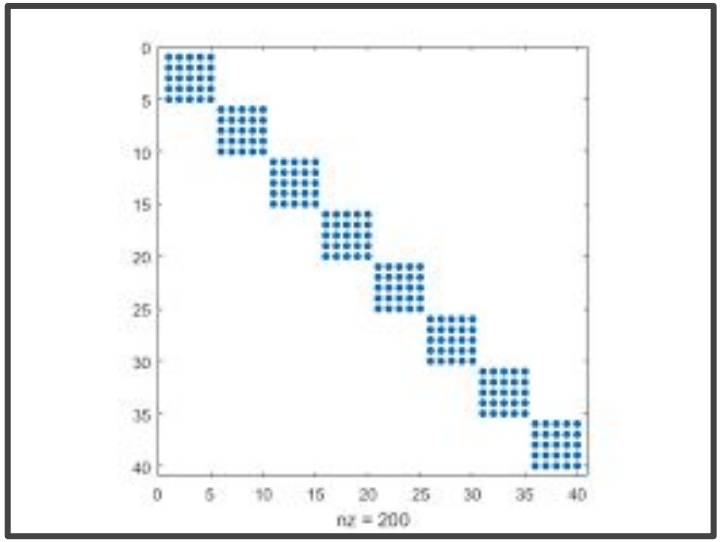
D_0 and D_1 Polymer moments (used to calculate the weight and density of the Polymer)

T Reactor Temperature

T_j Jacket Temperature

Supplementary - Block Diagonal Matrix

$$\begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{pmatrix} \& \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix} \rightarrow \begin{pmatrix} 1 & 2 & 3 & 0 & 0 \\ 4 & 5 & 6 & 0 & 0 \\ 7 & 8 & 9 & 0 & 0 \\ 0 & 0 & 0 & 1 & 2 \\ 0 & 0 & 0 & 3 & 4 \end{pmatrix}$$



Supplementary - GPU Specifications

```
+-----------------------------------------------------------------------------+
| NVIDIA-SMI 465.19.01    Driver Version: 460.32.03    CUDA Version: 11.2     |
|-------------------------------+----------------------+----------------------+
| GPU  Name        Persistence-M| Bus-Id        Disp.A | Volatile Uncorr. ECC |
| Fan  Temp  Perf  Pwr:Usage/Cap|         Memory-Usage | GPU-Util  Compute M. |
|                               |                      |               MIG M. |
|===============================+======================+======================|
|   0  Tesla T4            Off  | 00000000:00:04.0 Off |                    0 |
| N/A   71C    P0    31W /  70W |  11600MiB / 15109MiB |      0%      Default |
|                               |                      |                  N/A |
+-------------------------------+----------------------+----------------------+

+-----------------------------------------------------------------------------+
```

2560 CUDA Cores
Clock speed: 1582 MHz

Supplementary- RAM(VM) Specs GPU

```
Filesystem      Size  Used Avail Use% Mounted on
overlay          69G   39G   30G  57% /
tmpfs            64M     0   64M   0% /dev
tmpfs           6.4G     0  6.4G   0% /sys/fs/cgroup
shm             5.8G     0  5.8G   0% /dev/shm
/dev/sda1        75G   41G   35G  54% /opt/bin
tmpfs           6.4G   24K  6.4G   1% /var/colab
tmpfs           6.4G     0  6.4G   0% /proc/acpi
tmpfs           6.4G     0  6.4G   0% /proc/scsi
tmpfs           6.4G     0  6.4G   0% /sys/firmware
```

Supplementary - CPU Specifications(Processor 1)

```
processor   : 0
vendor id   : GenuineIntel
cpu family  : 6
model       : 63
model name  : Intel(R) Xeon(R) CPU @ 2.30GHz
stepping    : 0
microcode   : 0x1
cpu MHz             : 2299.998
cache size  : 46080 KB
physical id : 0
siblings    : 2
core id             : 0
cpu cores   : 1
apicid              : 0
initial apicid      : 0
fpu         : yes
fpu exception       : yes
cpuid level : 13
```

CPU Specs - Continued (Processor 1)

```
wp          : yes
flags       : fpu vme de pse tsc msr pae mce cx8 apic sep mtrr pge mca cmov pat pse36 clflush mmx fxsr
sse sse2 ss ht syscall nx pdpe1gb rdtscp lm constant tsc rep good nopl xtopology nonstop tsc cpuid
tsc_known_freq pni pclmulqdq ssse3 fma cx16 pcid sse4_1 sse4_2 x2apic movbe popcnt aes xsave avx f16c
rdrand hypervisor lahf lm abm invpcid single ssbd ibrs ibpb stibp fsgsbase tsc_adjust bmi1 avx2 smep
bmi2 erms invpcid xsaveopt arat md_clear arch_capabilities
bugs        : cpu_meltdown spectre_v1 spectre_v2 spec_store_bypass l1tf mds swapgs
bogomips    : 4599.99
clflush size     : 64
cache alignment  : 64
address sizes    : 46 bits physical, 48 bits virtual
```

CPU Specs continued (Processor 2)

```
processor   : 1
vendor id   : GenuineIntel
cpu family  : 6
model       : 63
model name  : Intel(R) Xeon(R) CPU @ 2.30GHz
stepping    : 0
microcode   : 0x1
cpu MHz             : 2299.998
cache size  : 46080 KB
physical id : 0
siblings    : 2
core id             : 0
cpu cores   : 1
apicid              : 1
```

CPU Specs Continued(Processor 2)

```
initial apicid   : 1
fpu         : yes
fpu exception    : yes
cpuid level : 13
wp          : yes
flags       : fpu vme de pse tsc msr pae mce cx8 apic sep mtrr pge mca cmov
pat pse36 clflush mmx fxsr sse sse2 ss ht syscall nx pdpe1gb rdtscp lm
constant tsc rep good nopl xtopology nonstop tsc cpuid tsc known freq pni
pclmulqdq ssse3 fma cx16 pcid sse4_1 sse4_2 x2apic movbe popcnt aes xsave
avx f16c rdrand hypervisor lahf_lm abm invpcid_single ssbd ibrs ibpb stibp
fsgsbase tsc adjust bmi1 avx2 smep bmi2 erms invpcid xsaveopt arat md_clear
arch_capabilities
bugs        : cpu_meltdown spectre_v1 spectre_v2 spec_store_bypass l1tf mds
swapgs
bogomips    : 4599.99
clflush size     : 64
cache_alignment  : 64
address sizes    : 46 bits physical, 48 bits virtual
power management:
```

CPU - VM specs

```
Filesystem      Size  Used Avail Use% Mounted on
overlay         108G   39G   70G  36% /
tmpfs            64M     0   64M   0% /dev
tmpfs           6.4G     0  6.4G   0% /sys/fs/cgroup
shm             5.9G     0  5.9G   0% /dev/shm
tmpfs           6.4G   32K  6.4G   1% /var/colab
/dev/sda1        114G   41G   74G  36% /etc/hosts
tmpfs           6.4G     0  6.4G   0% /proc/acpi
tmpfs           6.4G     0  6.4G   0% /proc/scsi
tmpfs           6.4G     0  6.4G   0% /sys/firmware
```

Graphics Processor

GPU Name:	TU104
GPU Variant:	TU104-895-A1
Architecture:	Turing
Foundry:	TSMC
Process Size:	12 nm
Transistors:	13,600 million
Die Size:	545 mm²

Memory

Memory Size:	16 GB
Memory Type:	GDDR6
Memory Bus:	256 bit
Bandwidth:	320.0 GB/s

Graphics Features

DirectX:	12 Ultimate (12_2)
OpenGL:	4.6
OpenCL:	3.0
Vulkan:	1.2
CUDA:	7.5
Shader Model:	6.6

Graphics Card

Release Date:	Sep 13th, 2018
Generation:	Tesla (Txx)
Production:	Active
Bus Interface:	PCIe 3.0 x16

Clock Speeds

Base Clock:	585 MHz
Boost Clock:	1590 MHz
Memory Clock:	1250 MHz 10 Gbps effective

Board Design

Slot Width:	Single-slot
Length:	168 mm 6.6 inches
TDP:	70 W
Suggested PSU:	250 W
Outputs:	No outputs
Power Connectors:	None
Board Number:	PG183 SKU 200

Relative Performance

Based on TPU review data: "Performance Summary" at 1920x1080, 4K for 2080 Ti and faster. Performance estimated based on architecture, shader count and clocks.

Render Config

Shading Units:	2560
TMUs:	160
ROPs:	64
SM Count:	40
Tensor Cores:	320
RT Cores:	40
L1 Cache:	64 KB (per SM)
L2 Cache:	4 MB

Theoretical Performance

Pixel Rate:	101.8 GPixel/s
Texture Rate:	254.4 GTexel/s
FP16 (half) performance:	65.13 TFLOPS (8:1)
FP32 (float) performance:	8.141 TFLOPS
FP64 (double) performance:	254.4 GFLOPS (1:32)

Tesla T4