GPUs TO MARS

Full Scale Simulation of SpaceX's Mars Rocket Engine

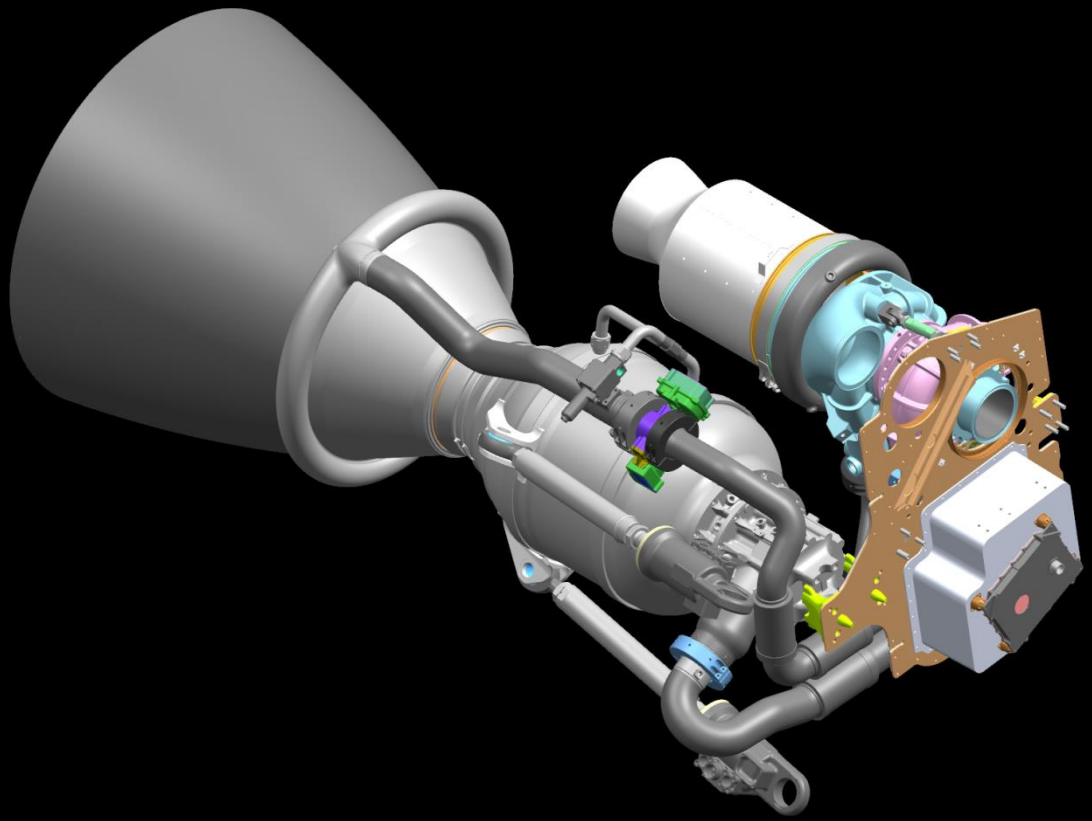
Adam Lichtl, Stephen Jones, GTC 2015

SPACEX

Background

- Independent space launch company
- Build and operate our own rocket & capsule
- Operations in CA, TX & FL
- Founded in 2002, first launch in 2008
- 18 successful missions to date

Design



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Build

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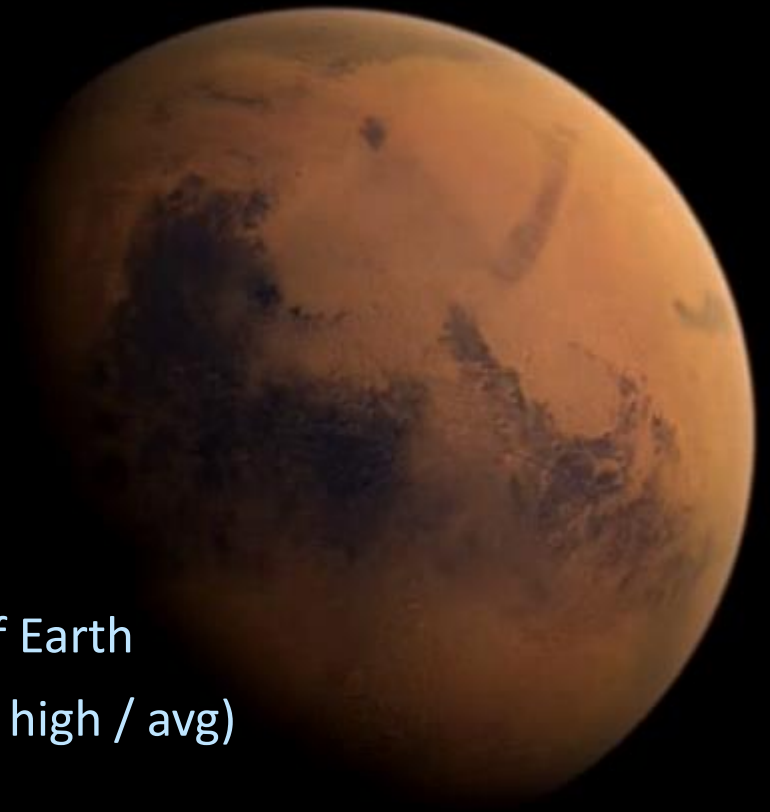
Launch

Mars

Length of day	24 hours, 40 minutes
Length of year	687 days
Gravity	$0.375g_s$
Distance from Sun	1.53 AU
Mars Air	CO_2 (96%), N_2 (2%)
Earth Air	O2 (21%), N2 (78%)
Atmosphere	1% density / pressure of Earth
Temperature	-284 / +86 / -81 F (low / high / avg)



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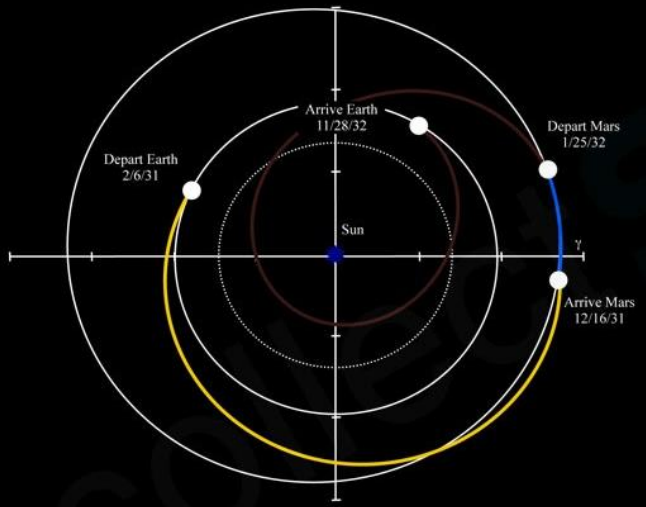
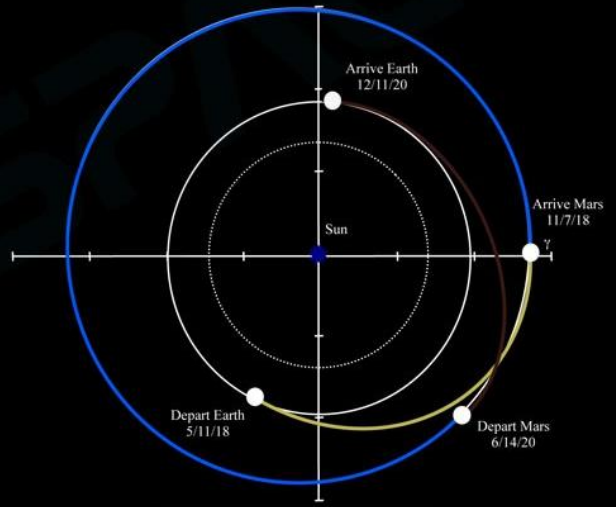
Human Mars Mission Classes

"Short-Stay" ("Opposition-Class")



MISSION TIMES	
Outbound	313 days
Stay	40 days
Return	308 days
Total Mission	661 days

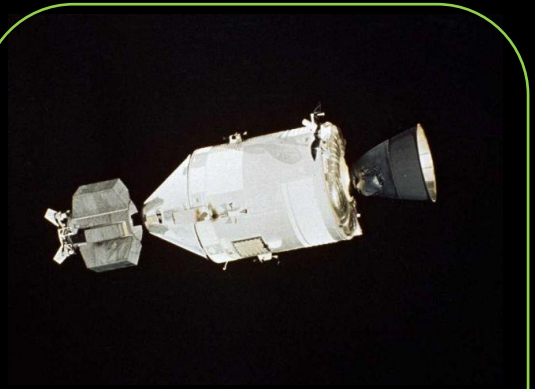
"Long-Stay" ("Conjunction-Class")



MISSION TIMES	
Outbound	180 days
Stay	545 days
Return	180 days
Total Mission	905 days

Credit: CollectSpace

Mass to Mars



Apollo Command & Service Module

- Mass: 46 tons
- Terrestrial assembly

Image Credit: NASA

International Space Station

- Mass: 450 tons
- 36x Space Shuttle, 5x Proton launches

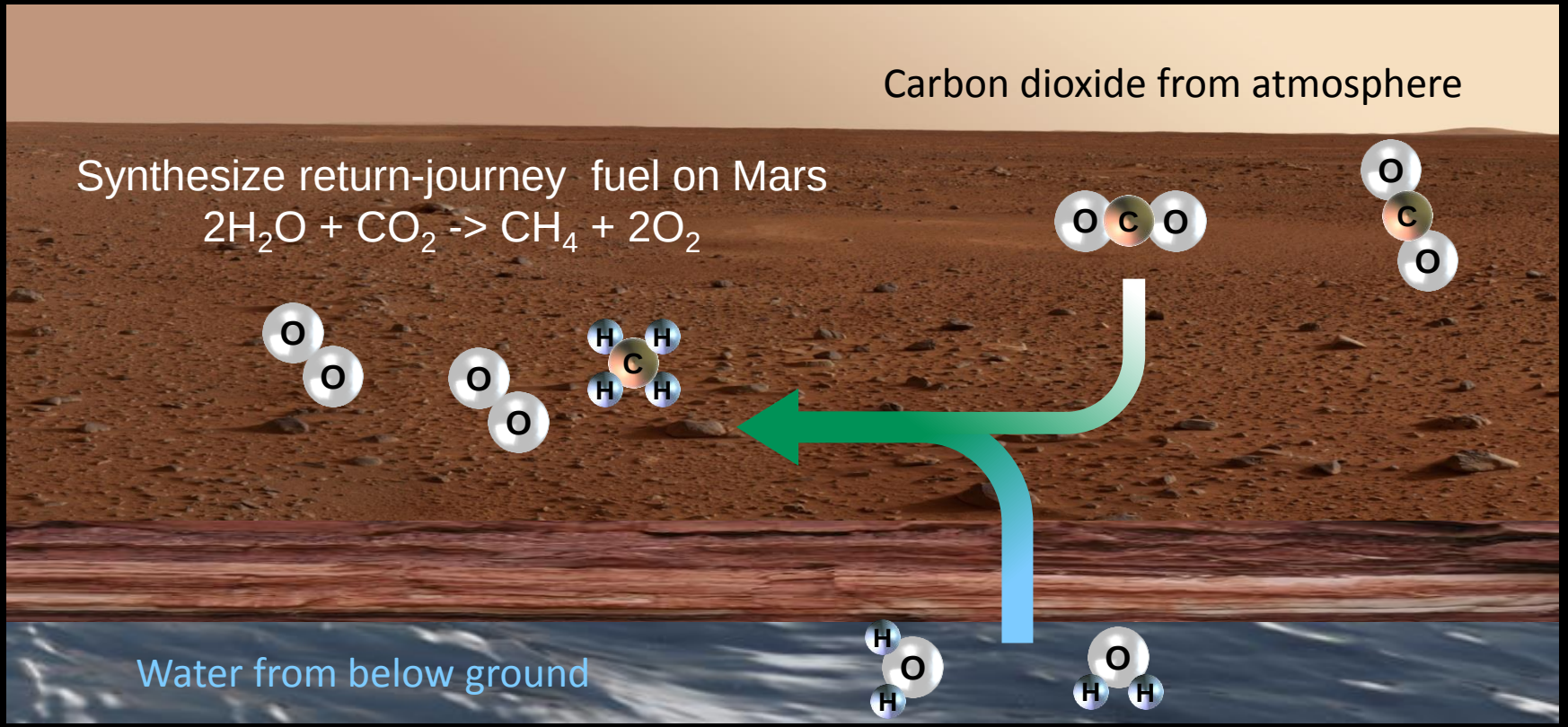
Image Credit: NASA

NASA Mars Architecture

- Mass: 300 tons
- 3x heavy-lift launches
- In-orbit assembly

Image Credit: Mark Benson & Kerbal Space Program

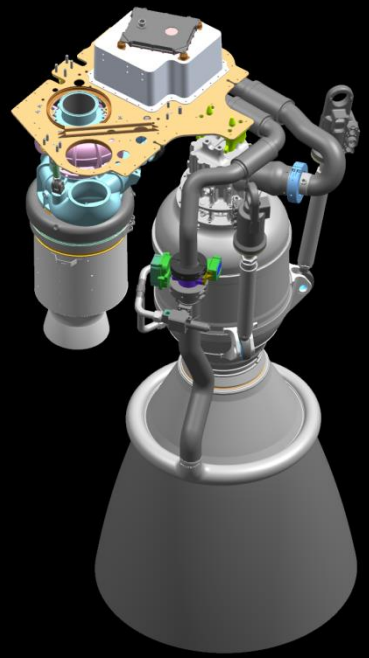
Methane Fuel



Rocket Engine Design

Why Simulation?

1. Investigate what cannot be measured
2. Reduce need for testing
3. Design optimisation: narrow design space
4. Proactive instead of reactionary design



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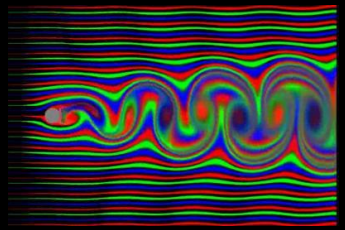
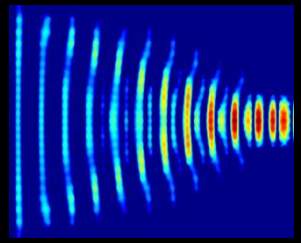
Time scales vary by 8 orders of magnitude

Diffusion

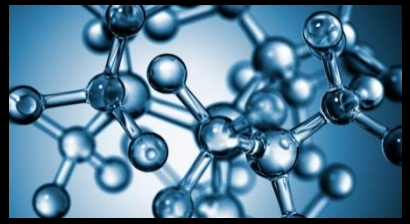
Advection



Acoustics



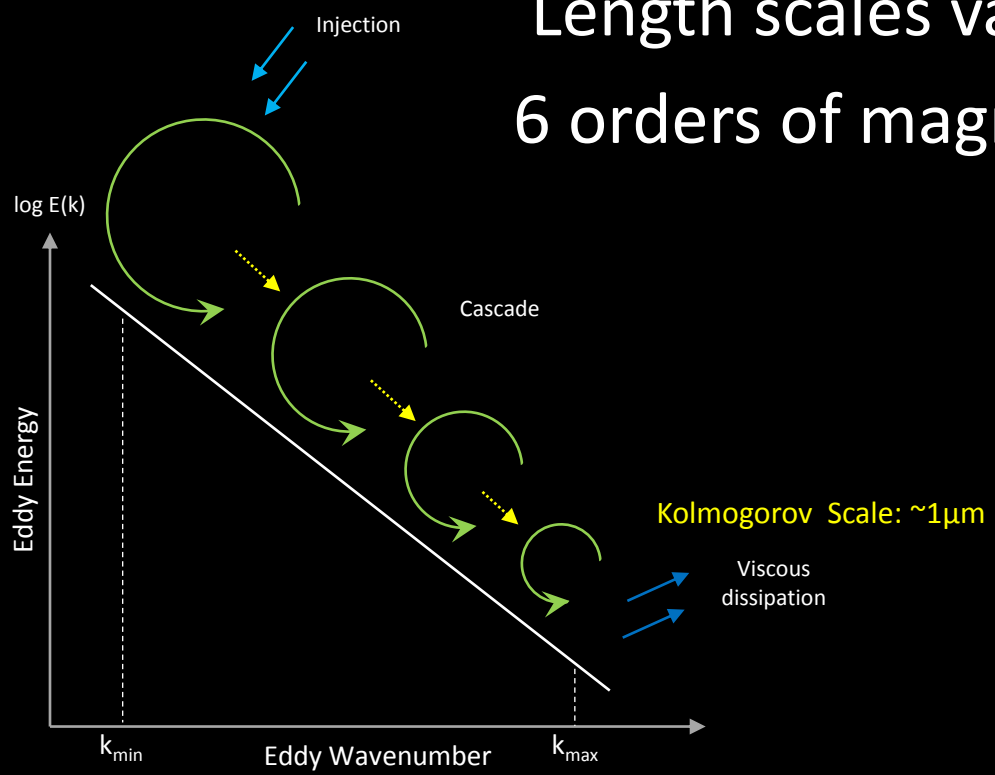
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} seconds

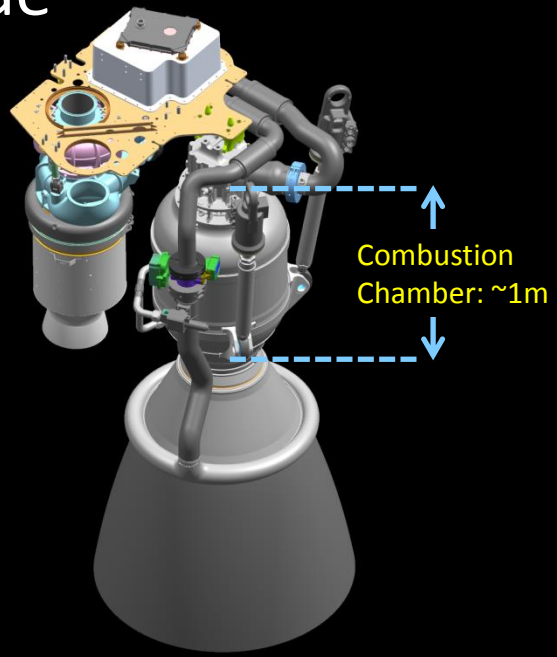


Reaction

Chamber Residence

Length scales vary by 6 orders of magnitude





Total points: $(10^3)^6 = 10^{18}$ = 1,000,000,000,000,000,000 points

@1kB per point -> Yottabytes of data

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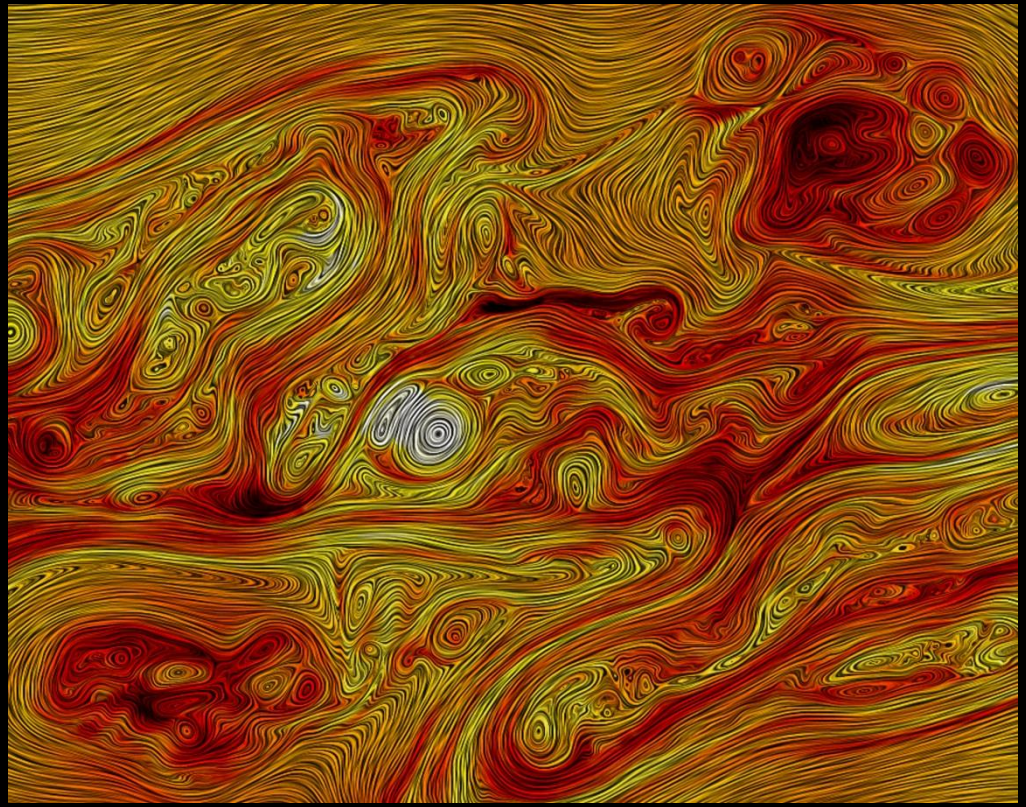
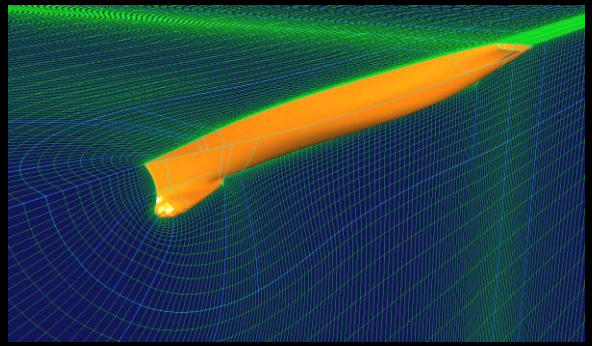
Structure in Turbulence

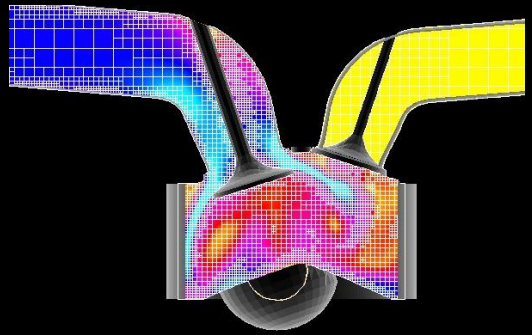


Credit: SpaceWeather

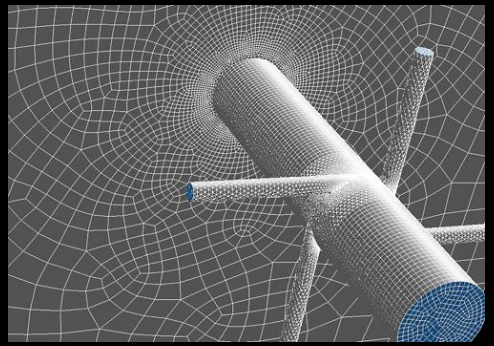
Simulation Meshing



Structured Grid

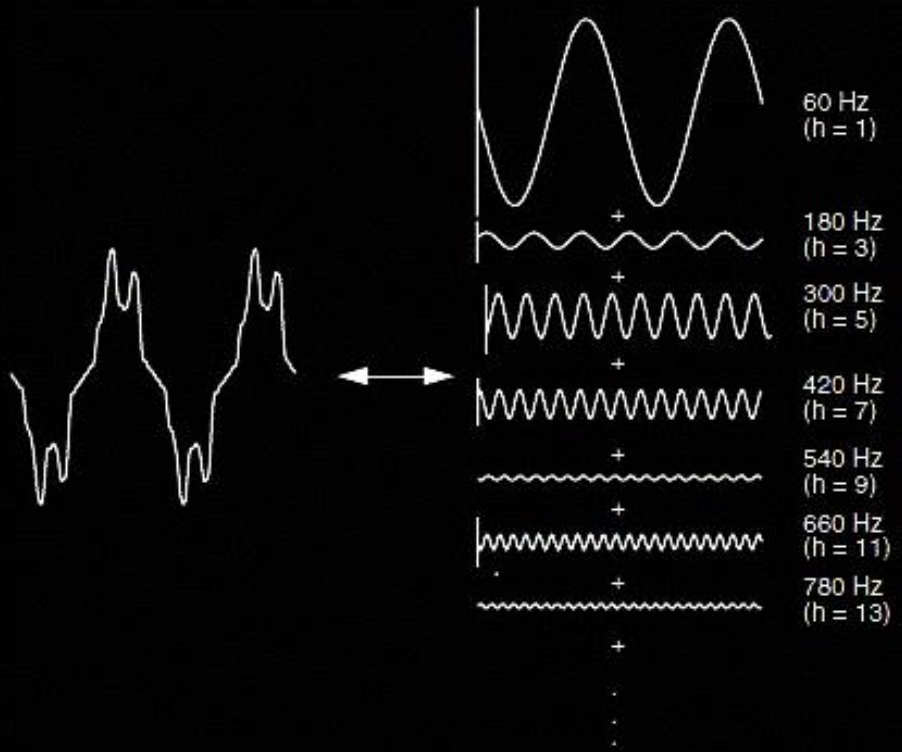


Adaptive Grid

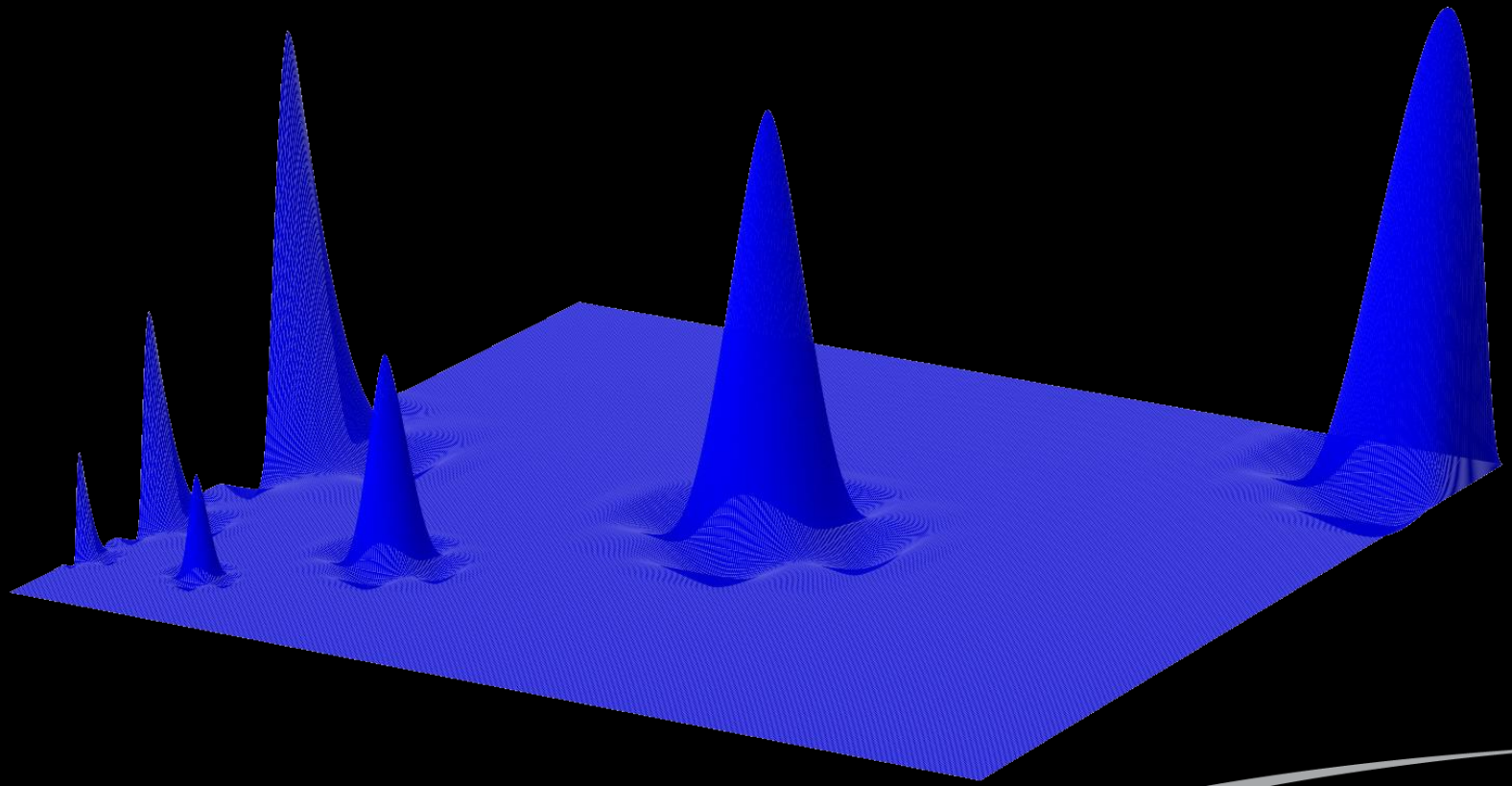


Unstructured Grid

Fourier Transform: Spectral Compression



Wavelets: Local Fractal Basis



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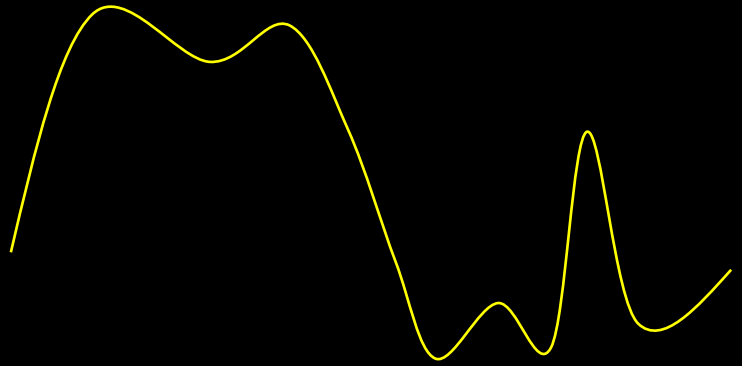
Wavelet Compression



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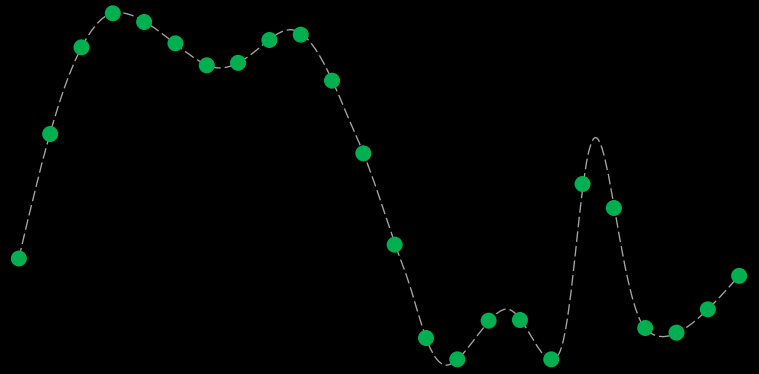

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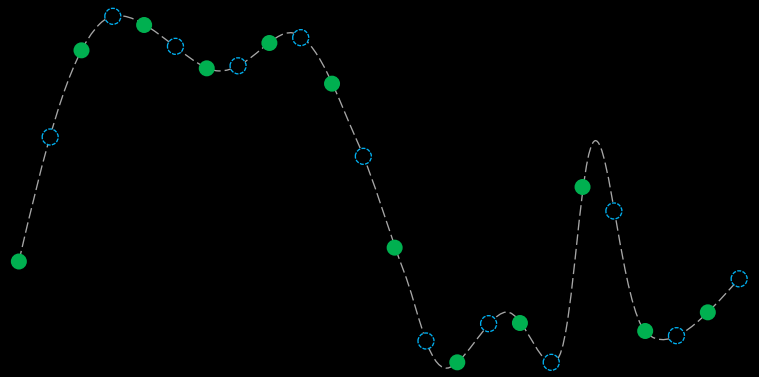

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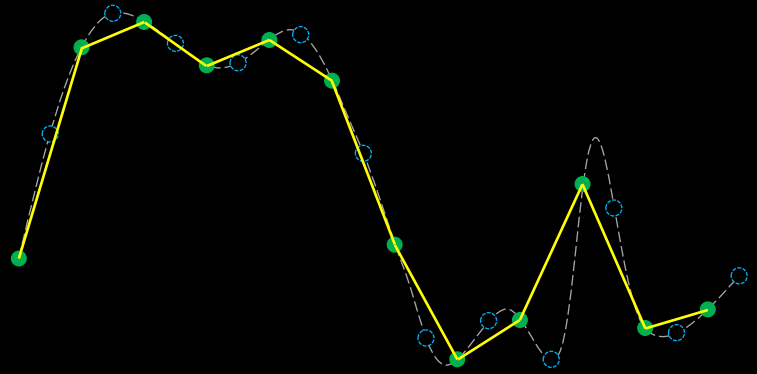

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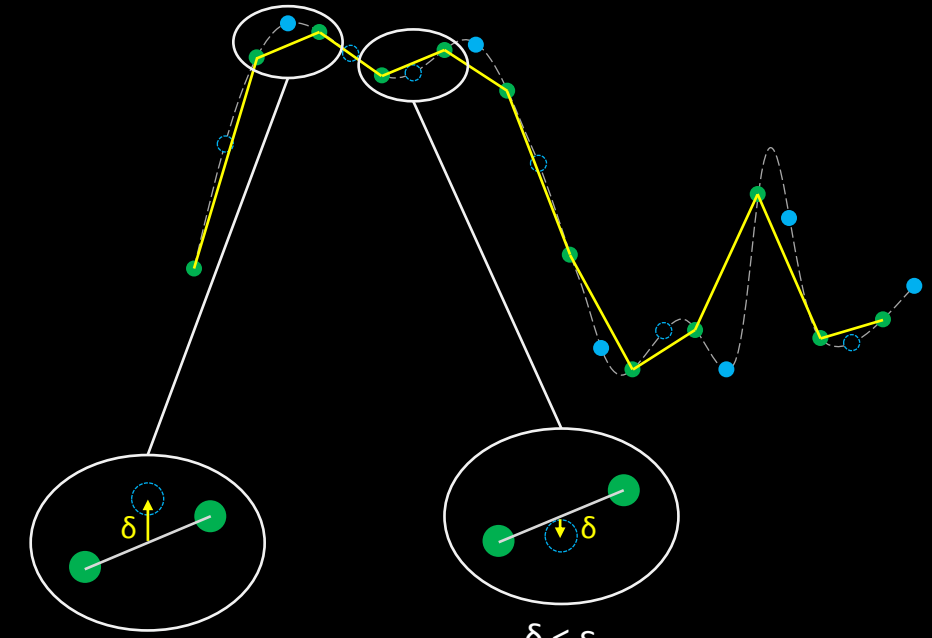

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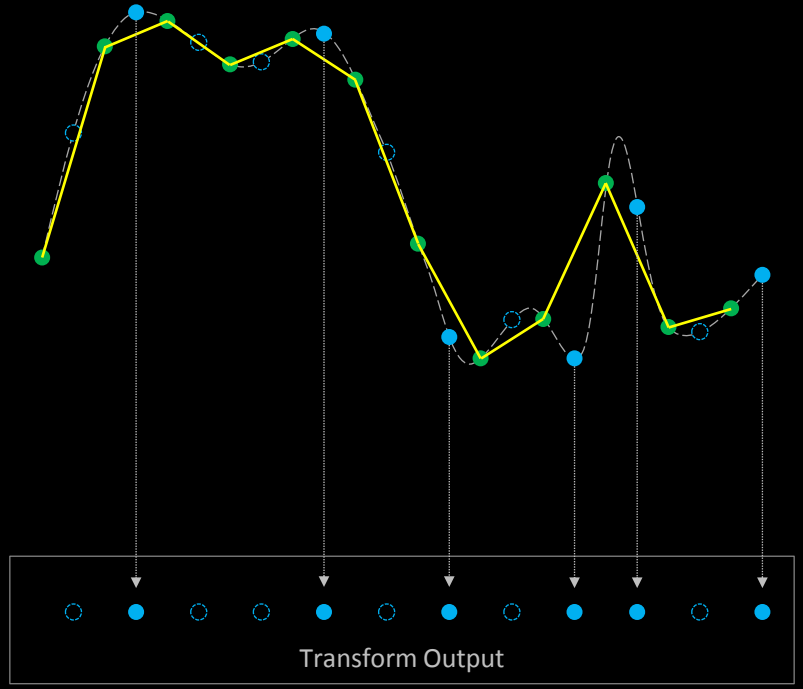

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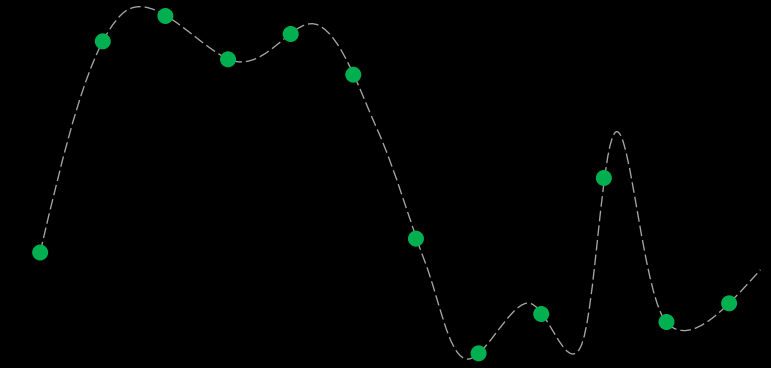

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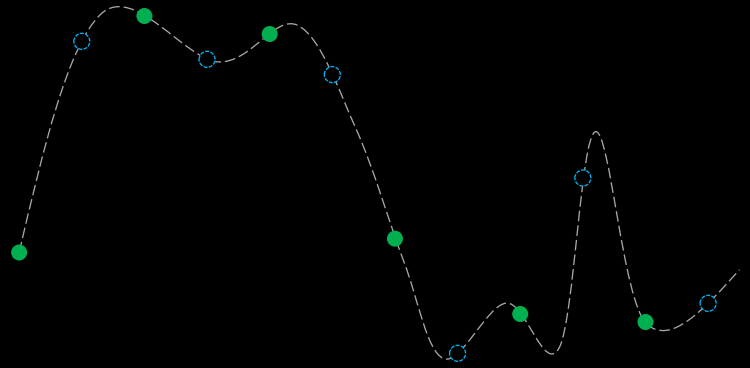

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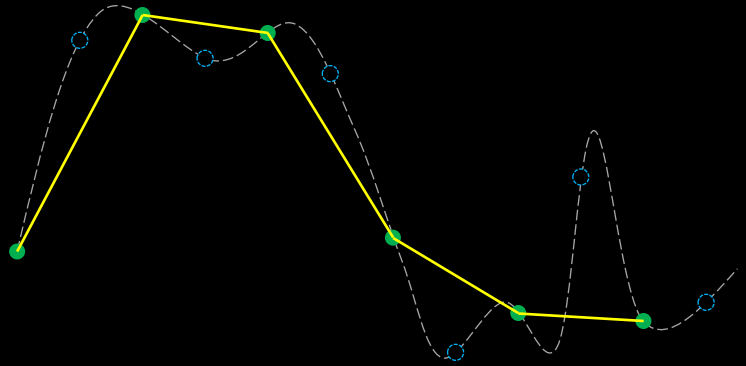

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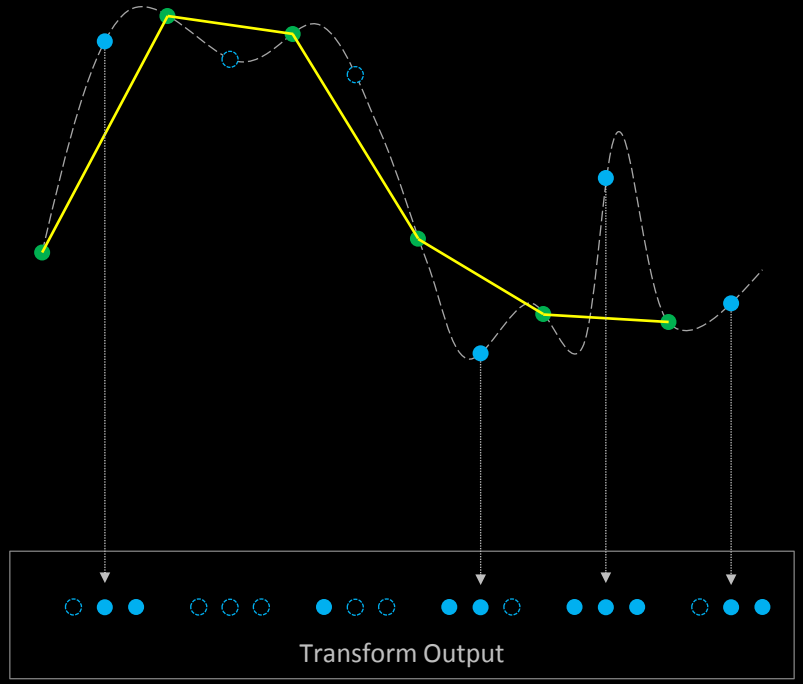

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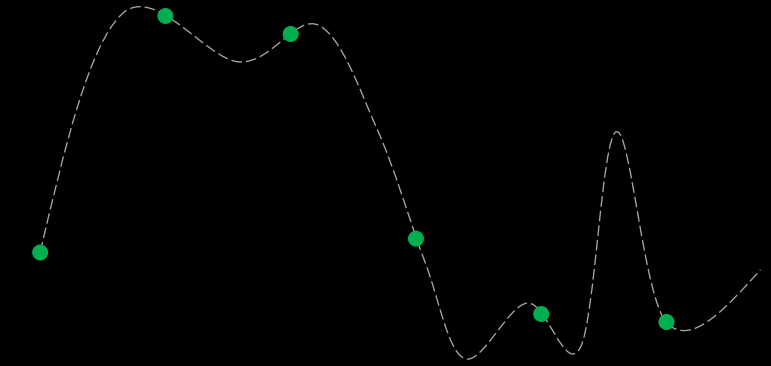

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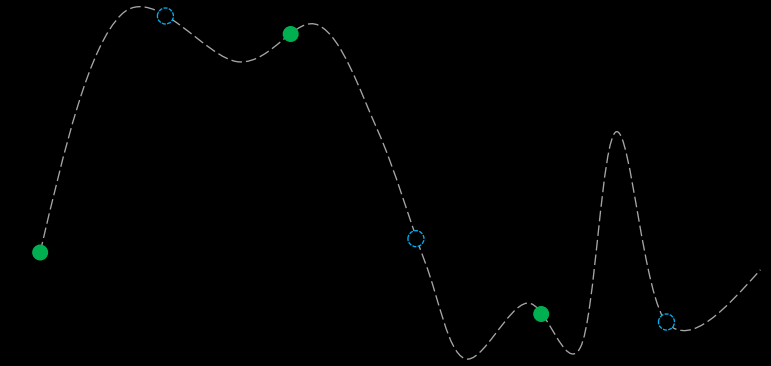

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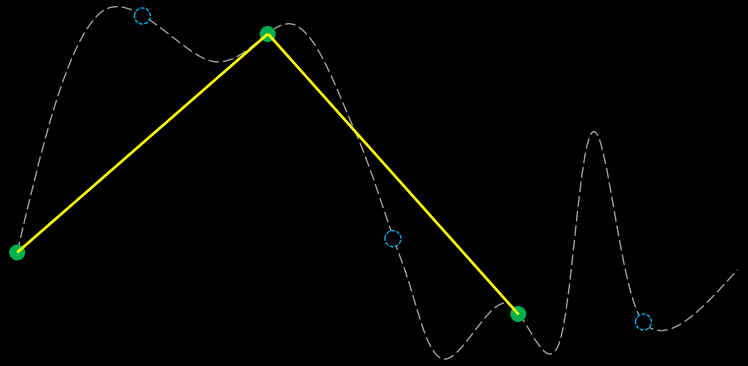

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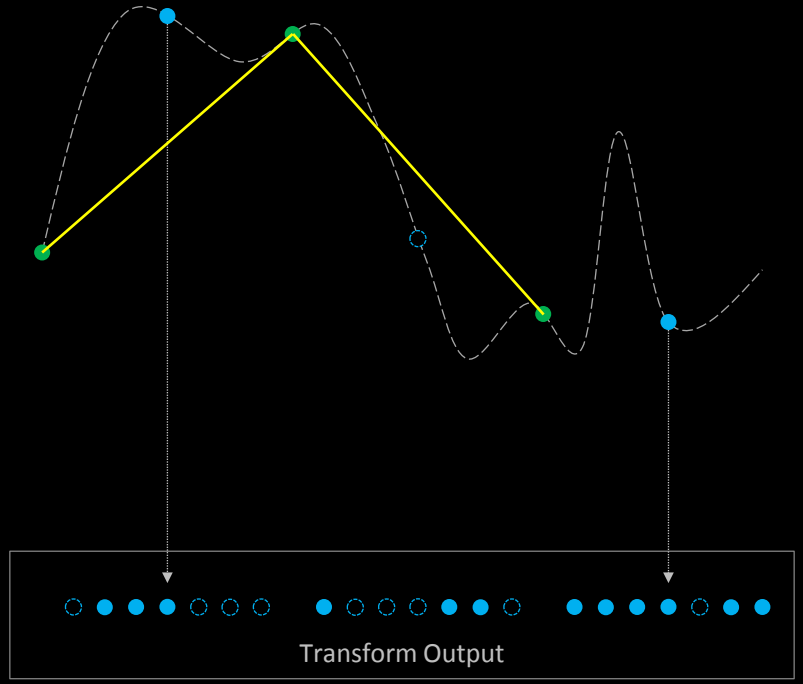

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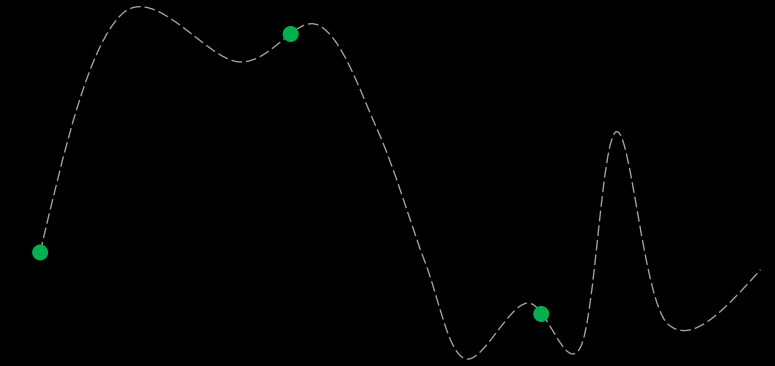

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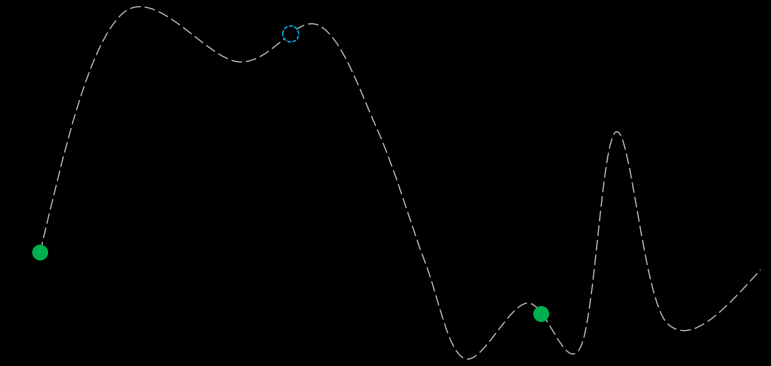

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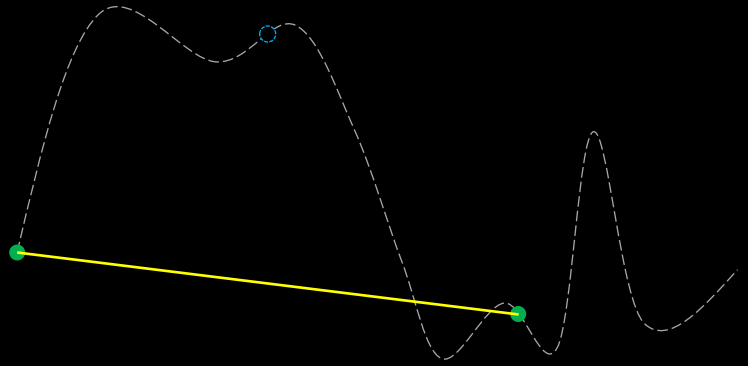

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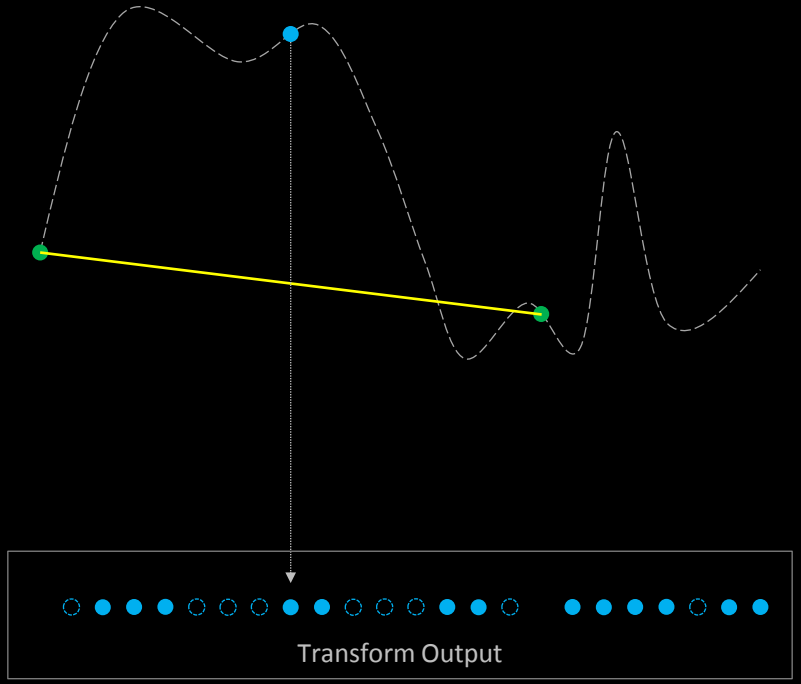

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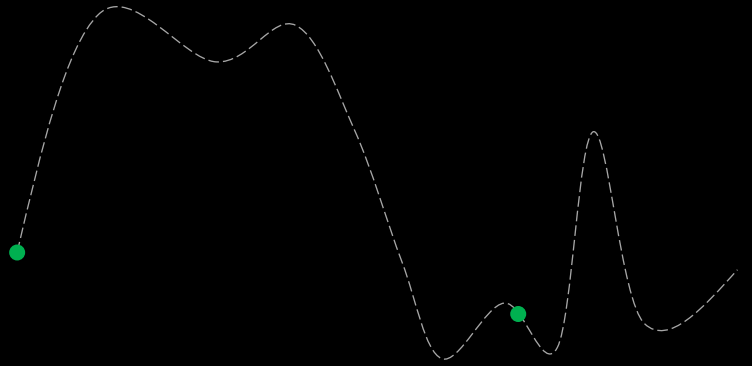

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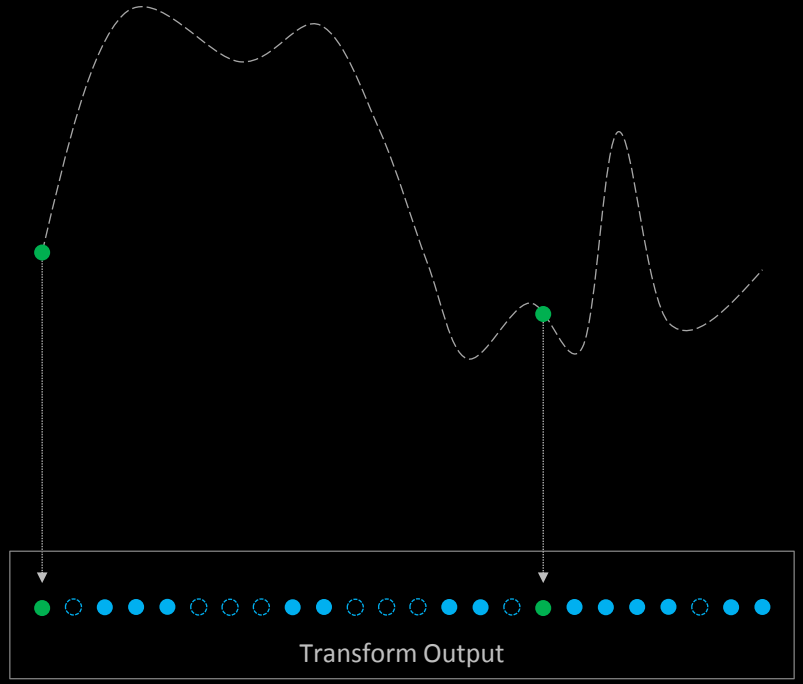

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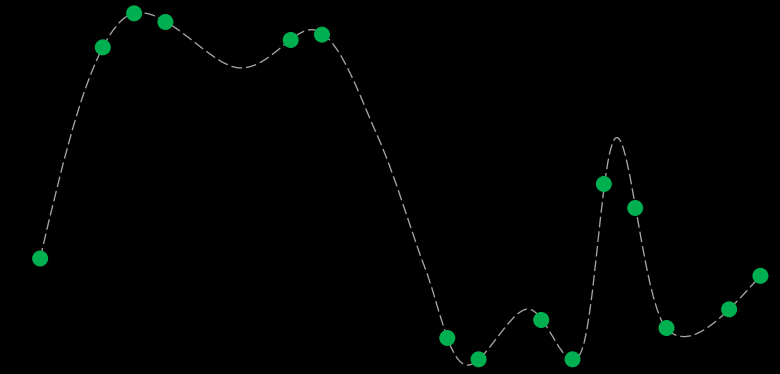

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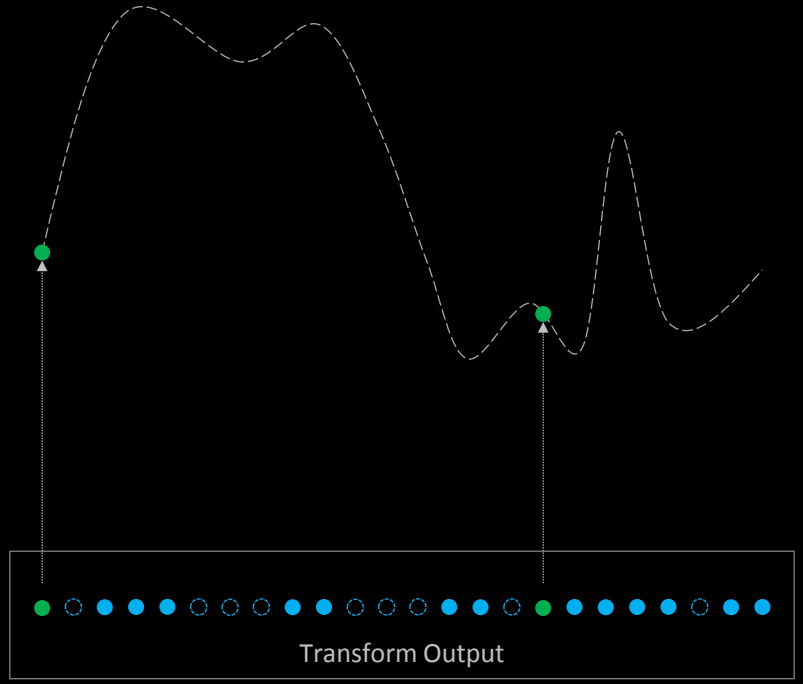

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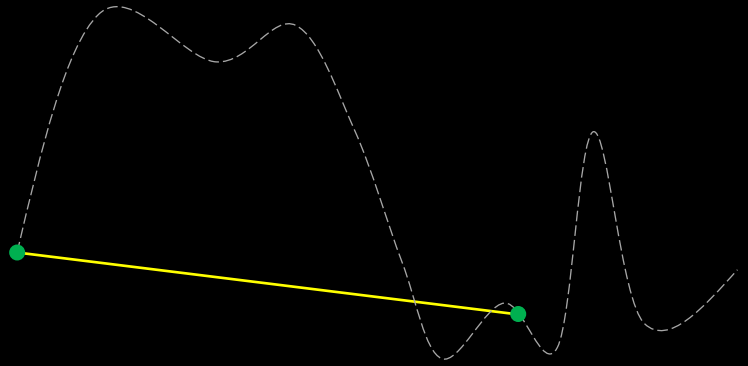

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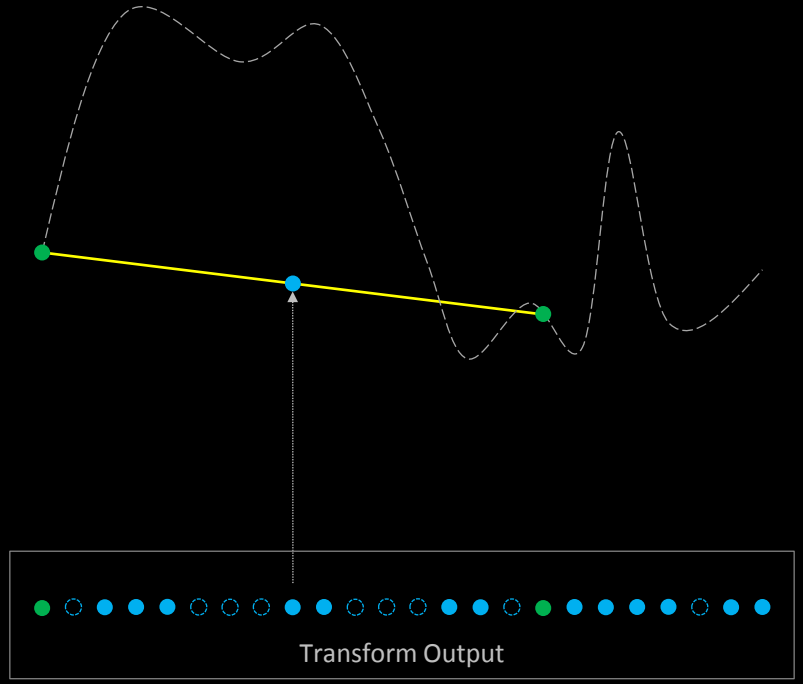

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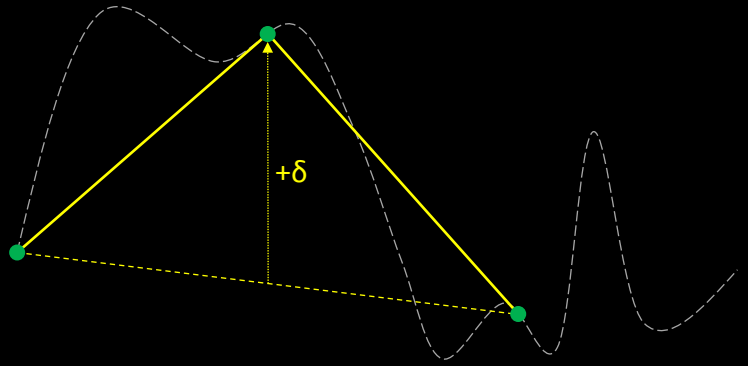

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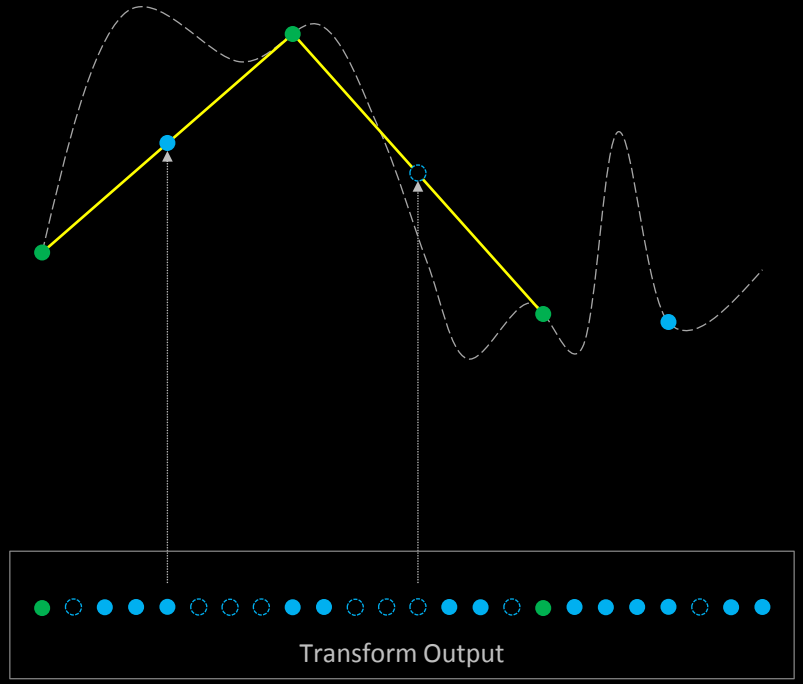

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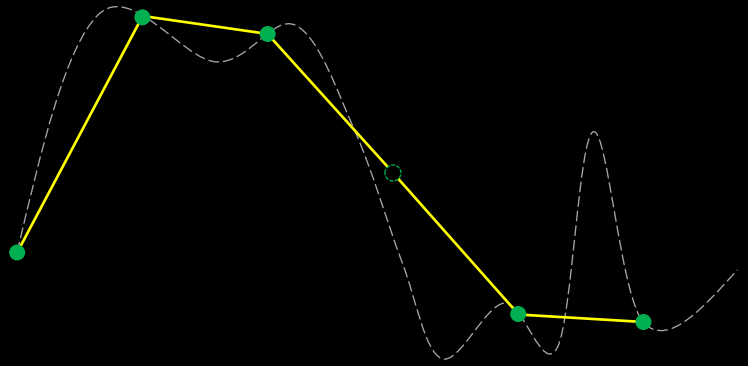

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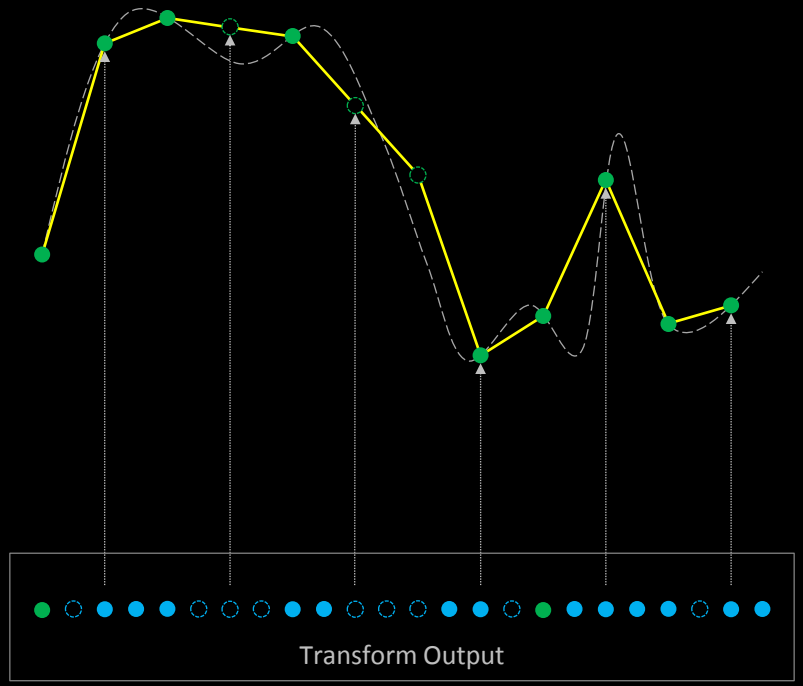

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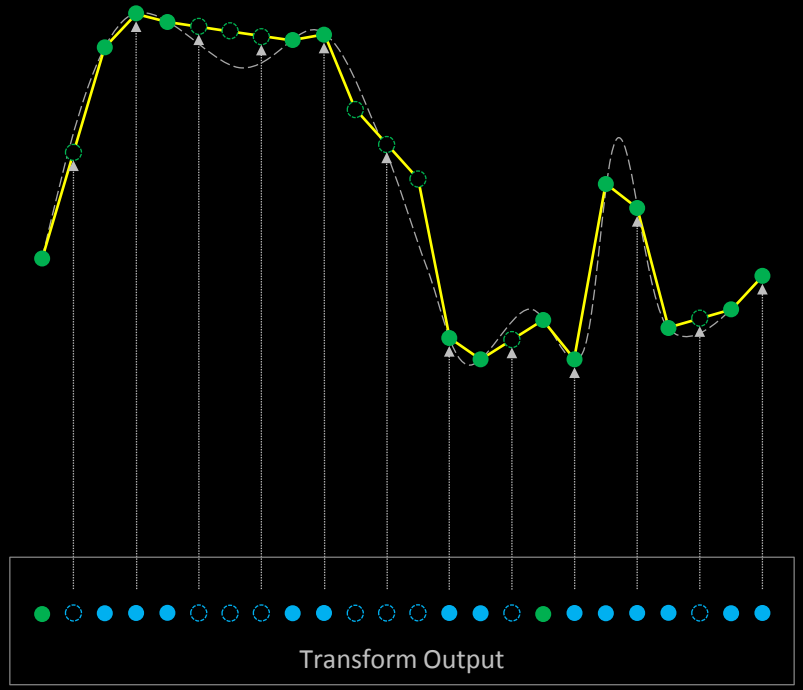

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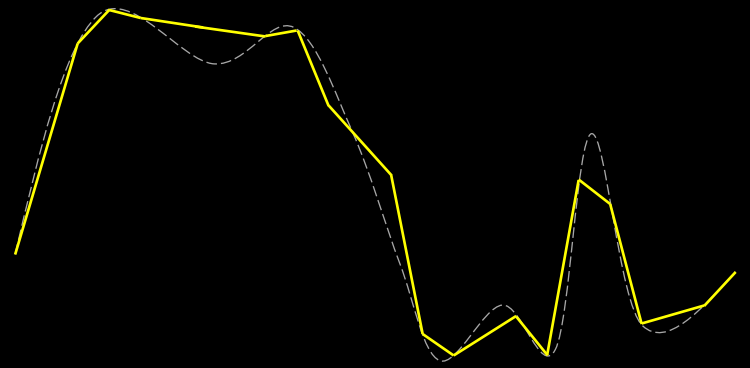

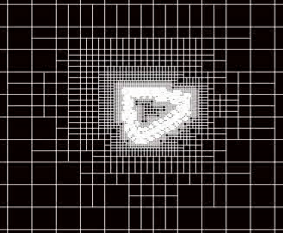

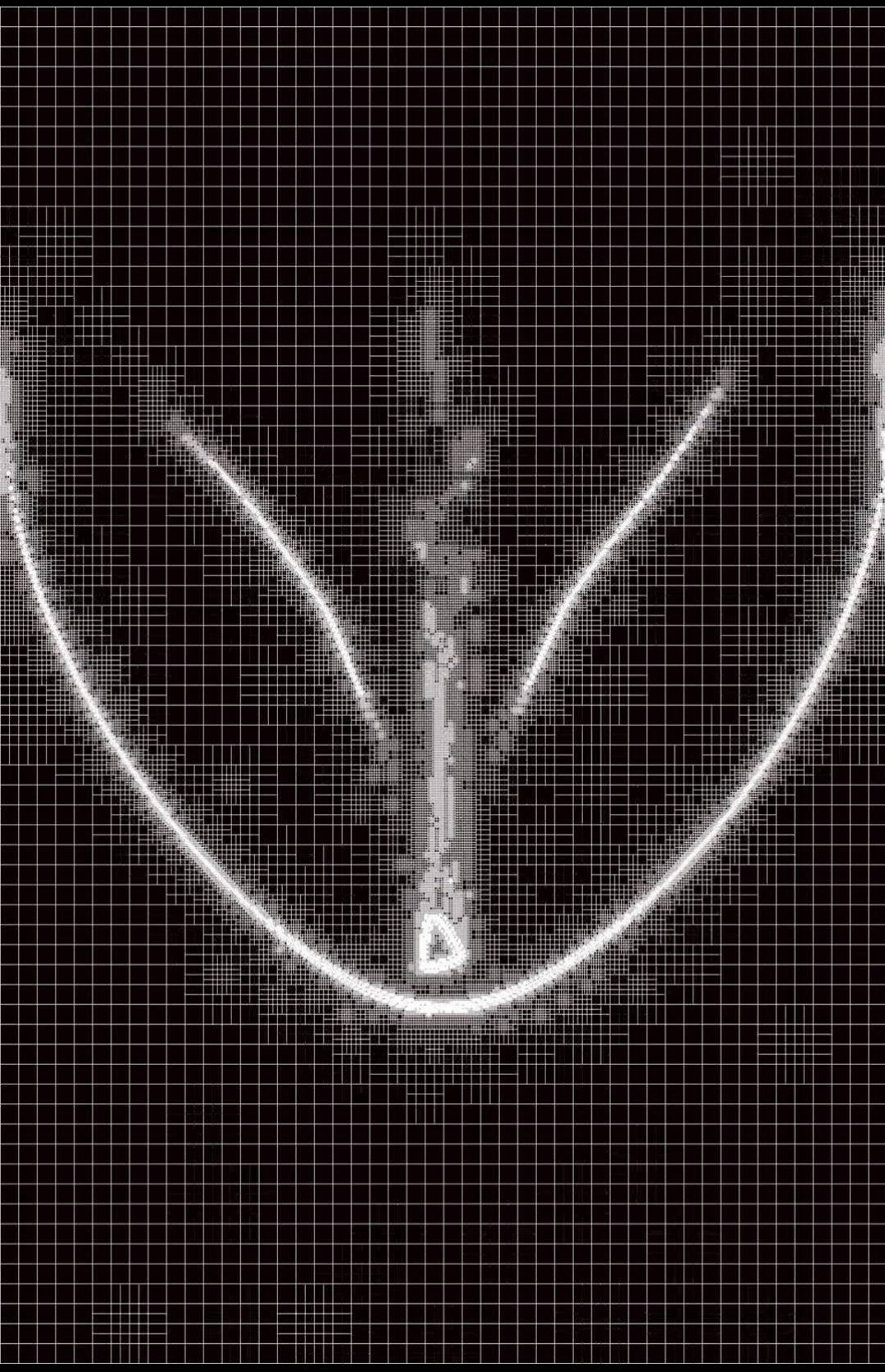

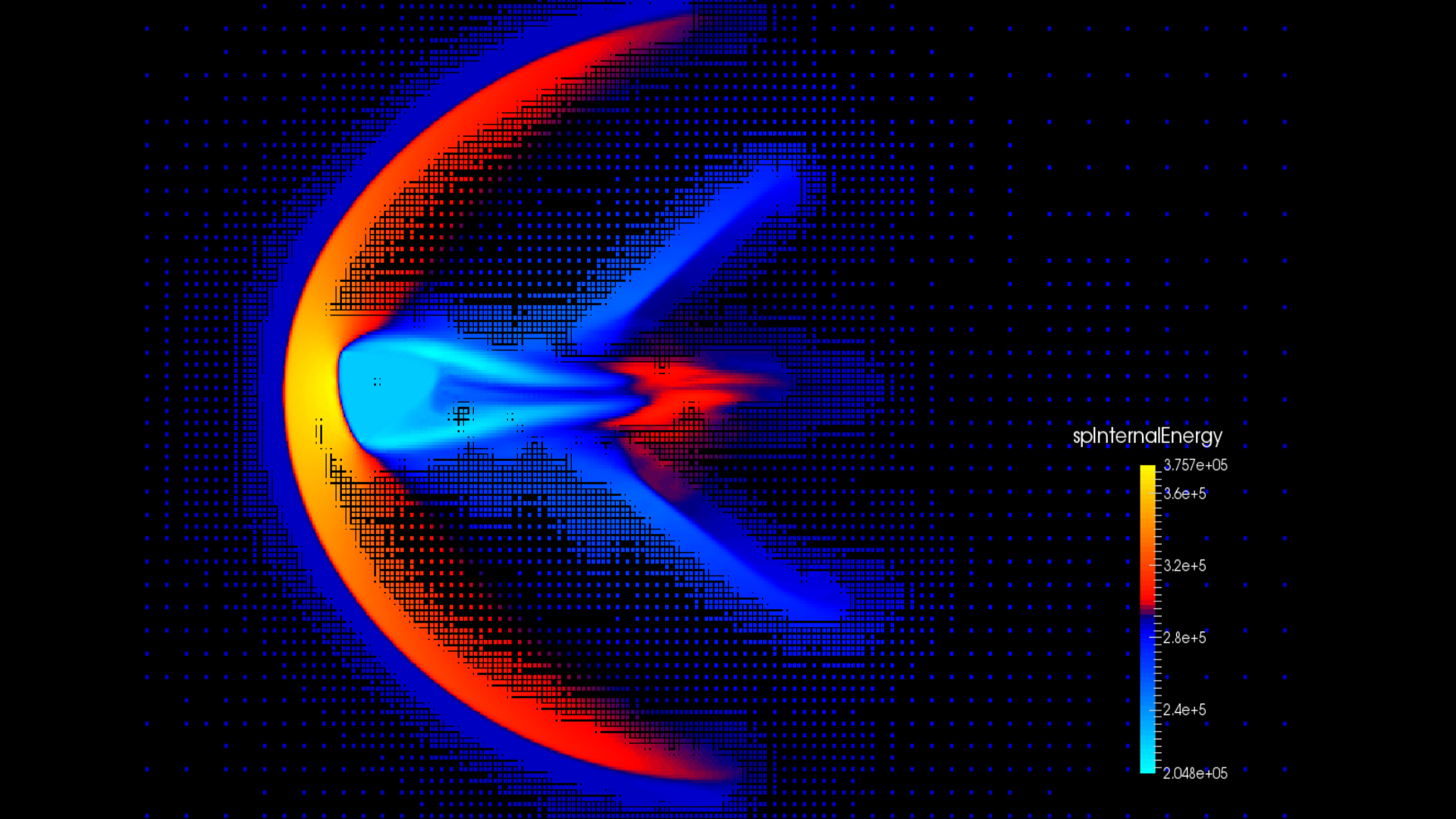
spInternalEnergy
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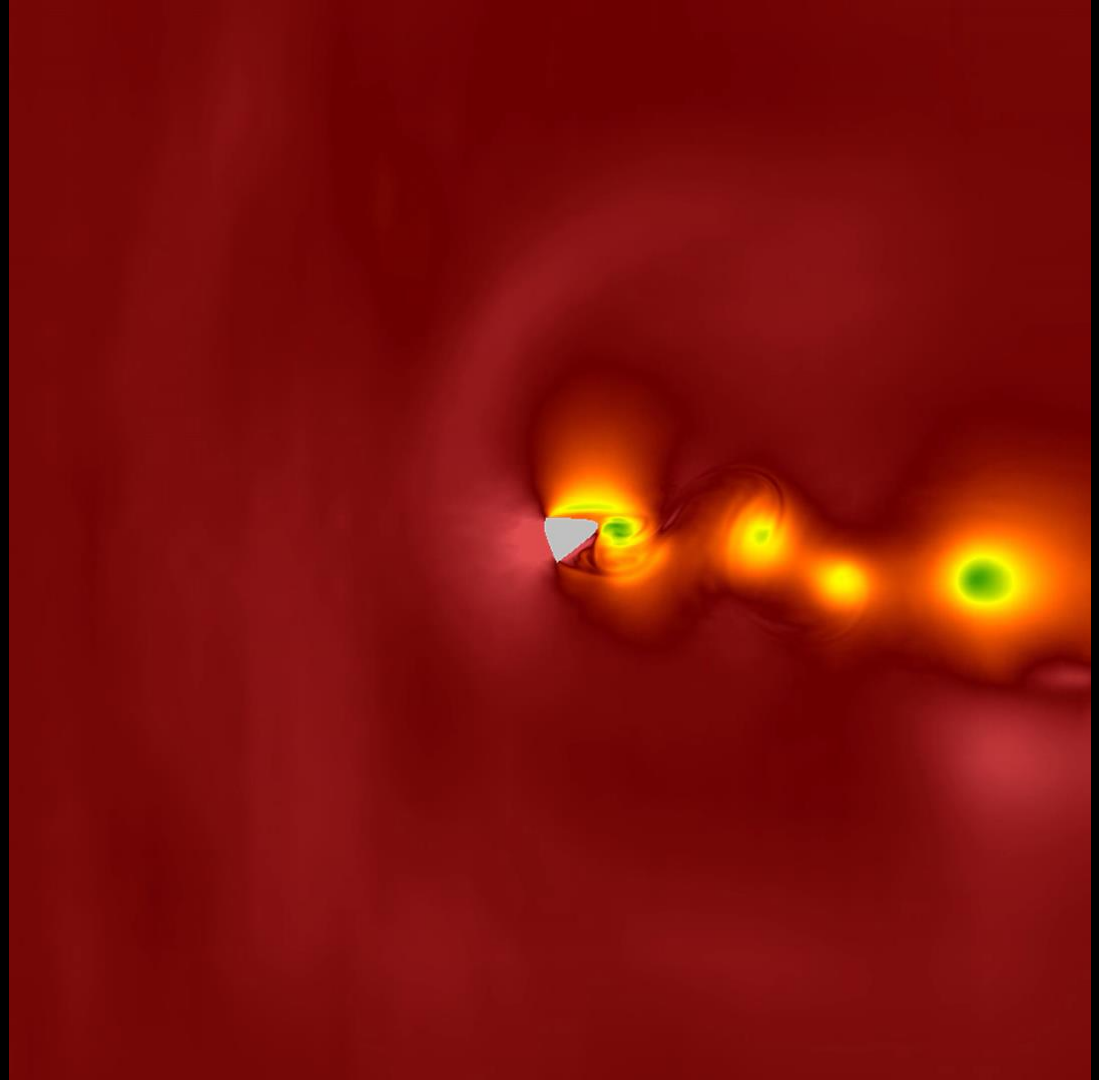
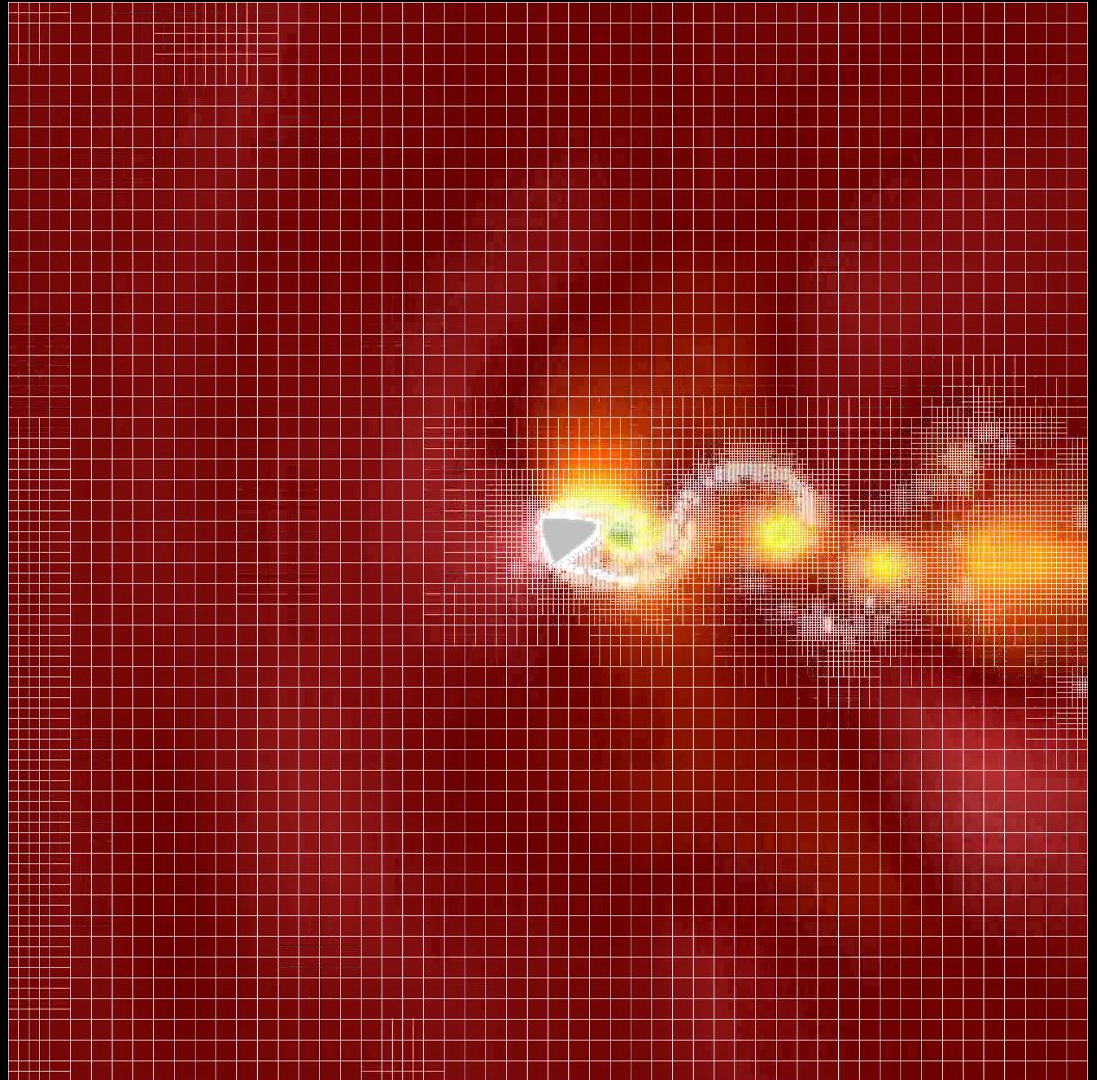
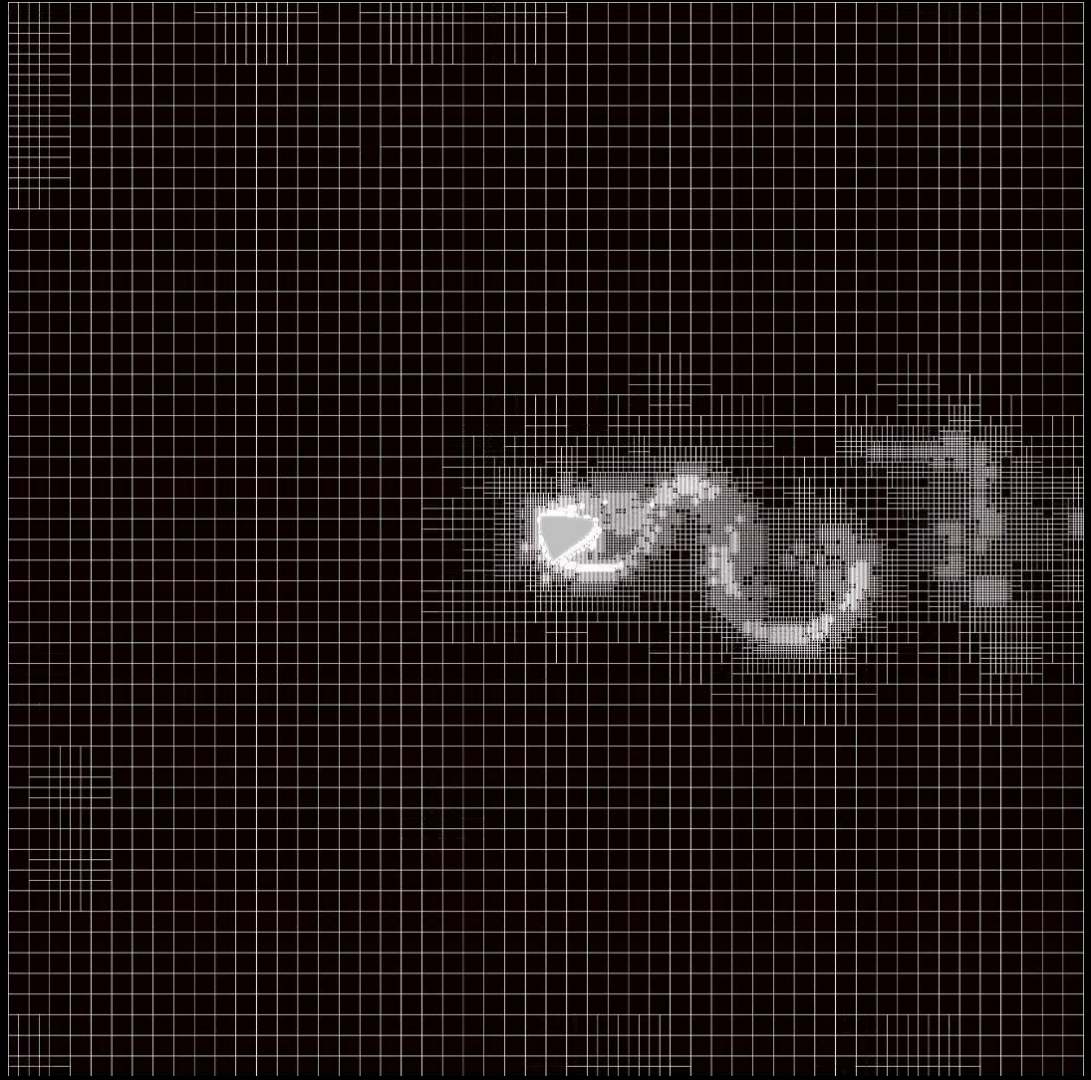
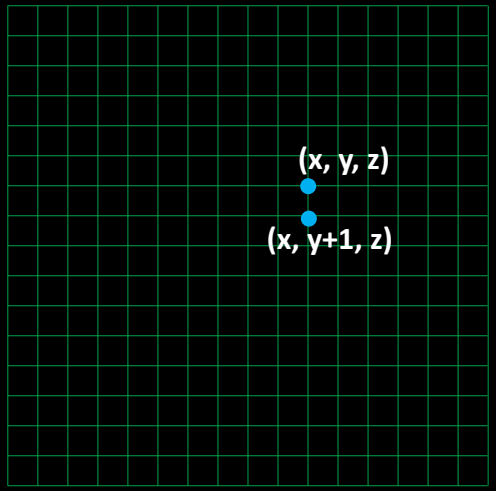
3.6e+5
3.2e+5
2.8e+5
2.4e+5
2.048e+05







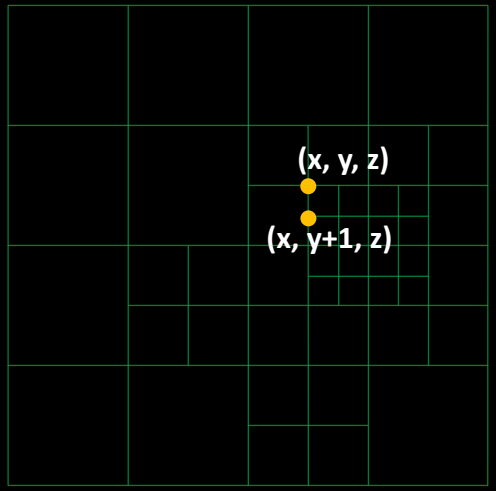
Regular Grid: Direct Indexing



Index (x, y, z) = p

Index (x, y+1, z) = p + N_x

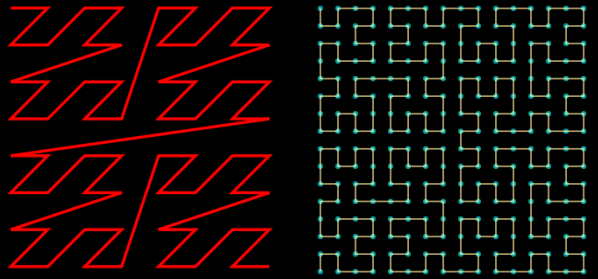
Sparse Grid: Difficult Indexing



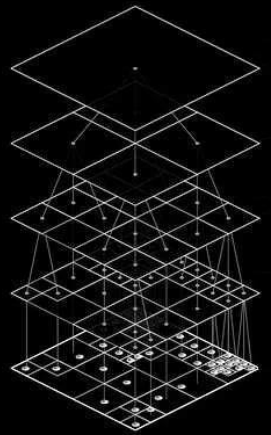
Index (x, y, z) = p

Index (x, y+1, z) = ???

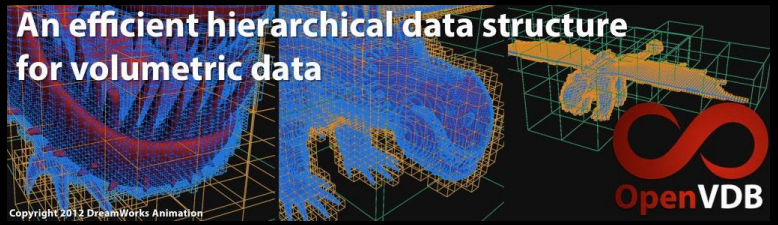
Sparse Grid Point Lookup



Linear search

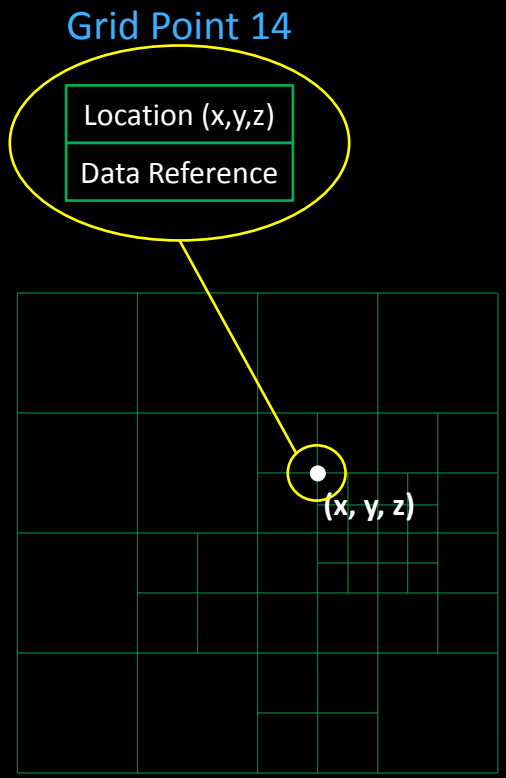


Tree-based search

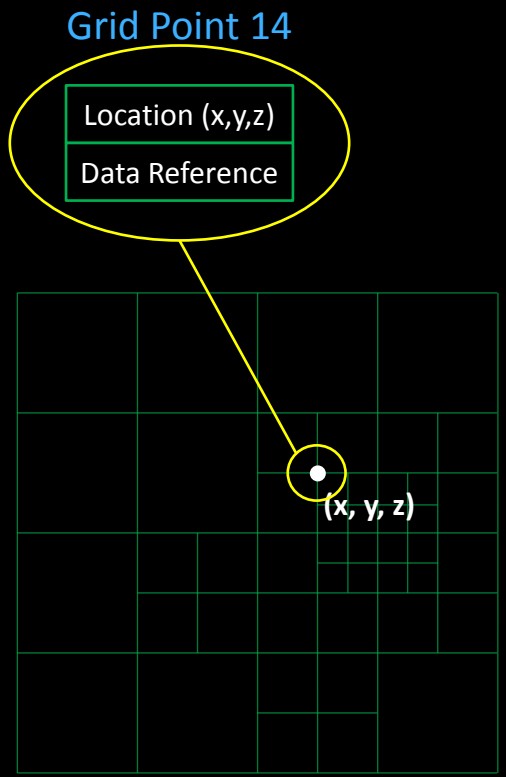


Hybrid tree search + dense indexing

Grid Point Contains *Reference* to Data



Grid Point Contains *Reference* to Data



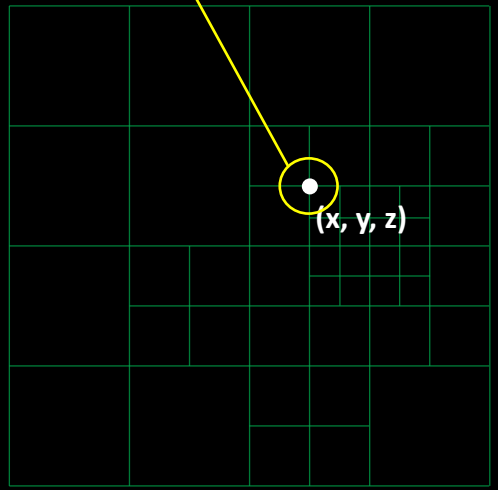
Grid Index	14	15	16
Grid Data	(11,11,5)	(11,12,5)	(Location)
	3	8	(Reference)

Grid Point Contains *Reference* to Data

Grid Point 14

Location (x,y,z)

Data Reference

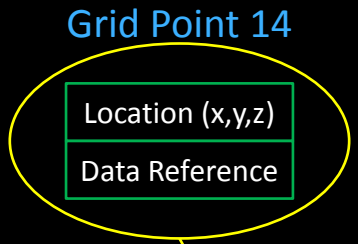


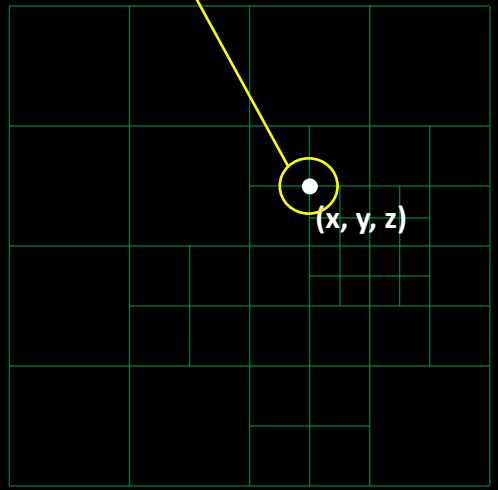
Grid Index	14	15	16
Grid Data	(11,11,5)	(11,12,5)	…
	3	8	…

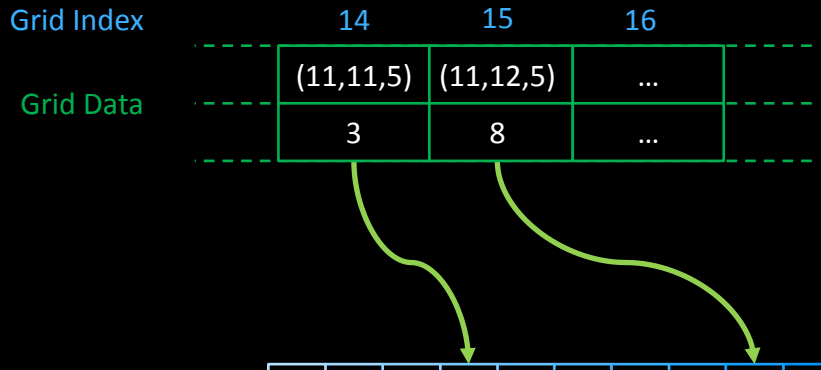
density	ρ_0	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9
X-momentum	ρu_0	ρu_1	ρu_2	ρu_3	ρu_4	ρu_5	ρu_6	ρu_7	ρu_8	ρu_9
Y-momentum	ρv_0	ρv_1	ρv_2	ρv_3	ρv_4	ρv_5	ρv_6	ρv_7	ρv_8	ρv_9
Z-Momentum	ρw_0	ρw_1	ρw_2	ρw_3	ρw_4	ρw_5	ρw_6	ρw_7	ρw_8	ρw_9
Energy	E_0	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9

Simulation Data

Grid Point Contains *Reference* to Data



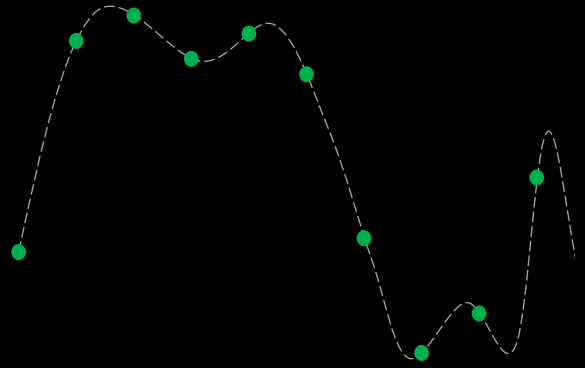




density	ρ_0	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9
X-momentum	ρu_0	ρu_1	ρu_2	ρu_3	ρu_4	ρu_5	ρu_6	ρu_7	ρu_8	ρu_9
Y-momentum	ρv_0	ρv_1	ρv_2	ρv_3	ρv_4	ρv_5	ρv_6	ρv_7	ρv_8	ρv_9
Z-Momentum	ρw_0	ρw_1	ρw_2	ρw_3	ρw_4	ρw_5	ρw_6	ρw_7	ρw_8	ρw_9
Energy	E_0	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9

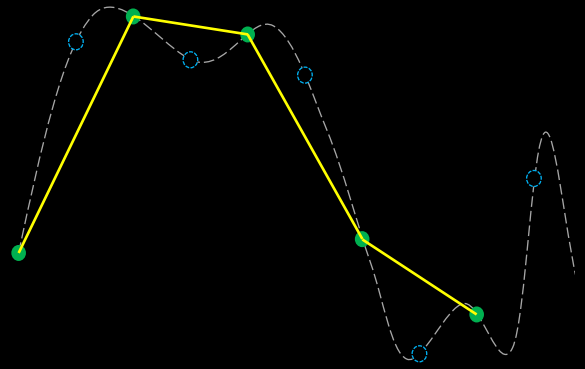
Simulation Data

Grid Adaptation



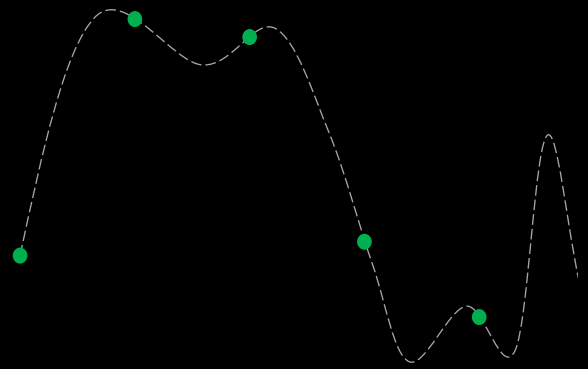
Grid Index	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Location	x_0y_0	x_1y_1	x_2y_2	x_3y_3	x_4y_4	x_5y_5	x_6y_6	x_7y_7	x_8y_8	x_9y_9
Reference	0	1	2	3	4	5	6	7	8	9

Grid Adaptation



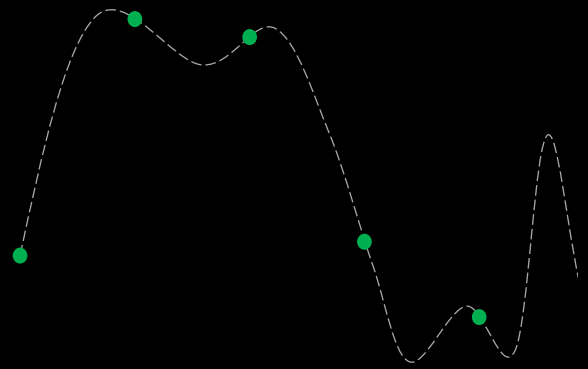
Grid Index	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Location	x_0y_0	x_1y_1	x_2y_2	x_3y_3	x_4y_4	x_5y_5	x_6y_6	x_7y_7	x_8y_8	x_9y_9
Reference	0	1	2	3	4	5	6	7	8	9

Grid Adaptation



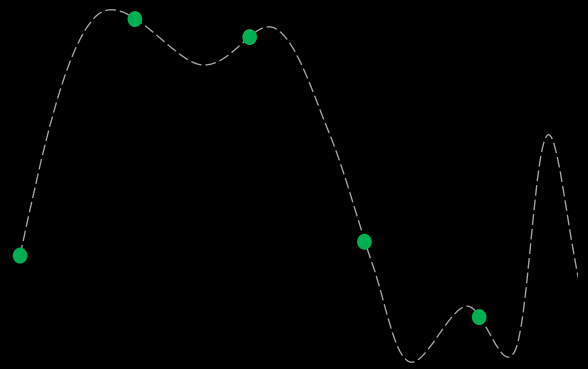
Grid Index	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Location	x_0y_0	x_1y_1	x_2y_2	x_3y_3	x_4y_4	x_5y_5	x_6y_6	x_7y_7	x_8y_8	x_9y_9
Reference	0	1	2	3	4	5	6	7	8	9

Grid Adaptation



Grid Index	P_0	P_2	P_4	P_6	P_8
Location	x_0y_0	x_2y_2	x_4y_4	x_6y_6	x_8y_8
Reference	0	2	4	6	8

Grid Adaptation



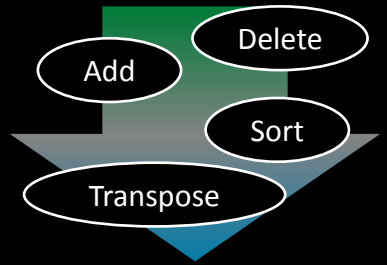
Grid Index	P_0	P_1	P_2	P_3	P_4
Location	x_0y_0	x_2y_2	x_4y_4	x_6y_6	x_8y_8
Reference	0	2	4	6	8

Grid Transformations Track Data

Grid Index	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Location	x_0y_0	x_1y_1	x_2y_2	x_3y_3	x_4y_4	x_5y_5	x_6y_6	x_7y_7	x_8y_8	x_9y_9
Reference	0	1	2	3	4	5	6	7	8	9

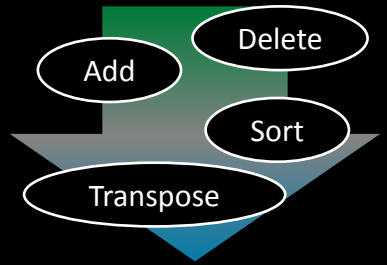
Grid Transformations Track Data

Grid Index	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Location	x_0y_0	x_1y_1	x_2y_2	x_3y_3	x_4y_4	x_5y_5	x_6y_6	x_7y_7	x_8y_8	x_9y_9
Reference	0	1	2	3	4	5	6	7	8	9



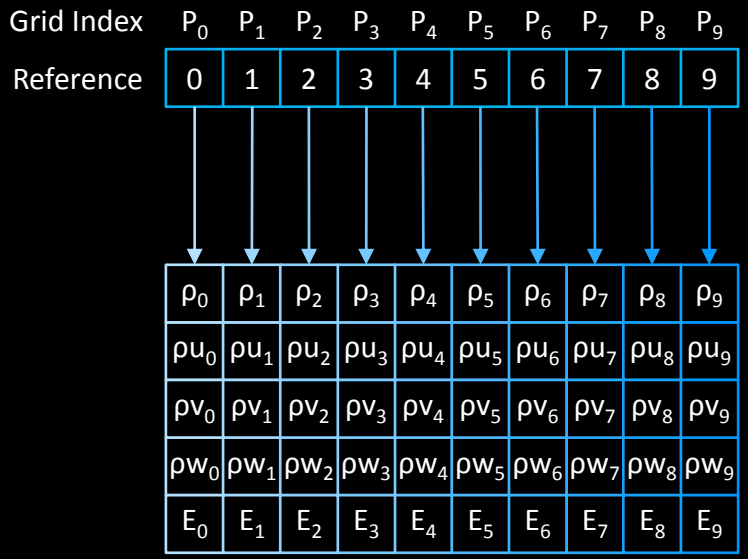
Grid Transformations Track Data

Grid Index	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Location	x_0y_0	x_1y_1	x_2y_2	x_3y_3	x_4y_4	x_5y_5	x_6y_6	x_7y_7	x_8y_8	x_9y_9
Reference	0	1	2	3	4	5	6	7	8	9



Grid Index	P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Location	x_4y_4	x_7y_7	x_9y_9	x_0y_0	x_5y_5	x_1y_1	x_8y_8	x_3y_3	x_6y_6	x_2y_2
Reference	4	7	9	0	5	1	8	3	6	2

Losing Coalesced Memory Access



Coalesced Simulation Data

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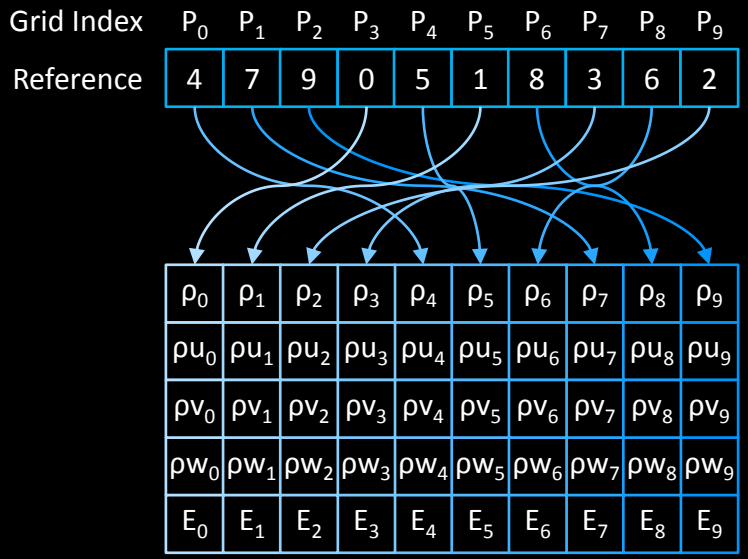
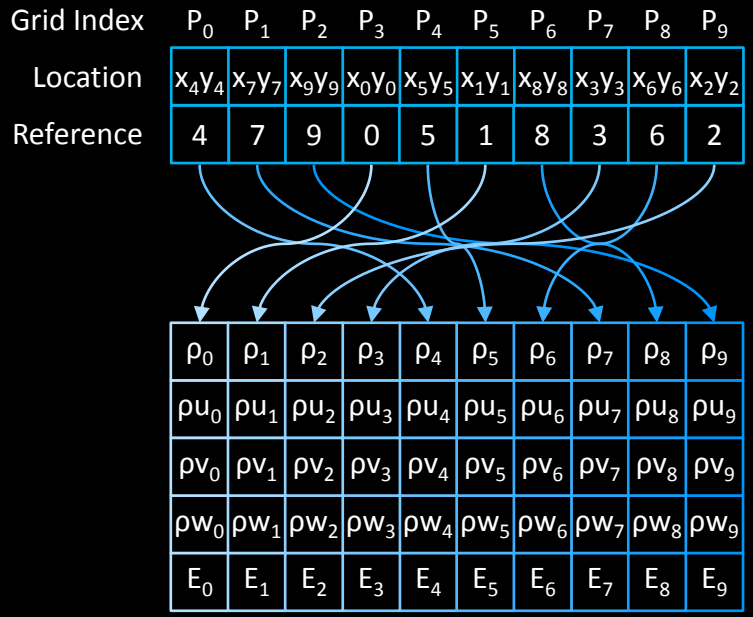
Losing Coalesced Memory Access



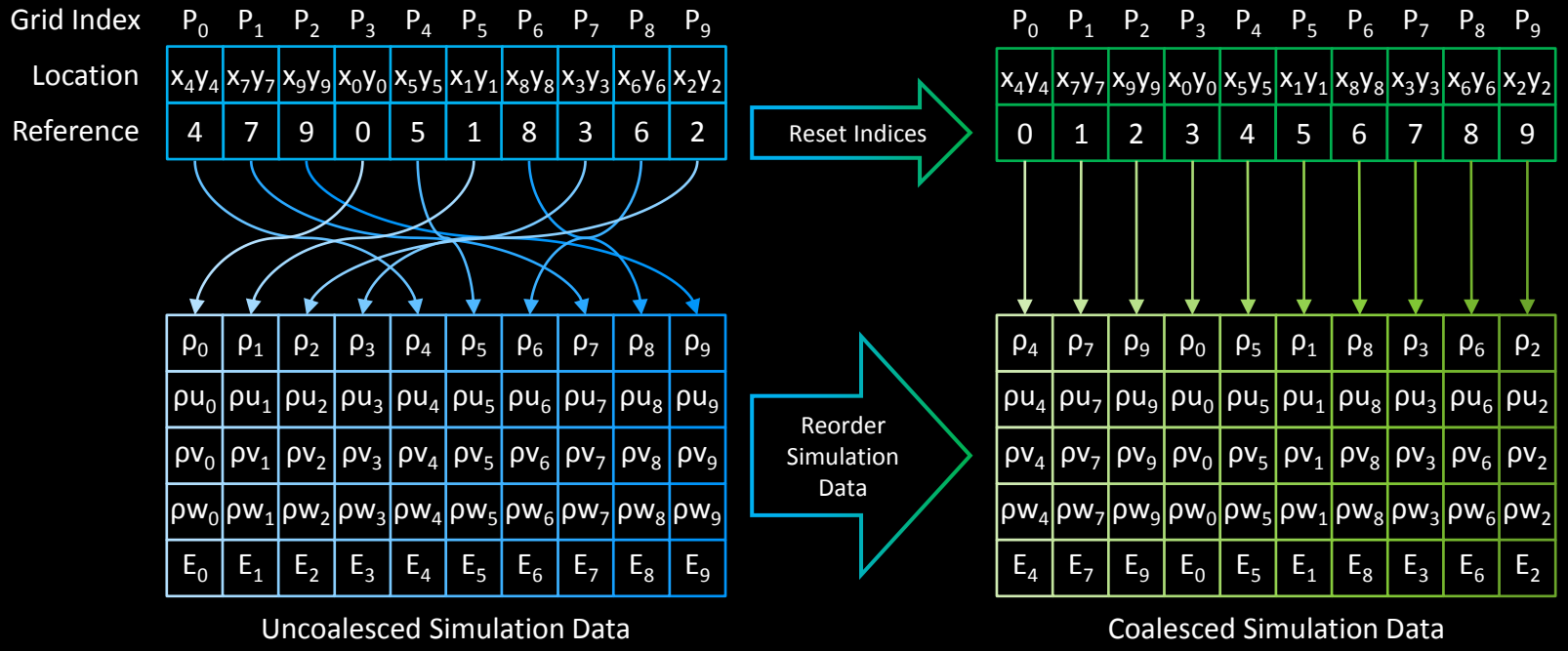
Uncoalesced Simulation Data

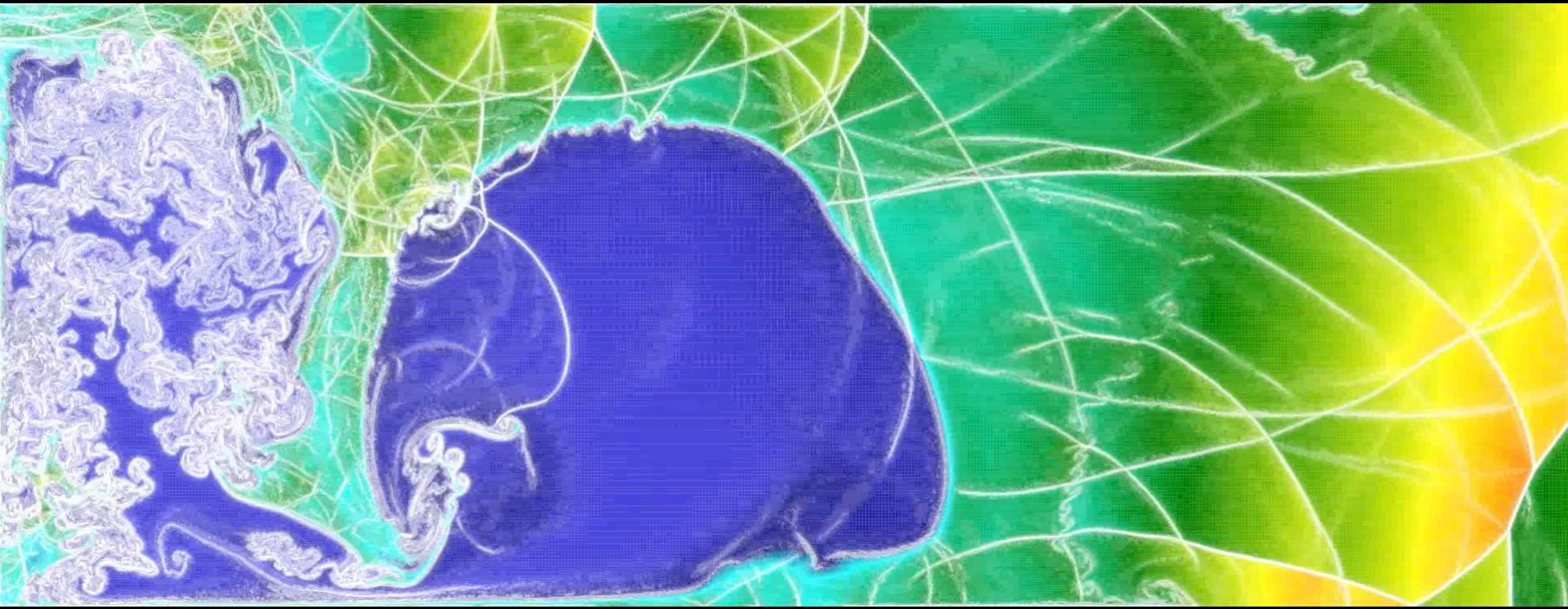
Restoring Coalesced Memory Access

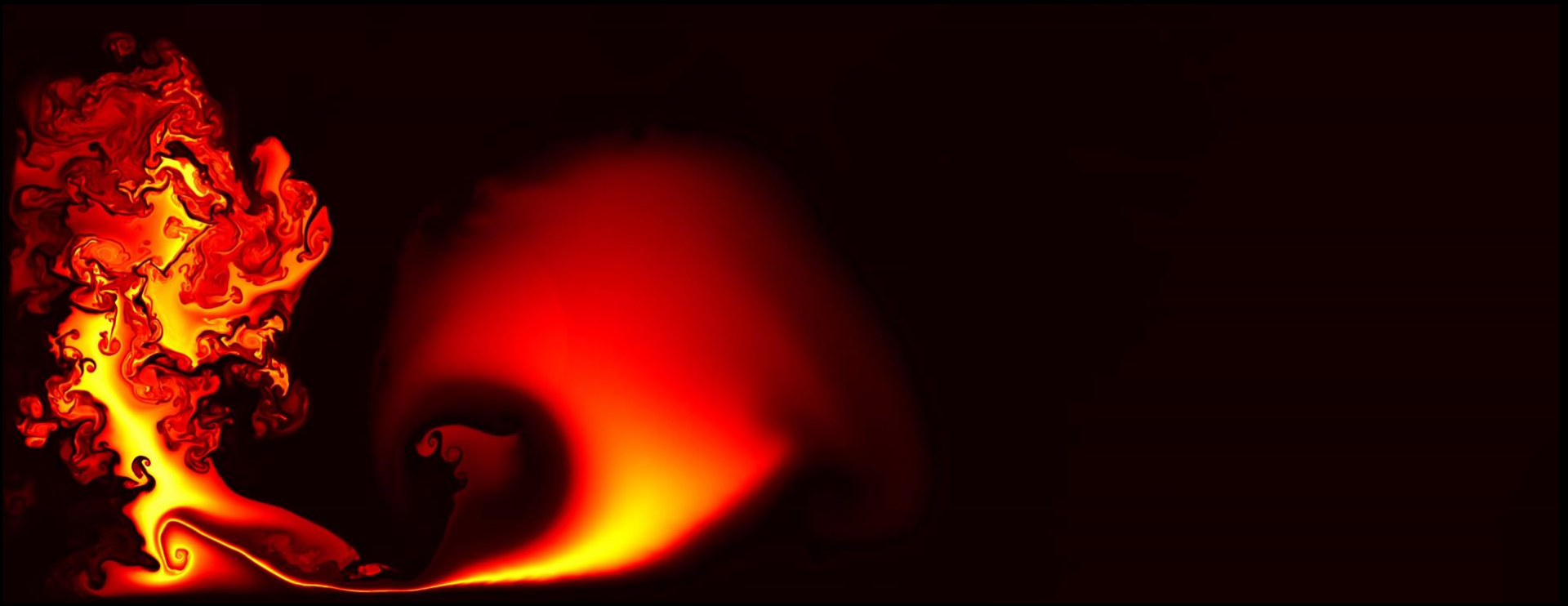


Uncoalesced Simulation Data

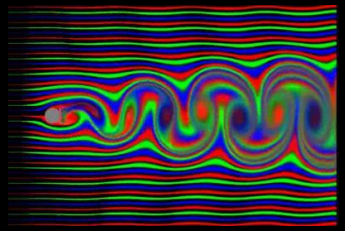
Restoring Coalesced Memory Access







Coupled Multi-Physics



Advection

Chemistry

Thermodynamics

Diffusion

SPACEX

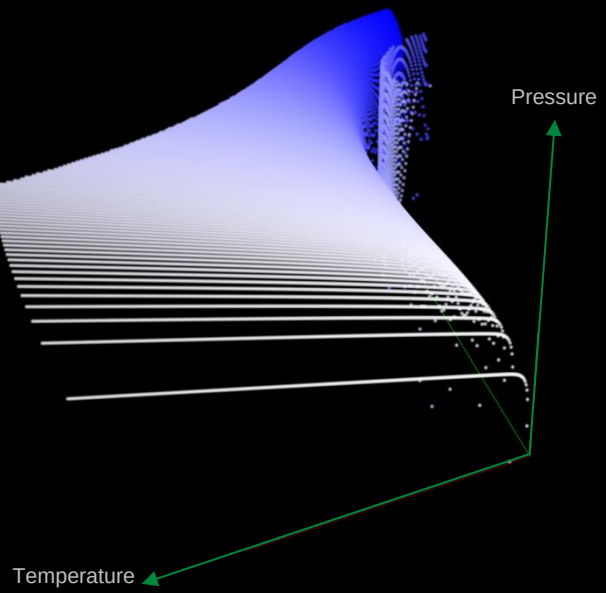
Real Gas Properties

Extreme pressure requires real-gas properties, evaluated at each grid node

- Viscosity
- Conductivity
- Diffusion constants
- Per-species diffusion rates

Independent Calculations

Massively Parallelizable



O_2 phase diagram, Z-axis is density
(colour: liquid is blue, gas is white)

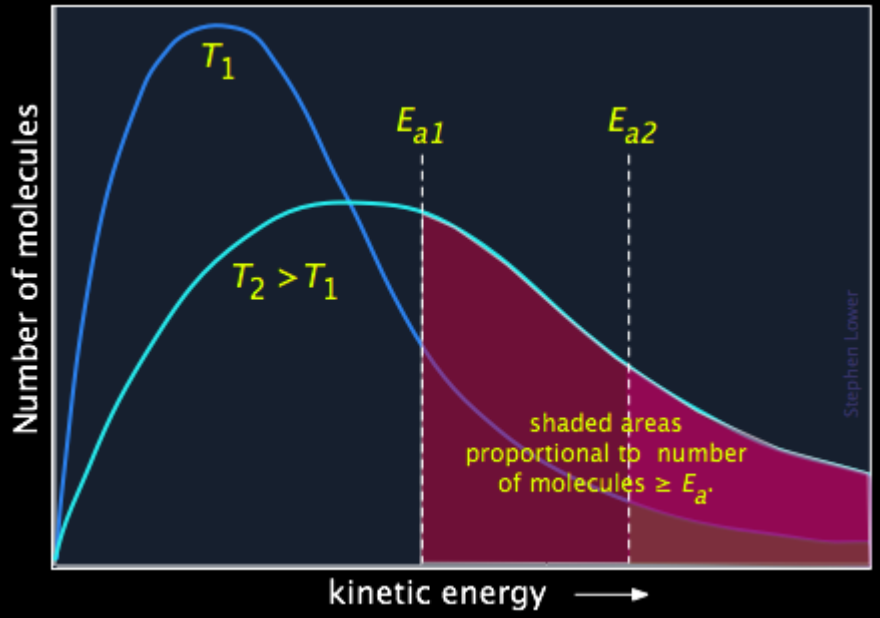
Strong Temperature Dependence

Arrhenius equation includes temperature in exponent

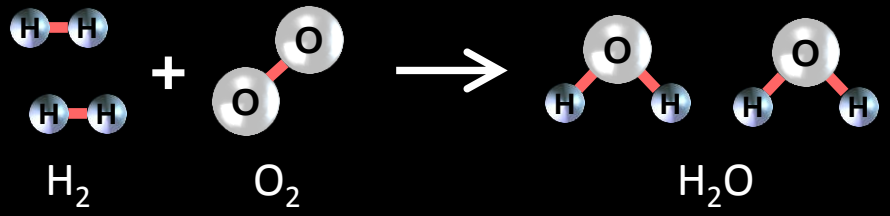
$$k = Ae^{-\frac{E_a}{RT}} \quad or \quad ln\ k = -\frac{E_a}{RT} + ln\ A$$

Where:

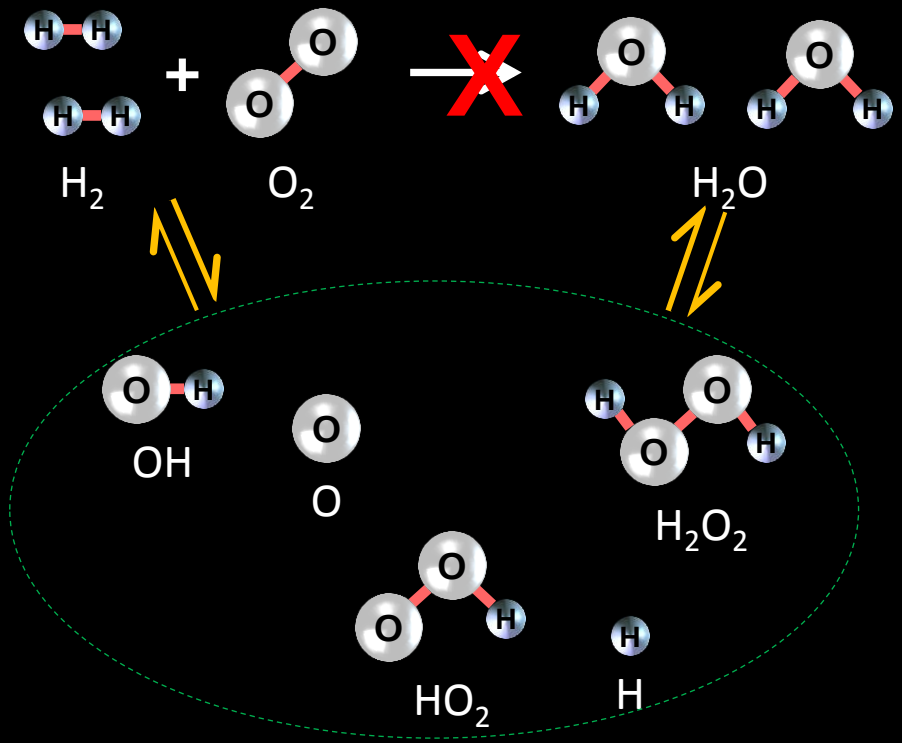
k =	Chemical Reaction Rate
A =	Pre-exponential Factor
E_a =	Activation Energy
R =	Gas Constant
T =	Temperature in Kelvin



Chemical Kinetic Model

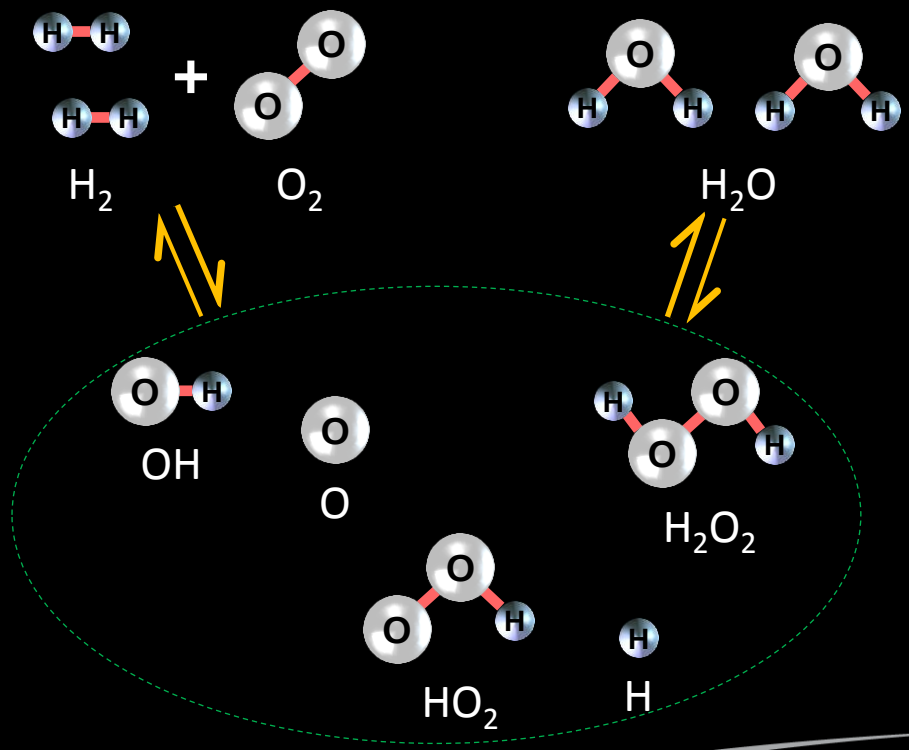


Chemical Kinetic Model



Chemical Kinetic Model

	Reaction	A	b	E_A
1	$H_2 + O_2 \rightleftharpoons 2OH$	0.170×10^{14}	0.0	47780
2	$OH + H_2 \rightleftharpoons H_2O + H$	0.117×10^{10}	1.30	3626
3	$O + OH \rightleftharpoons O_2 + H$	0.400×10^{15}	−0.50	0
4	$O + H_2 \rightleftharpoons OH + H$	0.506×10^{14}	2.67	6290
5	$H + O_2 + M \rightleftharpoons HO_2 + M$	0.361×10^{18}	−0.72	0
6	$OH + HO_2 \rightleftharpoons H_2O + O_2$	0.750×10^{13}	0.00	0
7	$H + HO_2 \rightleftharpoons 2OH$	0.140×10^{15}	0.00	1073
8	$O + HO_2 \rightleftharpoons O_2 + OH$	0.140×10^{14}	0.00	1073
9	$2OH \rightleftharpoons O + H_2O$	0.600×10^{9}	1.30	0
10	$H + H + M \rightleftharpoons H_2 + M$	0.100×10^{19}	−1.00	0
11	$H + H + H_2 \rightleftharpoons H_2 + H_2$	0.920×10^{17}	−0.60	0
12	$H + H + H_2O \rightleftharpoons H_2 + H_2O$	0.600×10^{20}	−1.25	0
13	$H + OH + M \rightleftharpoons H_2O + M$	0.160×10^{23}	−2.00	0
14	$H + O + M \rightleftharpoons OH + M$	0.620×10^{17}	−0.60	0
15	$O + O + M \rightleftharpoons O_2 + M$	0.189×10^{14}	0.00	−1788
16	$H + HO_2 \rightleftharpoons H_2 + O_2$	0.125×10^{14}	0.00	0
17	$HO_2 + HO_2 \rightleftharpoons H_2O_2 + O_2$	0.200×10^{13}	0.00	0
18	$H_2O_2 + M \rightleftharpoons OH + OH + M$	0.130×10^{18}	0.00	45500
19	$H_2O_2 + H \rightleftharpoons HO_2 + H_2$	0.160×10^{13}	0.00	3800
20	$H_2O_2 + OH \rightleftharpoons H_2O + HO_2$	0.100×10^{14}	0.00	1800
21	$O + N_2 \rightleftharpoons NO + N$	0.140×10^{15}	0.00	75800
22	$N + O_2 \rightleftharpoons NO + O$	0.640×10^{10}	1.00	6280
23	$OH + N \rightleftharpoons NO + H$	0.400×10^{14}	0.00	0



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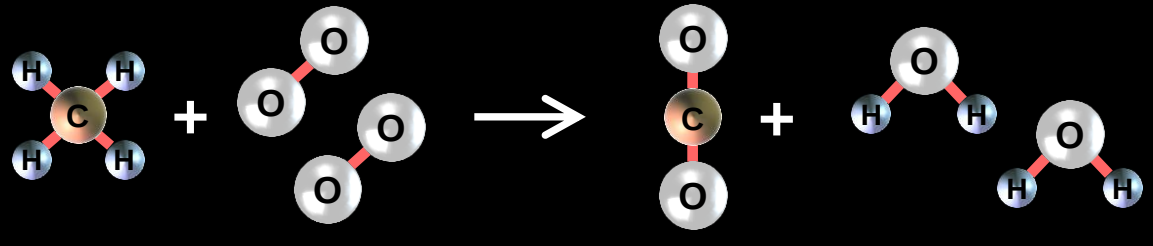
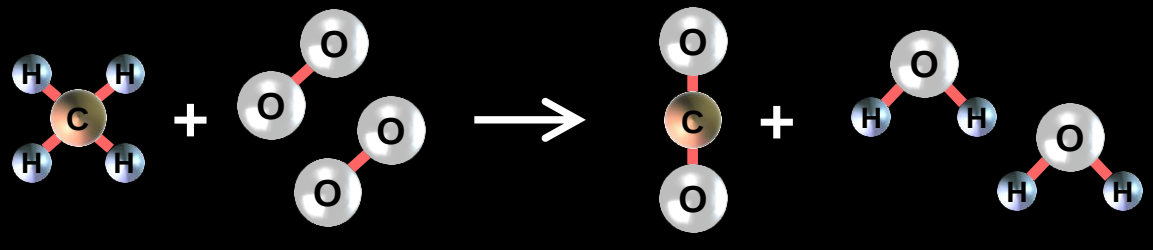
Methane Chemistry



CH_4 + O_2 → CO_2 + H_2O

Methane Chemistry

53 Species, 325 Reactions



CH_4 O_2 CO_2 H_2O

H+C3H8<=>C3H7+H2	1.320E+06	2.540	6756.00
OH+C3H8<=>C3H7+H2O	3.160E+07	1.800	934.00
C3H7+H2O2<=>HO2+C3H8	3.780E+02	2.720	1500.00
CH3+C3H8<=>C3H7+CH4	0.903E+00	3.650	7154.00
CH3+C2H4(+M)<=>C3H7(+M)	2.550E+06	1.600	5700.00
O+C3H7<=>C2H5+CH2O	9.640E+13	.000	.00
H+C3H7(+M)<=>C3H8(+M)	3.613E+13	.000	.00
H+C3H7<=>CH3+C2H5	4.060E+06	2.190	890.00
OH+C3H7<=>C2H5+CH2OH	2.410E+13	.000	.00
HO2+C3H7<=>O2+C3H8	2.550E+10	0.255	-943.00
HO2+C3H7=>OH+C2H5+CH2O	2.410E+13	.000	.00
CH3+C3H7<=>2C2H5	1.927E+13	-0.320	.00

SPACEX

(Actual simulation data, rendered with a ray tracer)

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Acknowledgements

Oleg Vasilyev, University of Colorado Boulder
Department of Mechanical Engineering

Jonathan Regele, Iowa State University
Department of Aerospace Engineering

Don Lamb
The Flash Center for Computational Science

Praveen Ramaprabhu
University of North Carolina at Charlotte

Joseph Oefelein, Sandia National Laboratories
Combustion Research Facility

Marc Massot
Ecole Centrale, Paris

Want To Help?

If you have a software or physics background and you're interested in working with us, please contact

research@spacex.com

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