The Potential for Real-time Computational Fluid Dynamics via GPU acceleration

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Overview

- GPU accelerated CFD
- Defining Realtime Simulation and its potential
- The numbers: a recent example and current status

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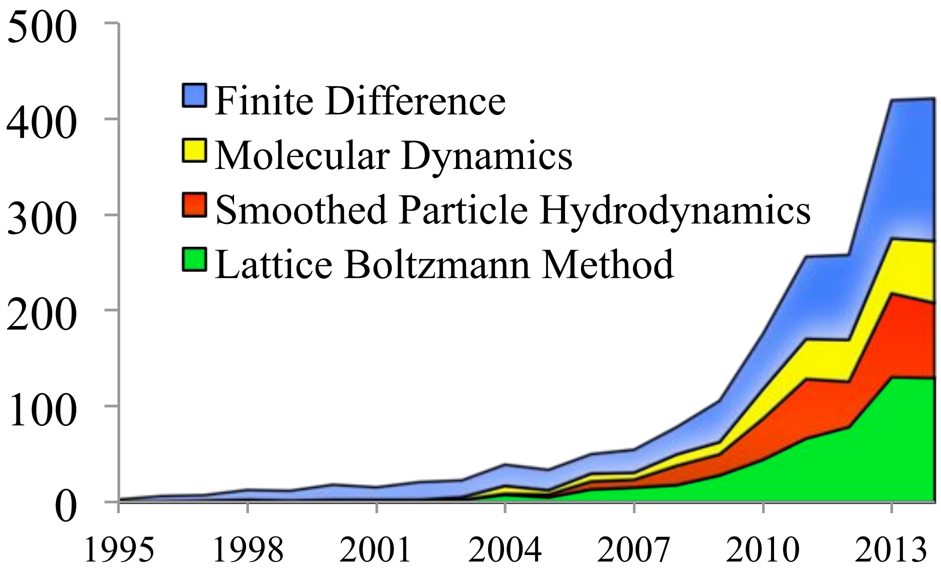
- **GPU accelerated CFD**
- **Defining Realtime Simulation and its potential**
- **The numbers: a recent example and current status**

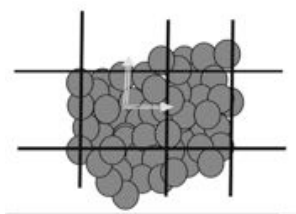
CFD on GPU

- **Development of CFD algorithms on GPU**
  - Originally driven by animating realistic physics
  - increasing application to particle based methods
- **initial activity**
  - appreciation of the challenge
  - difficulties porting codes
- **approach changed**
  - codes designed ground up
  - range of CFD methods
  - Pyfr, SPHysics, Sailfish
- **renewed potential**

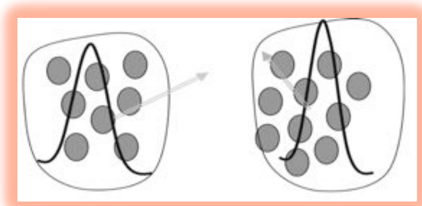


Overview of LBM

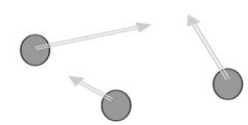
- **Lattice Boltzmann Makes use of Statistical Mechanics**
  - In this room there are billions of molecules hitting us at speeds of order 400m/s !
  - *Do we feel them? Do we need to know the behaviour of each molecule?*



MACRO



MESO

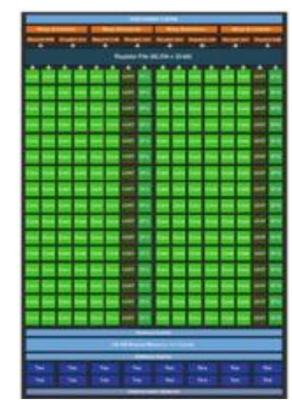


MICRO

- **In LBM a collection of particles is represented by a distribution function**
  - bridges scales by considering a collection of particles as a unit

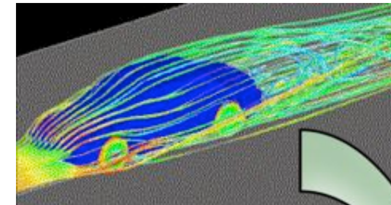
- **There are also some great advantages for GPU**
  - *Navier Stokes: non-linear and non-local*
  - *Lattice Boltzmann is linear and local*
  - perfect for parallelization on many core architectures

Ideal for GPU



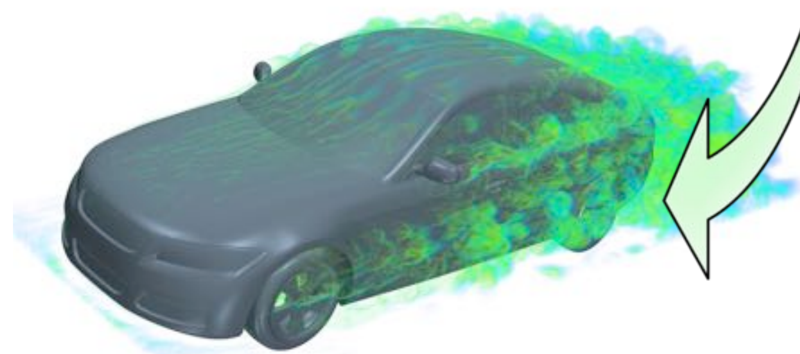
Gaming vs Physics
(~15 years)

- Realism vs Accuracy
- Detail vs. Developing Intuition
- Cost, Speed & Convenience
- Potential for closer collaboration?



~1M cells steady RANS
order 100 CPU hours

PhysX FleX
instantaneous on a single GPU



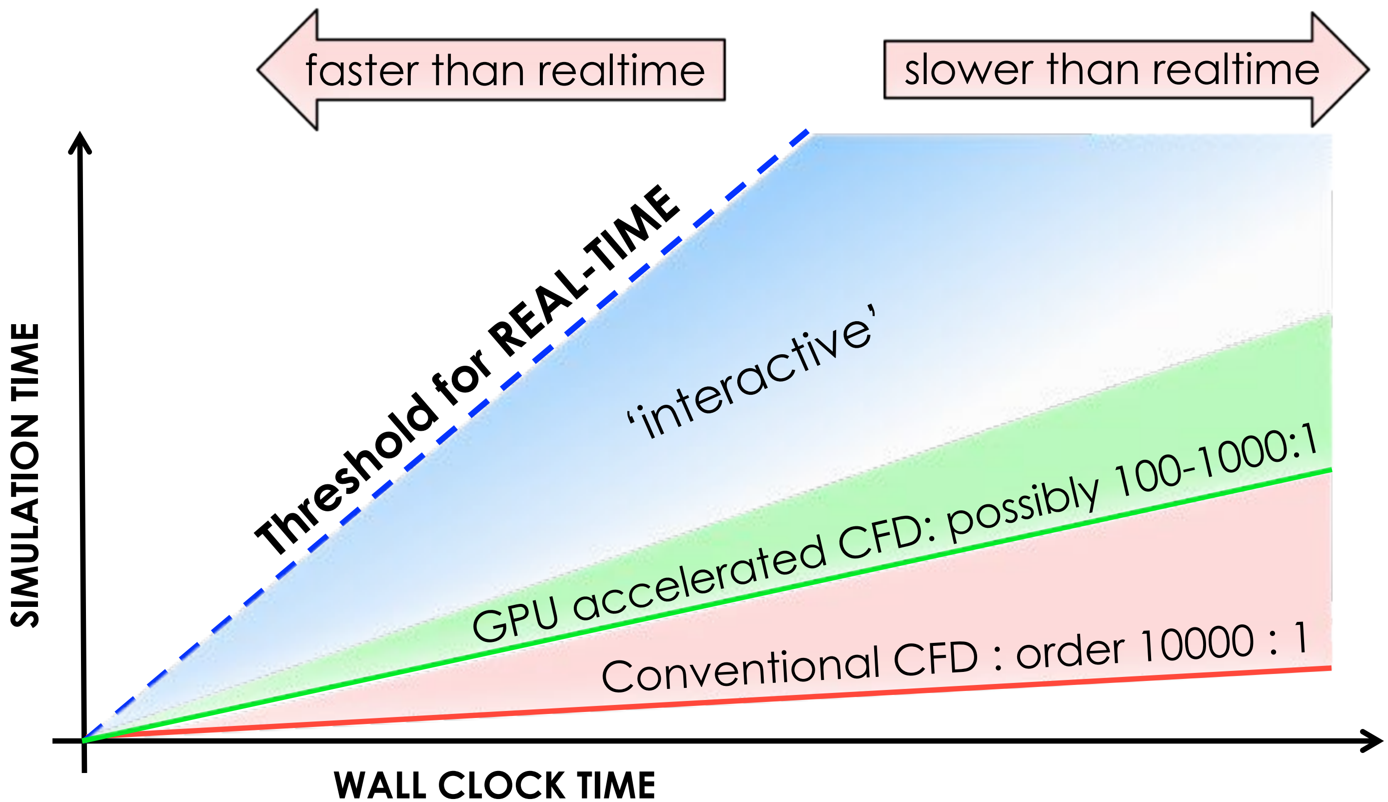
STAR-CCM+ 300M cells IDDES
order 100,000 CPU hours

Overview

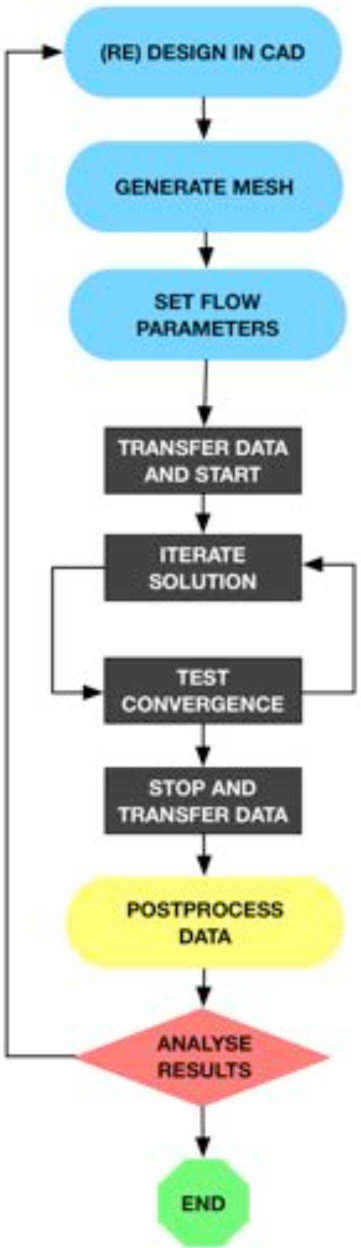
- GPU accelerated CFD
- **Defining Realtime Simulation and its potential**
- The numbers: a recent example and current status

Defining Simulation Speed

- **Game physics is instantaneous**
  - Engineering Simulation is not!
- **‘Realtime’ has a clear definition**
  - Interactive is open to interpretation

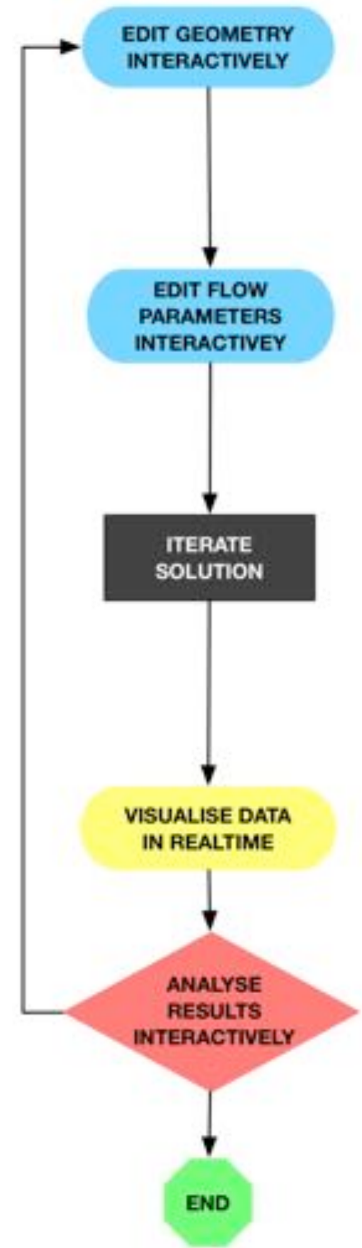


Conventional vs Realtime CFD



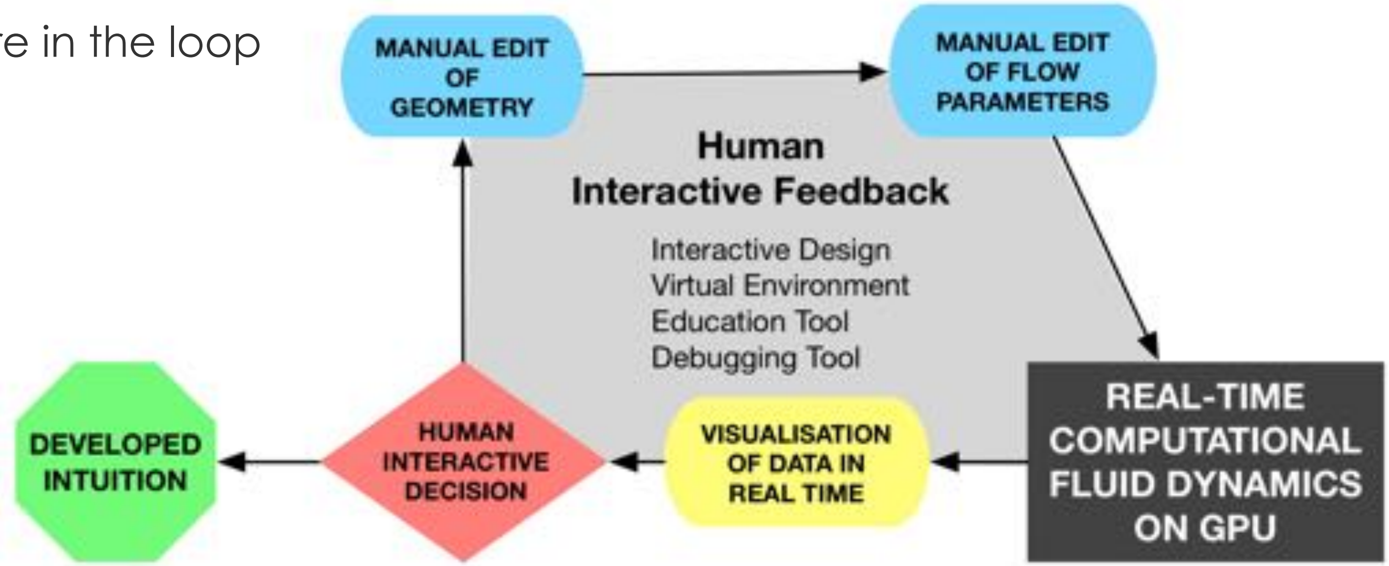
- **Typical CFD design has 2 loops**
  - design loop
  - solution loop
- **pre-processing main bottleneck**
- **bottlenecks also in data transfer**
  - increasingly for larger calculations

- **interactive CFD can have 1 loop**
  - geometry modification, solution and visualization in a single loop
- **various means of interacting**
  - input devices, augmented reality
- **data can't be saved/transferred**
  - faster to view in situ



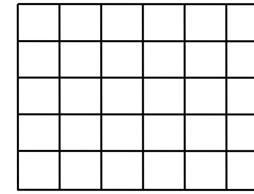
Human Systems

- **Applications for Realtime simulations can fall into two categories**
  - Humans in the loop
  - Hardware in the loop

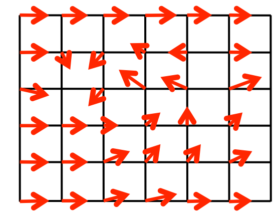


- **Most obvious is creation of a virtual environment**
  - e.g. for training
  - realtime is impotant
- **But realtime isn't necessary for all applications**
  - developing intuition, interactive design

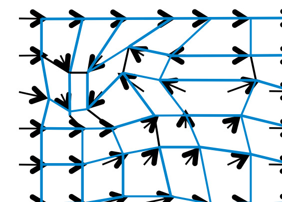
Visualization output



Original mesh

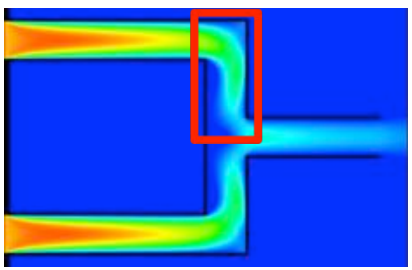


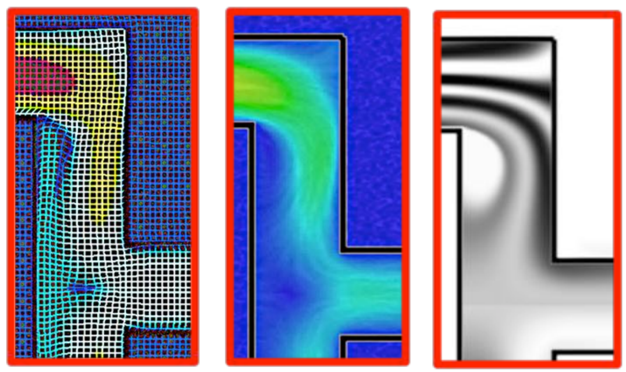
Vectors from flow



Distorted mesh

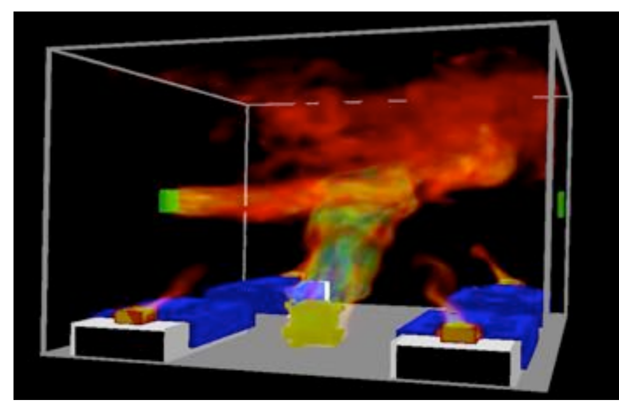
- **A range of techniques available from GPU libraries**
  - Contour flood (of e.g. velocity magnitude)
  - colormap is stored on GPU to speed up visualisation
- **e.g. Imaged Based Flow Visualisation (van Wijk, 2002)**
  - simulates advection of particles through a flow field





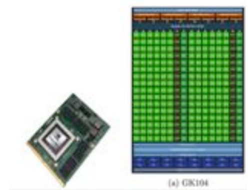
IBVF: mesh | Random noise | Dye injection

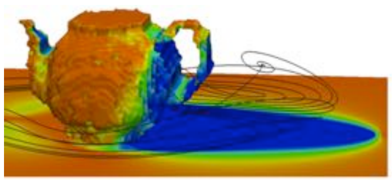
- **Volume Rendering too:**
  - libraries exist from Nvidia
  - e.g. Nicolas Delbosc's work at Univ. Leeds
  - see his Youtube account:



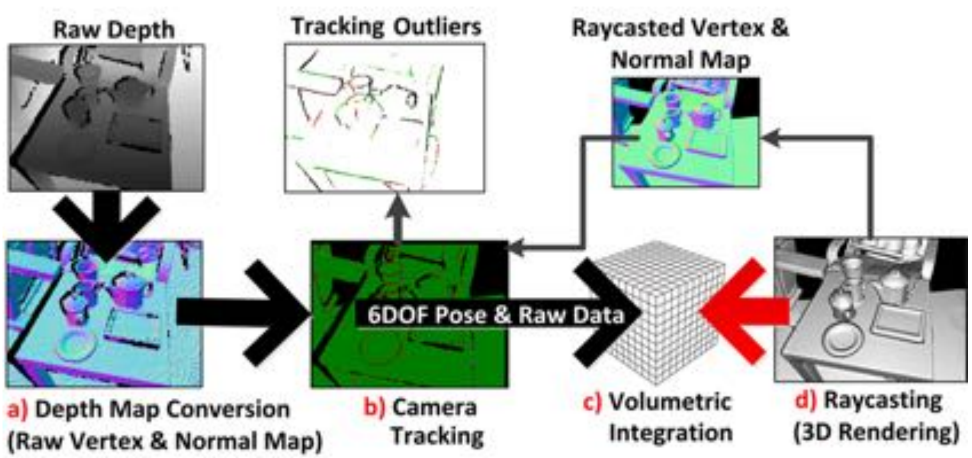
Kinect input: virtual windtunnel

- **Input geometry can be obtained from any source**
  - E.g. we demonstrate with a Microsoft Kinect (Mawson 2013)
  - Toolkit enables rapid integration with the flow solver

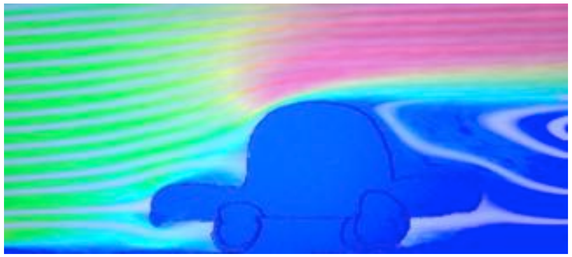





- **Kinect Fusion**



Human Systems: examples

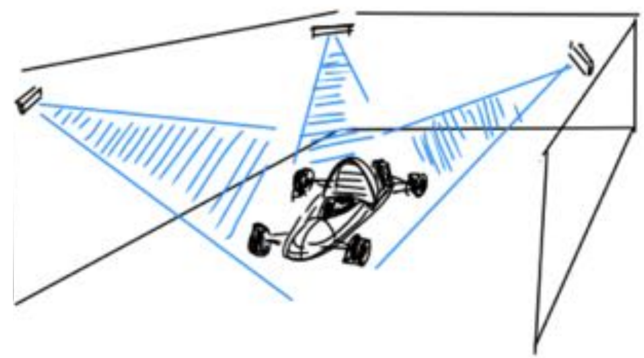


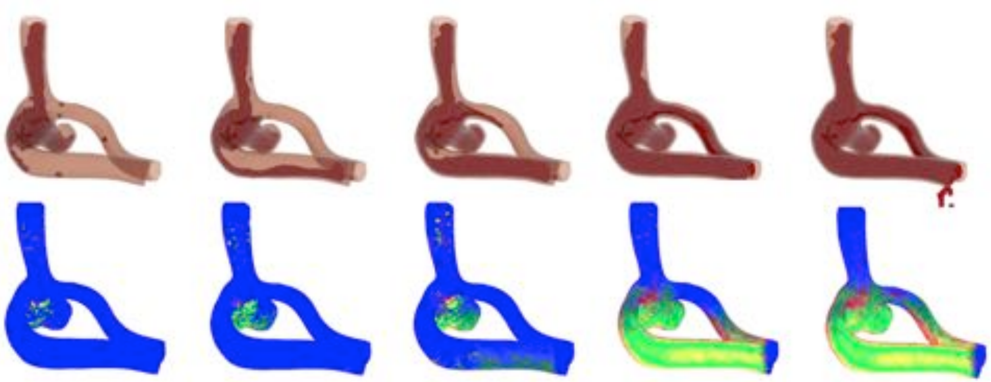
Teaching/Debugging tool

- Used currently in syllabus and in science fairs
- Provides direct understanding

Interactive Design concept

- Reduce design-engineer loop
- Modest aims at this stage





SPH by Guo et al 2015 Comp Animation and virtual worlds

Surgical Training

- Geometry captured in advance
- force visualised in realtime

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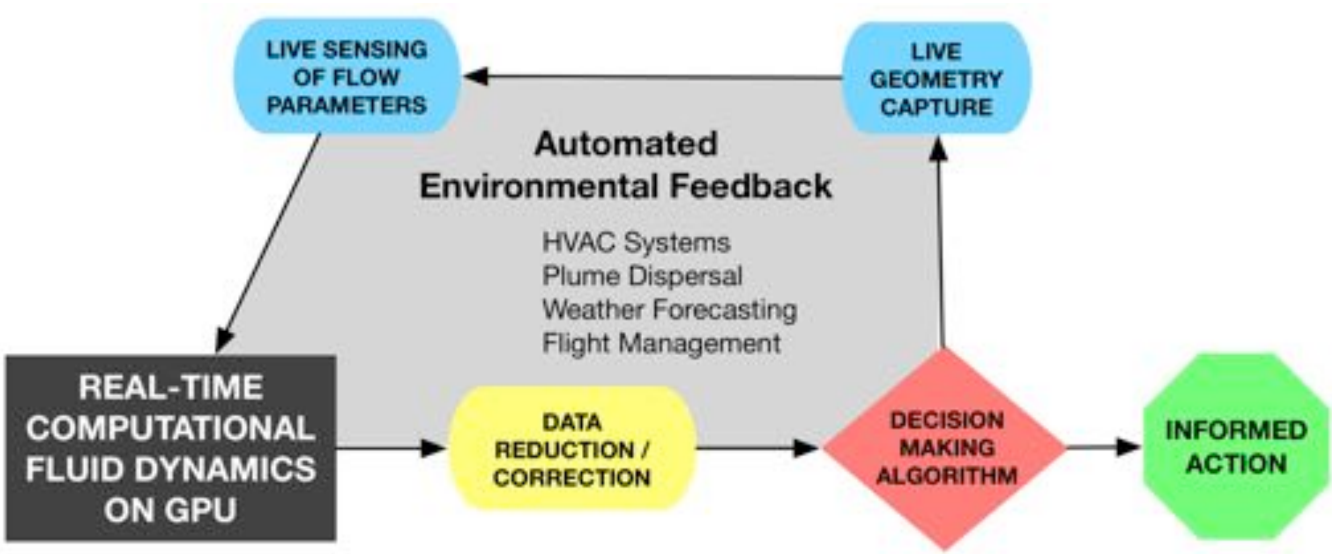
Automated Systems



- **Realtime is generally more important in these cases**
  - Used as part of a environmental monitoring system
- **Forecasting: Faster than Realtime**
  - e.g. extremely local weather forecasting
  - Early warning system: predicting path of contaminant
- **Ability to incorporate other sensors and ‘autocorrect’ simulation**

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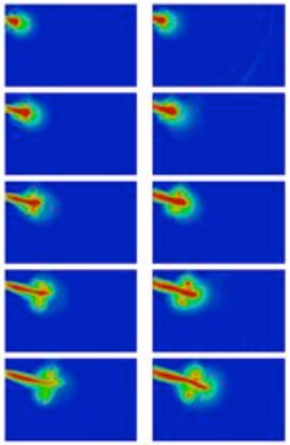
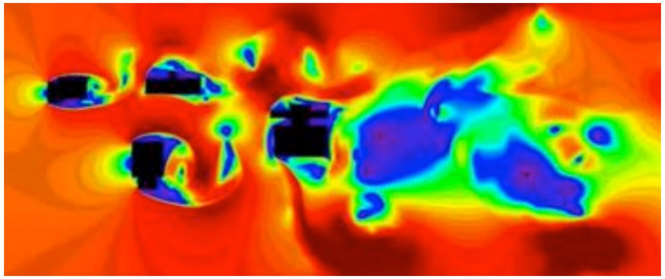
Automated systems: examples

Work on Data centre cooling at Leeds

- identify need for different levels of cooling in realtime
- simulated flow at a Reynolds number of 10,000, using
  - LBM simulations on a single Tesla K40: 0.34 s per second
  - Fluent on a CPU server across 16 nodes: 7 minutes per second



Khan et al 2014, Building Simulation

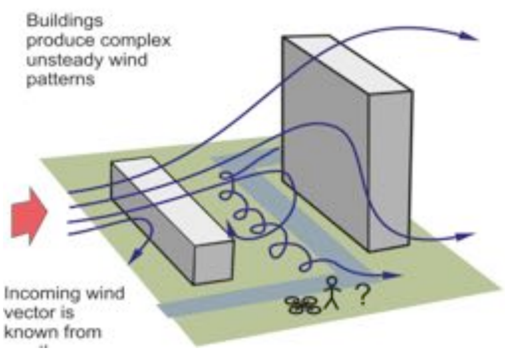


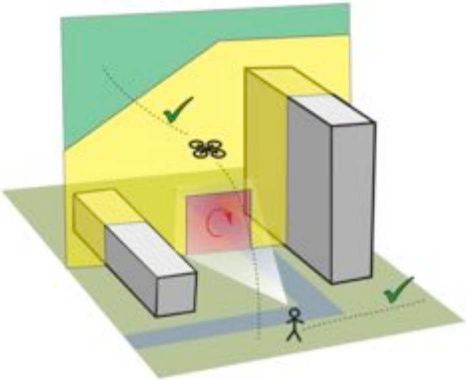
Contaminant tracking

- potential to be used to track spread of contaminant/pollutant/fire
- in combination with other sensors

Flight Management

- use as a local wind speed prediction tool for drones
- sensing buildings
- combining with forecasts

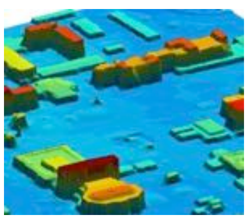




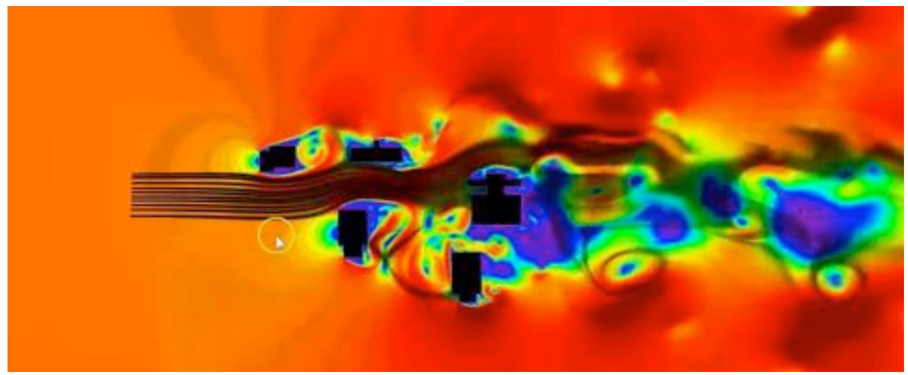
Data reduction

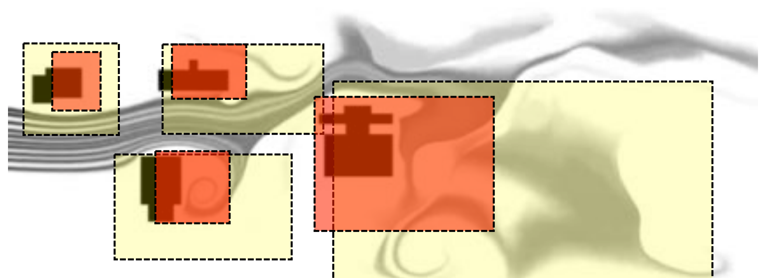
- when detailed flow information is not required the challenge is to reduce/extract meaningful data on the fly

Geometry capture



Interactive simulation (visualisation not needed)





Data reduction for communication/interpretation

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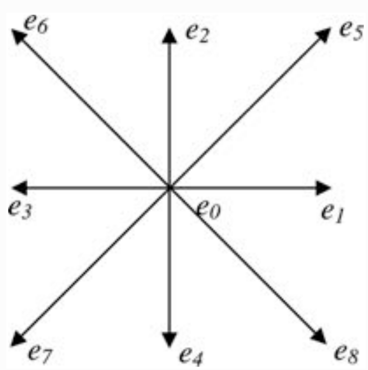
Discretisation of LBM

- **The LBE is discretised as follows:**

$$f_i(r + c_i\Delta t, t + \Delta t) = f_i(r,t) + \frac{\Delta t}{\tau}[f_i^{\mathrm{eq}}(r,t) - f_i(r,t)]$$

- **and is used together with a specific set of discrete velocities defined as**
  - **DnQm**: for **n dimensions** and **m discrete velocities**
  - In our work we use

D2Q9

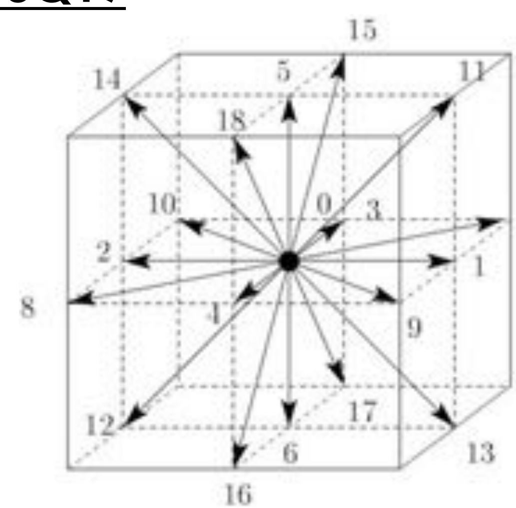


$$w_0 = \frac{4}{9}$$

$$w_{1-4} = \frac{1}{9}$$

$$w_{5-8} = \frac{1}{36}$$

D3Q19



$$w_0 = \frac{12}{36}$$

$$w_{1-6} = \frac{2}{36}$$

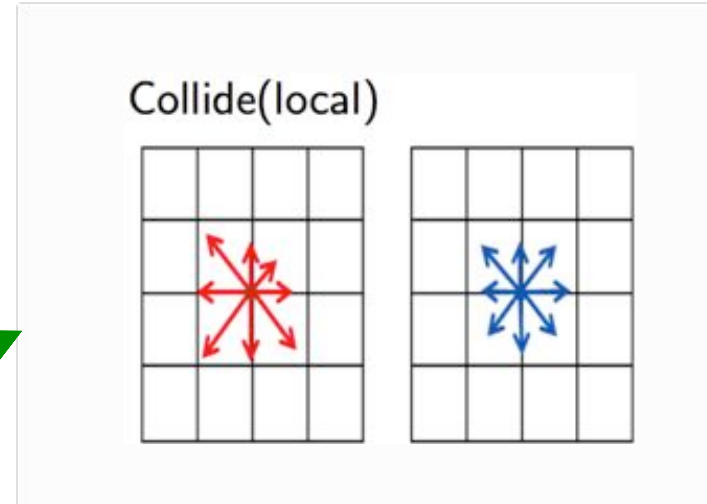
$$w_{7-18} = \frac{1}{36}$$

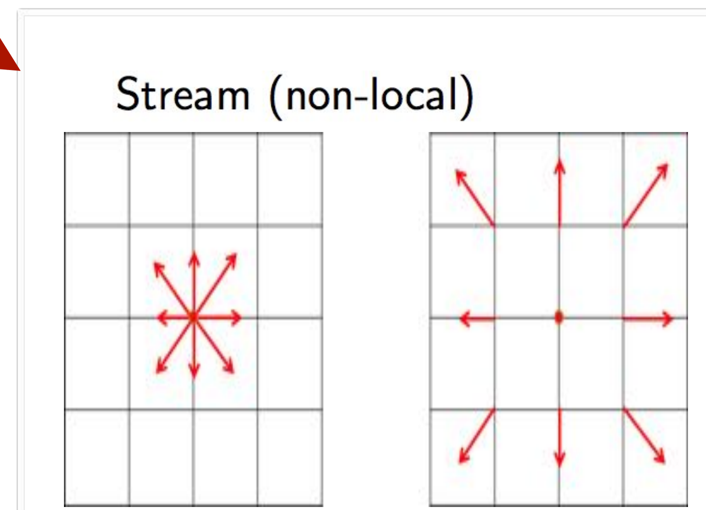
Algorithm

- The algorithm for LBM can now be defined as follows

1. Initialise
2. Compute equilibrium function
3. Collide
4. Stream
5. apply Boundary conditions
6. Compute Macroscopic values
7. Output data

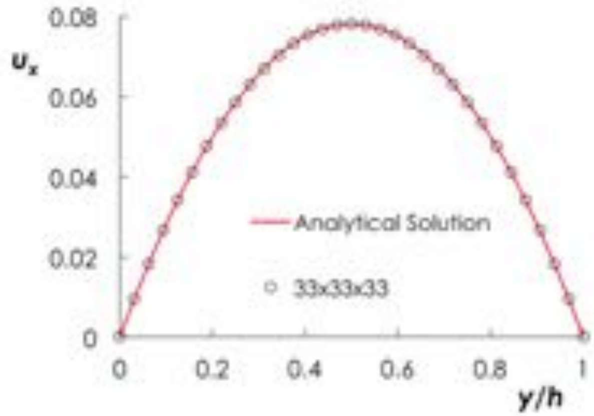
time loop

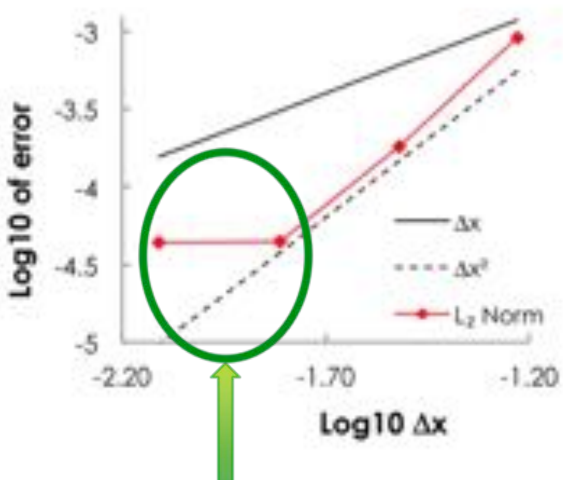




LBM Validation - 1: Poiseuille flow

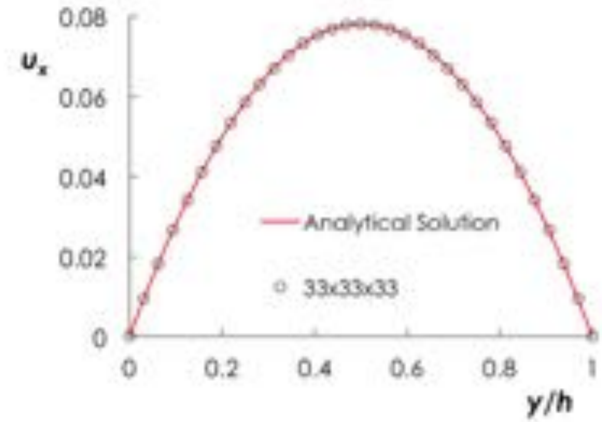
single precision

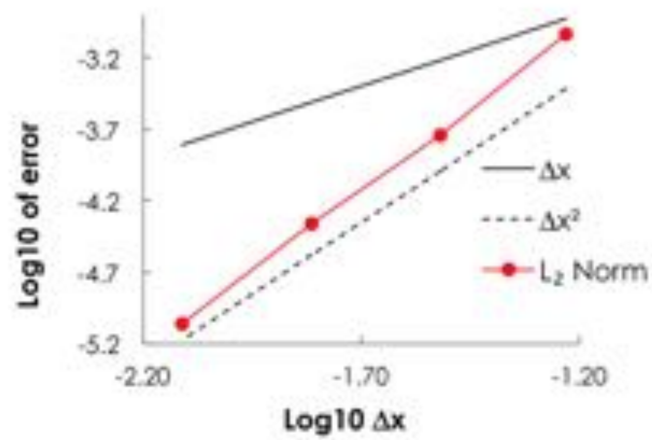




2[nd] order convergence up to floating point precision in 3D

double precision

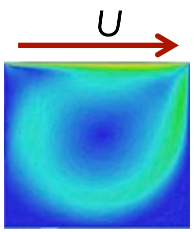


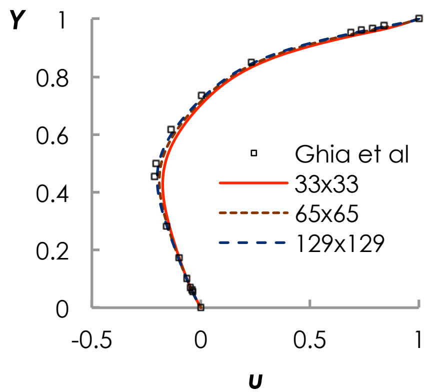


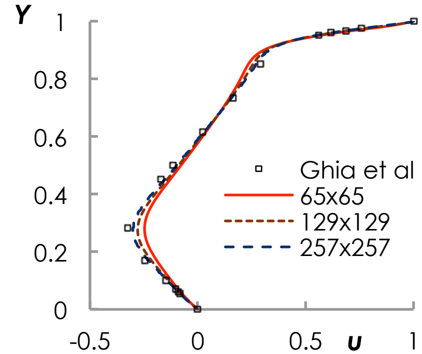
in DP memory limit hit before floating point error

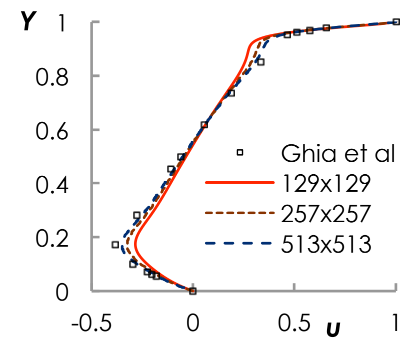
LBM Validation - 2 : LDC

2D Lid Driven Cavity



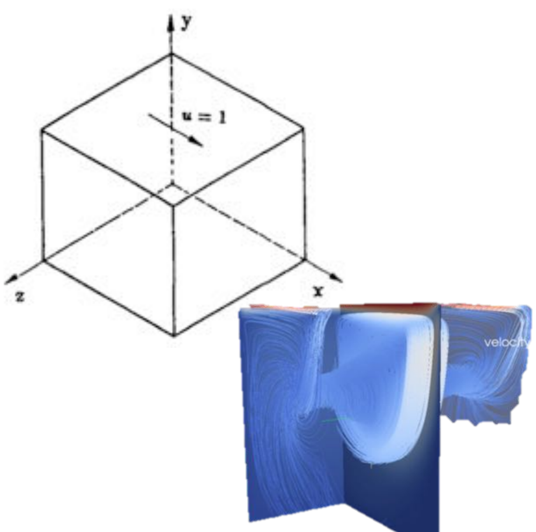


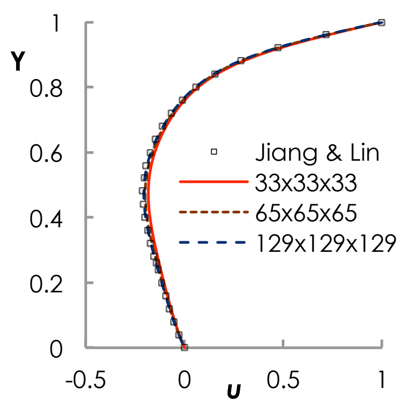


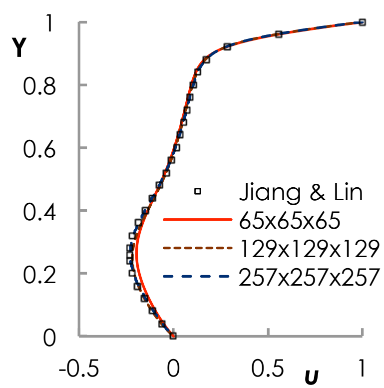


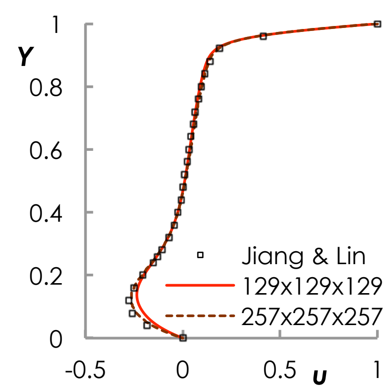
3D Lid driven Cavity

Centreline *u* profiles for Re=100,400 and 1000









Code optimised for GPU (Mawson 2013)

(a) GK104 (b) GK110

Feature	FK104 :K5000M	GK110: K20c
cores (SMX x cores/SMC)	1344 (7 x 192)	2496 (13 x 192)
regs / thread	63	255
DRAM	4GB	4.7GB
SP/DP ratio	24:1	3:1
Peak performance (single precision)	1.6 TFLOPS	3.5 TFLOPS
DRAM Bandwidth	66 GB/s (measured)	143 GB/s (measured)

Optimization steps

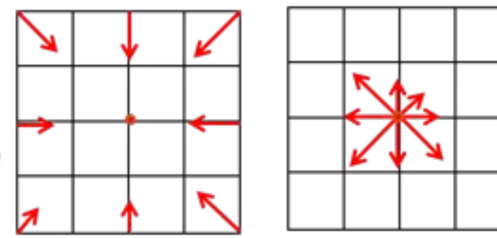
- fold arrays flat
- write arrays using f direction first and rely on 'un-coallesced' access
- Change algorithm order to reduce read/write of data during loop

PUSH

1. initialise
2. compute forces
3. compute $f^{(eq)}$
4. collide (local)
5. stream (non-local)
    - i.e. requires synchronisation
6. impose bcs.
7. compute macroscopic quantities

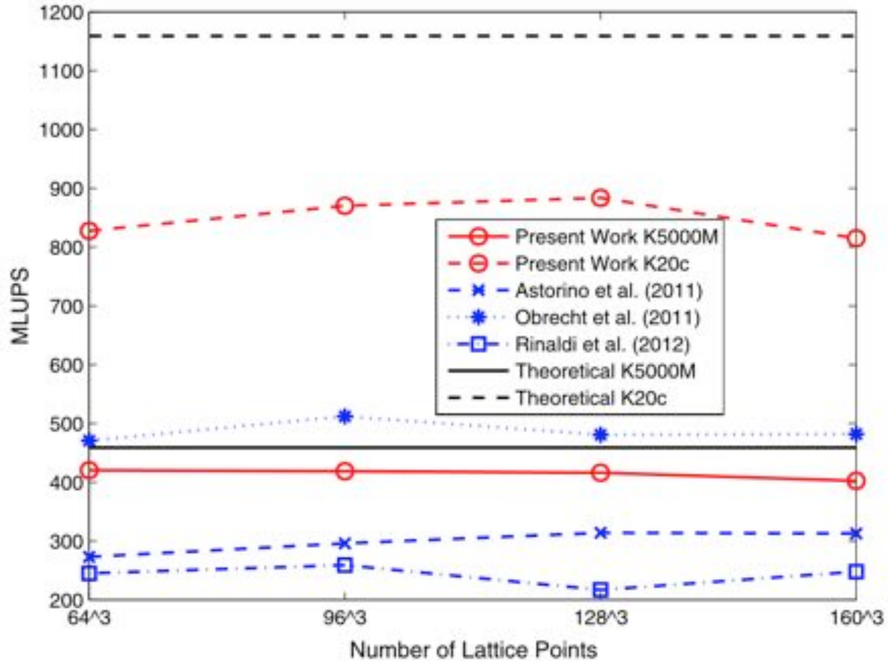
PULL

1. initialise
5. stream
   i.e. read values from host into new location
6. impose bcs.
7. compute macroscopic quantities
2. compute forces
3. compute $f^{(eq)}$
4. collide

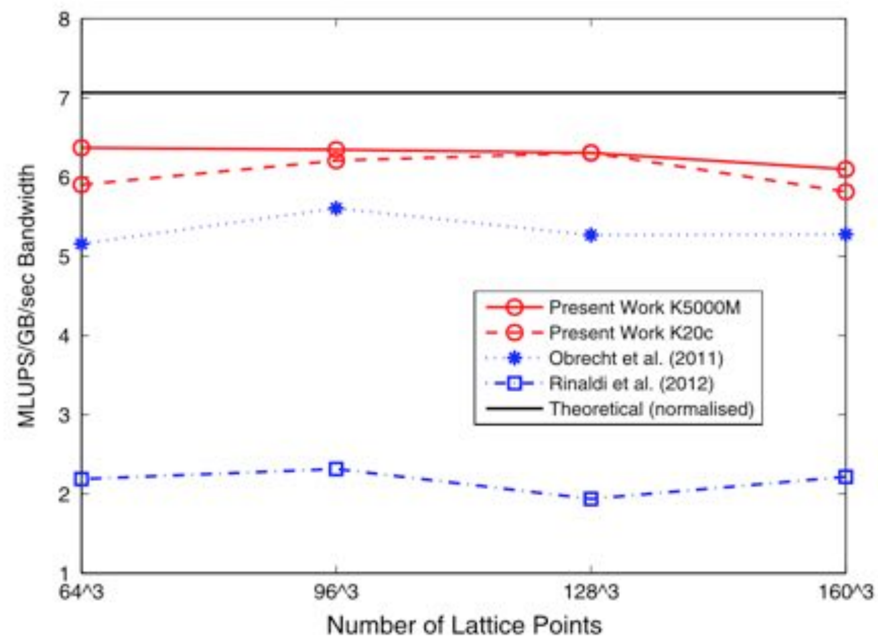


Overall performance-3D

main difference is hardware & memory access



scaling for bandwidth equalizes hardware differences



- Peak 814MLUPS K20c; **~92% of bandwidth scaled performance**
- For realtime CFD this means a resolution of 160^3 at a refresh rate of 200fps
- Main limitation was on board memory
- Current hardware is a factor 2-3 faster with larger memory

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Challenges for realtime

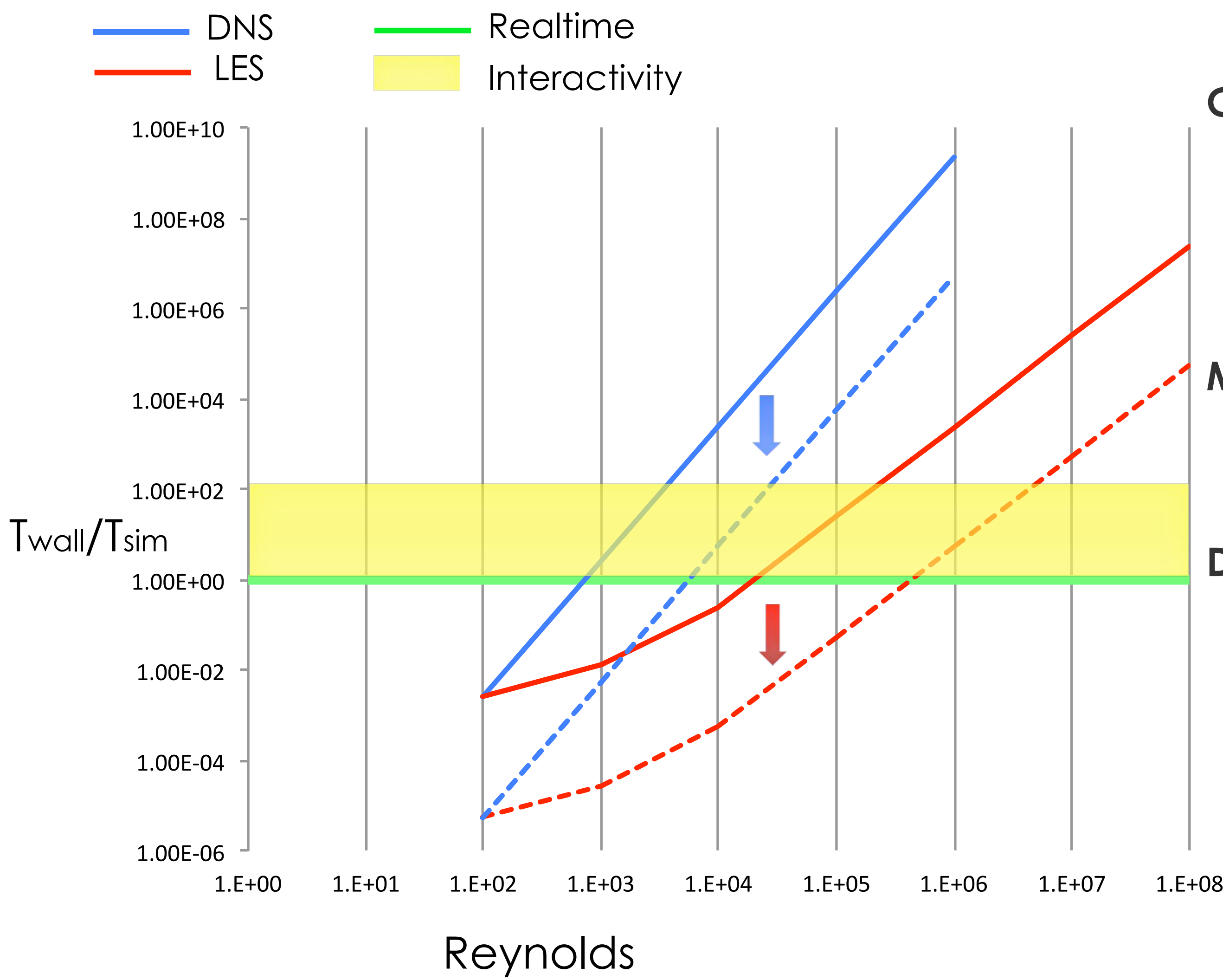
- **True realtime is > 24 frames/second**
  - so graphics output interval is 40ms
  - Visualisation, used carefully and on board is not restrictive

- **Data output must be minimal**
  - 1000 MLUPS and higher, 1GB-1TB data can be generated per second
  - e.g. from Delbosc (2015): for 128^3 LDC the following are per iteration

1.4 ms	LBM
6.8 ms	GPU to CPU
1700 ms	write data (total 24GB / second)
0.1 ms	display results using OpenGL

- **LBM structure imposes limitations**
  - high numbers of registers in LBM (e.g. in 3D 19 pops, 4 macro + other integers)
  - memory requirements also limit domain size on GPU
  - new developments: e.g. *Link-Wise Artificial Compressibility* (Asinari, Obrecht)

Current status



Capacity for LES/DNS

- solid lines based on desktop with 4 K20s
- ~ peak 3000 MLUPS

Memory limitation

- corresponding to ~15M points

Dashed lines indicate Titan

- multi GPU LBM implementation (Robertsen & Mattila 2015)
- 16384 GPUs
- ~ peak 1 800 000 MLUPS
- i.e. 2 x 10^{12} LUPS

numbers based on LDC calculations and classic scaling laws, also using results in the literature

Conclusions

- **'Realtime' CFD is on the horizon**
  - hardware in the loop, automated CFD analysis for predictive purposes
  - currently up to Re~10^4 for LES on a desktop with multiGPU
- **Use of interactive CFD is increasing**
  - range of applications for virtual environments, learning, testing & design
- **Main focus has been on LBM**
  - Many challenges remain: wall modelling, reduction of memory overhead

Acknowledgements

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