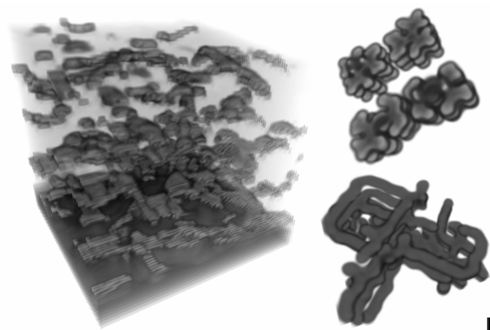
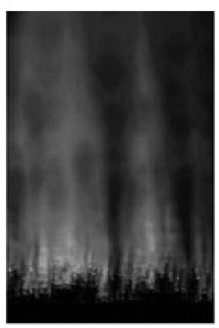
Physically-Based Simulation on Graphics Hardware





Elder Scrolls III: Morrowind

GameDevelopers Conference

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UNC Chapel Hill
Greg James
NVIDIA Corp.

Physically-Based Simulation

- Games are using it
  - Newtonian physics on the CPU
    - Rigid body dynamics, projectile and particle motion, inverse kinematics
  - PDEs and non-linear fun on the CPU/VPU
    - Water simulation (geometry), special effects
- It's cool, but computationally expensive
  - Complex non-rigid body dynamics & effects
    - Water, fire, smoke, fluid flow, glow and HDR
  - High data bandwidth
  - Lots of math. Much can be done in parallel

Physically-Based Simulation

- Graphics processors are perfect for many simulation algorithms
  - GeForce 3, 4, GeForce FX, Radeon 9xxx
  - Direct3D8, Direct3D9 support
- Free parallelism, GFlops of math, vector processors
  - 500 Mhz * 8 pix/clk * 4-floats/pixel = 16 GFlops
- Current generation has 16 and 32-bit float precision throughout

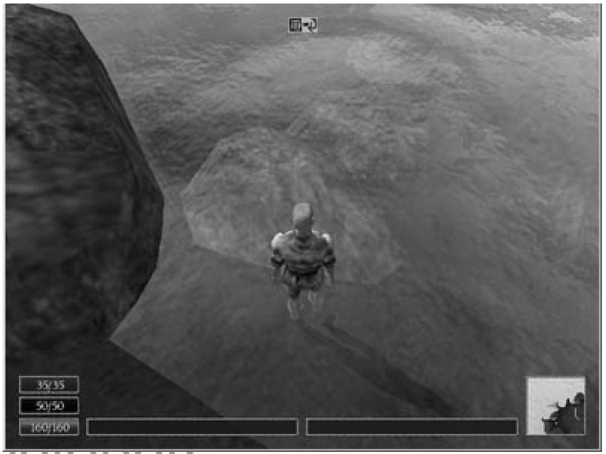
Games Doing Simulation and Effects on the GPU

(partial list)

- PC
  - Elder Scrolls III: Morrowind
  - Dark Age of Camelot
  - Tron 2.0
  - Tiger Woods 2.0
  - 3DMark2003
- XBox
  - Halo 2
  - Wreckless
- PS2
  - Baldur's Gate: Dark Alliance

Visual Simulation

- Goal is *visual* interest
  - Not numerical accuracy
  - Often not physical accuracy, just the right feel
- Approximations and home-brew methods produce great results
  - Dynamic scenes, interesting reaction to inputs
  - If the user is convinced, the method, math, and stability don't matter!!
- 8-bit math and results are ok (last year's hardware)



Elder Scrolls III: Morrowind
Bethesda Softworks

Practical Techniques

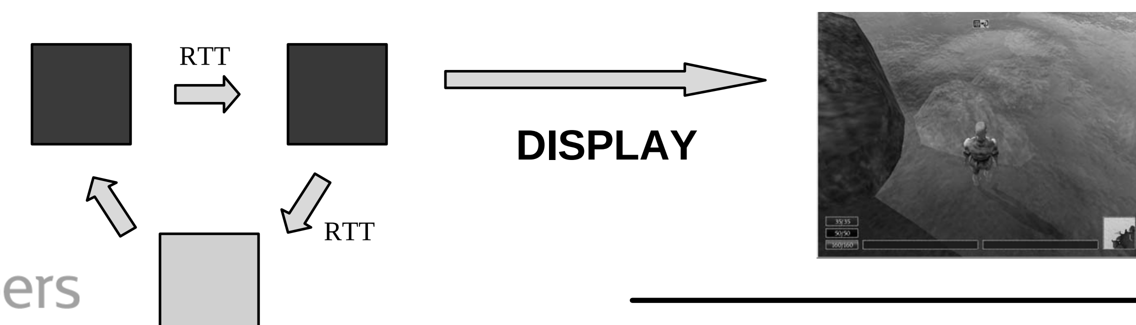
- Interesting phenomena
  - Useful in real-time scenes
- Interactive: Can react to characters, events, and the environment
- Effects themselves run at 150-500 fps
  - Doesn't kill your framerate
- Free modular source code
- Developer support
  - Just ask!

How Does It Work?

- Graphics processor renders colors
  - 8 bits per channel or 32 bits per channel
- Colors store the state of the simulation
  - Blue = 1D position, Green = velocity, Red = force
  - RGB_1 = 3D position, RGB_2 = 3D velocity
- Rendered colors are read back in and used to render new colors (the next time step)
  - Render To Texture ("RTT")
  - Redirect color to a vertex stream (coming soon to OGL)
- Iterate, storing temporaries and results in video memory textures

The Result

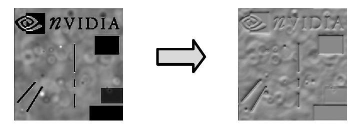
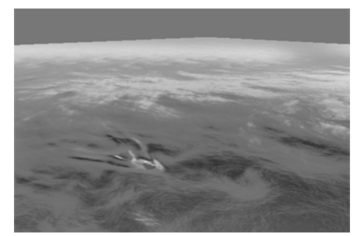
- Graphics hardware textures are used to create or animate other textures
- Animated textures can be used in the scene
  - Data & temporaries might never been seen
- Fast, endless, non-repeating or repeating
- A little video memory can go a long way!
  - Much less storage than ‘canned’ animation
  - 2 textures can make an endless animation



What Can We Do?

- Blur and glow
- Animated blur, dissolves, distortions
- Animated bump maps
  - Normal maps, EMBM du / dv maps
- Cellular Automata (CA)
  - Noise, animated patterns
  - Allows for very complex rules
- Physical Simulation
  - On N-dimensional grids
    - CA, CML, LBM



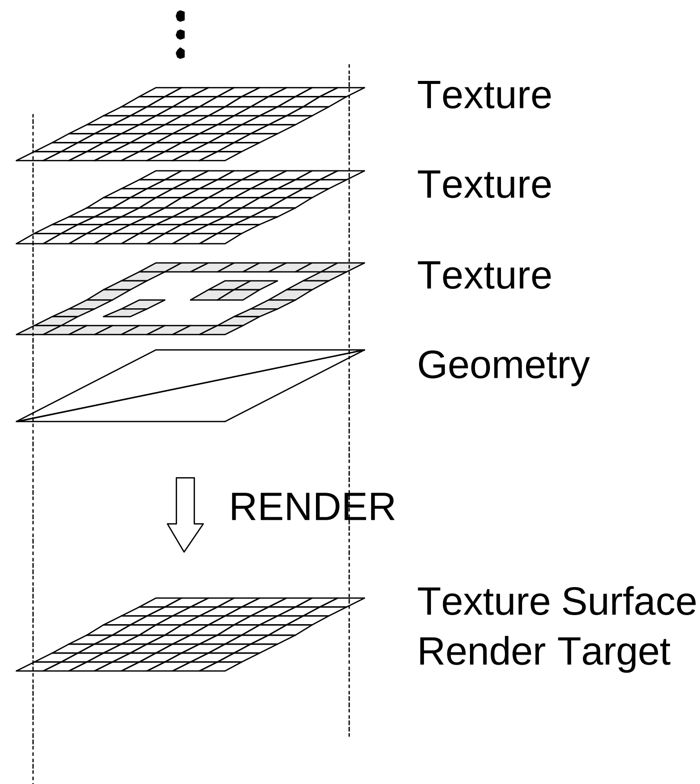




How to do it

- **Objective - Keep it ALL on the GPU!**
  - Efficient calculation
  - No CPU or GPU pipeline stalls for synchronization
  - No AGP texture transfer between CPU and GPU
  - Saves a ton of CPU MHz
- **Geometry drives the processing**
- **Programmable Pixel Shaders do the math**
  - Each <u>Texture Coordinate</u> reads data from specific location
    - Location is absolute or relative to pixel being rendered
  - N texture fetches gives N RGBA data inputs
    - Sample neighboring texels, or any texels
    - Compute slopes, derivatives, gradients, divergence

Geometry Drives Processing

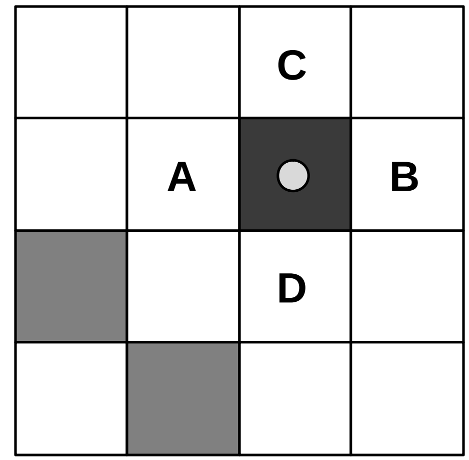
- **Textures store input, temporary, and final results**
- **Geometry's texture coordinates get interpolated**
- **Fetch texture data at interpolated coords**
- **Do calculations on the texture data in the programmable pixel shader**

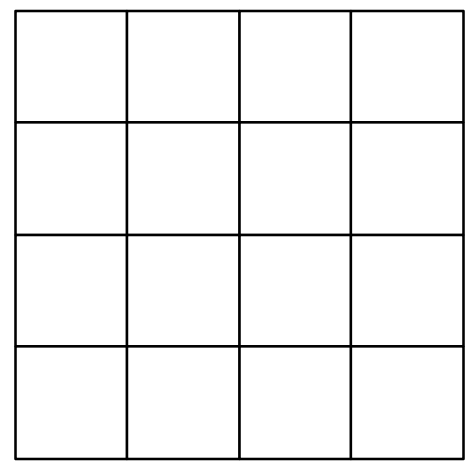


Example 1: Sample and Combine Each Texel's Neighbors

- Source texture 'src' is (x,y) texels in size
  - SetTexture(0, src);
  - SetTexture(1, src);
  - SetTexture(2, src);
  - SetTexture(3, src);
- texel width 'tw' = 1/x
- texel height 'th' = 1/y

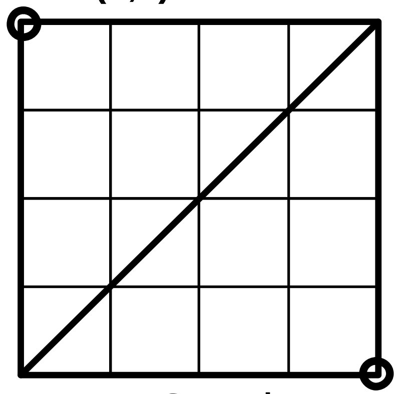
- Render target is also a texture (x,y) pixels in size
  - SetRenderTarget(dest_tex);





Example 1 Contd.

- **Render a quad exactly covering the render target**
  - Texture coords from (0,0) to (1,1)
  - Unmodified, these would copy the source exactly into the dest



- **Vertex Shader reads input coordinate 'tc0'**
- **Writes 4 output coordinates**
  - Each coordinate offset by a different vector: VA, VB, VC, VD

    VA = (-tw, 0, 0, 0)

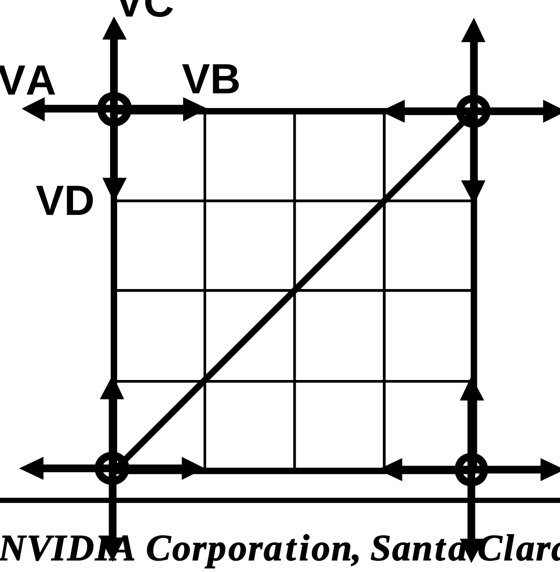
    VD = (0, th, 0, 0)

    out_T0 = tc0 + VA

    out_T1 = tc0 + VB

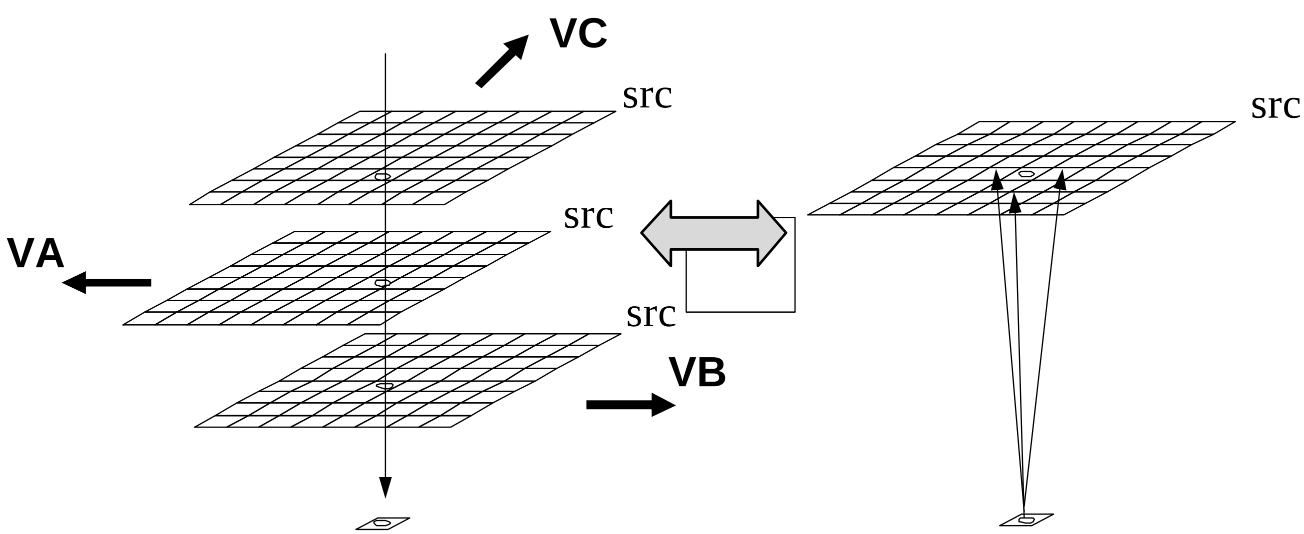
    out_T2 = tc0 + VC

    out_T3 = tc0 + VD



Example 1 Contd.

- **The offset coordinates translate the source textures, so that a pattern of neighbors is sampled for each pixel rendered**

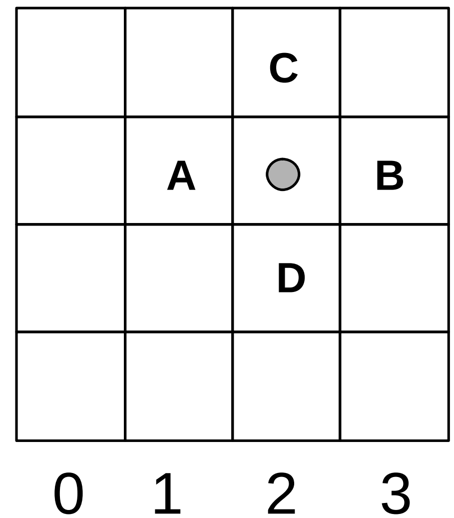


Sampling From Neighbors

- When destination pixel, is rendered

If VA, VB, VC, VD are (0,0) then:
  - t0 = pixel at (2,1)
  - t1 = pixel at (2,1)
  - t2 = pixel at (2,1)
  - t3 = pixel at (2,1)

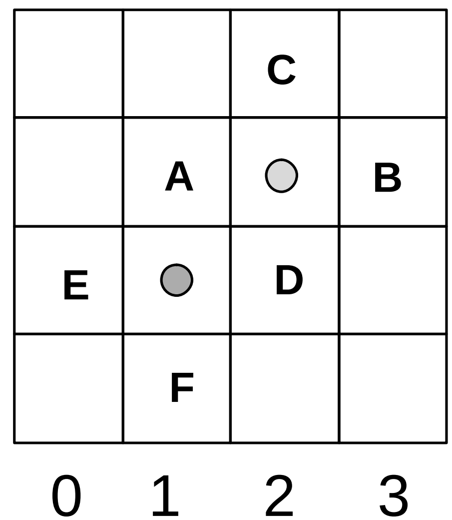
If VA=(-tw,0), VB=(tw,0), VC=(0,-th) VD=(0,th) then:
  - t0 = pixel A at (1,1)
  - t1 = pixel B at (3,1)
  - t2 = pixel C at (2,0)
  - t3 = pixel D at (2,2)



Sampling From Neighbors

- Same pattern is sampled for each pixel rendered to the destination

- When pixel ○ is rendered, it samples from:
  - t0 = pixel E
  - t1 = pixel D
  - t2 = pixel A
  - t3 = pixel F



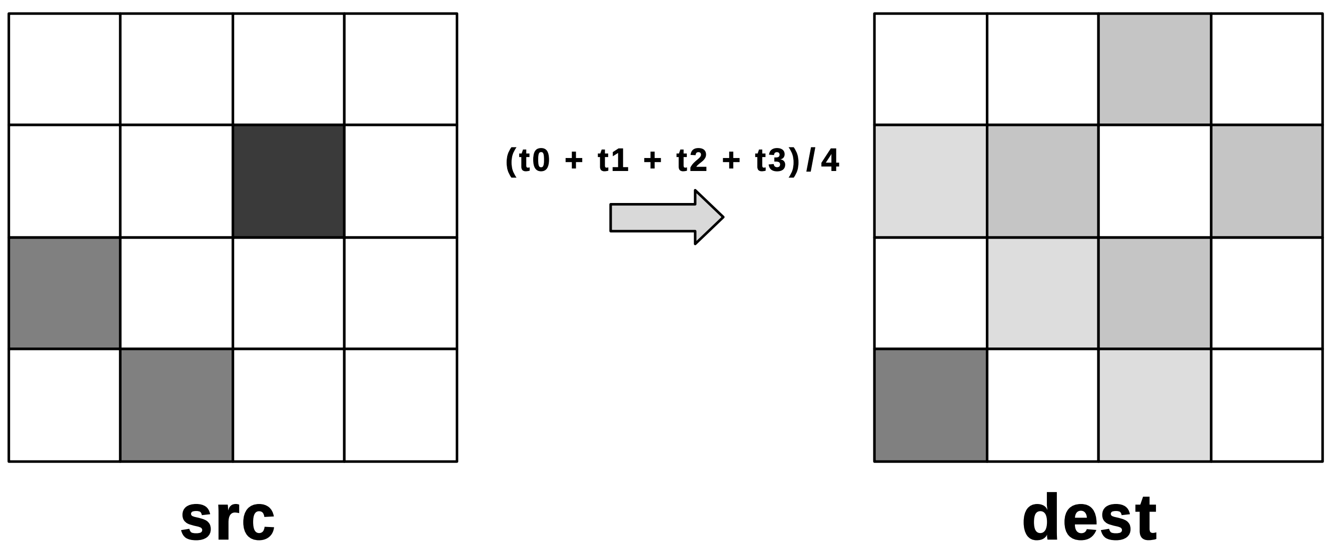
Example 2: Samples Processed in Pixel Shader

- **Do whatever math you like**

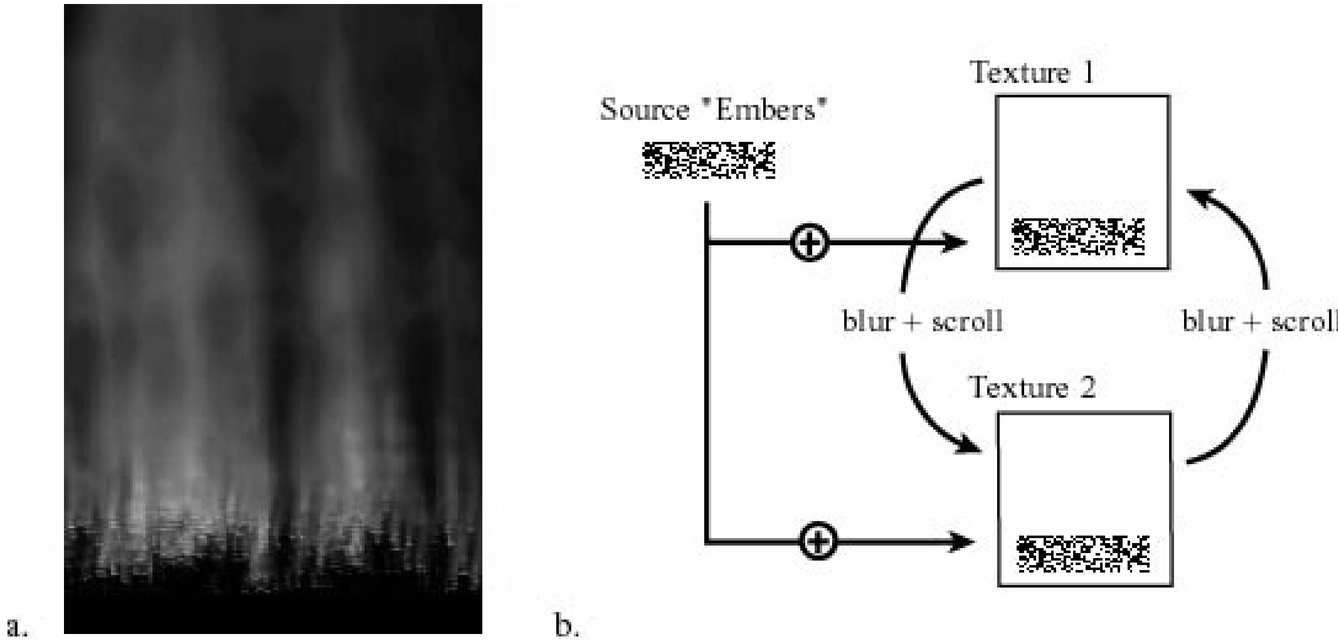
  out color = (t0 + t1 + t2 + t3) / 4

  out color = (t0-t1) CROSS (t2-t3)

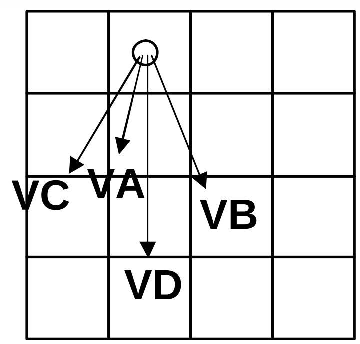
  etc...



Simple Fire Effect



- Blur and scroll upward
- Trails of blur emerge from bright source 'embers' at the bottom

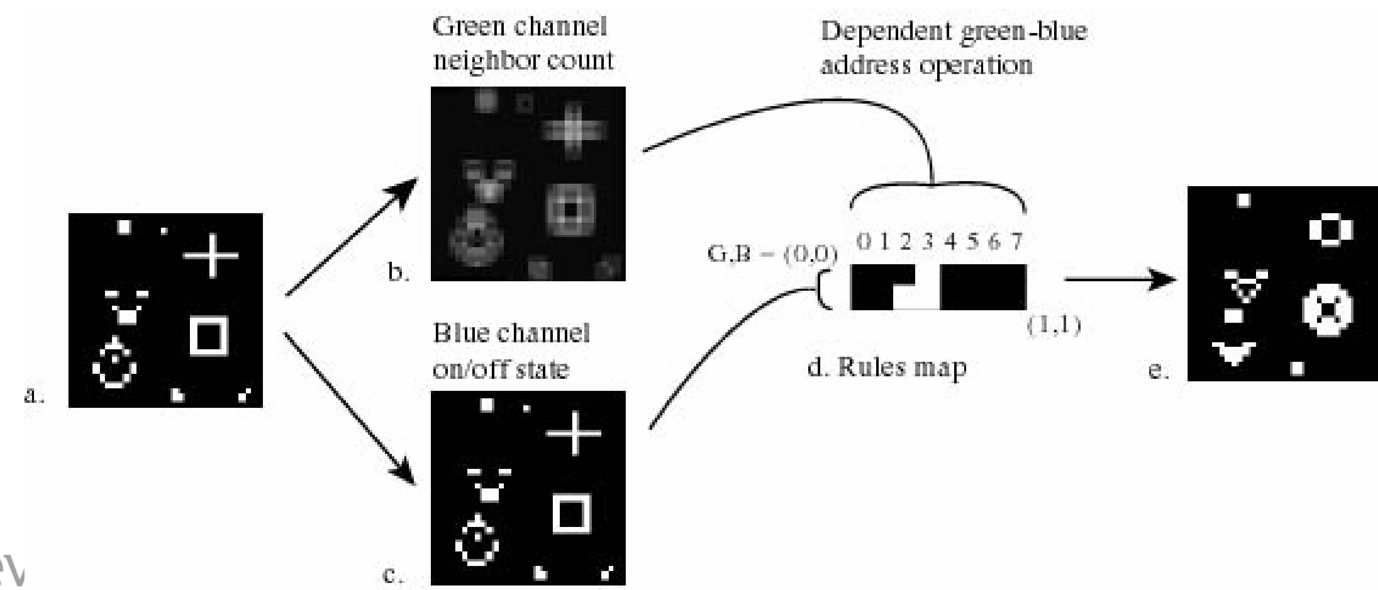


Fire Effect

- Jitter texture sampling
  - Vary VA..VD offsets for a wind effect
  - Turbulence: Tessellate underlying geometry and jitter texture coords or positions
- Change color averaging multiplier
  - Brighten or extinguish the smoke
  - Change its color as it rises
- How to improve:
  - Better jitter patterns (not random jumps)
  - Re-map colors
    - Dependent texture read
  - Use a real physics model!
    - Mark will elaborate

Cellular Automata

- **Great for generating noise and other animated patterns to use in blending**
- **Game of Life in a Pixel Shader**
  - **Cell 'state' relative to the rules is computed at each texel**
  - **Dependent texture read**
  - **State accesses 'rules' table, which is a texture**
- **Highly complex rules are easy!**



Water Simulation

- Used in Morrowind, Tiger Woods, Dark Age of Camelot, ...
- Real physics
- 3 main parts, all done on the GPU
  - Animate water height
  - Convert height to surface normal map to render shading and reflections
  - Couple two simulations together
    - One for local unique detail
    - One for tiled endless water surface

Water Simulation Details

- Physics in glorious 8-bit precision
  - 8 bits is enough, barely!
- Each texel is one point on water surface
- Each texel holds
  - Water height, H
  - Velocity, V
  - Force, F - computed from height of neighbors
- Damped + Driven system
  - Not “stability”, but consistent behavior over time
  - Easier and faster than true conservation methods

Water Simulation Details

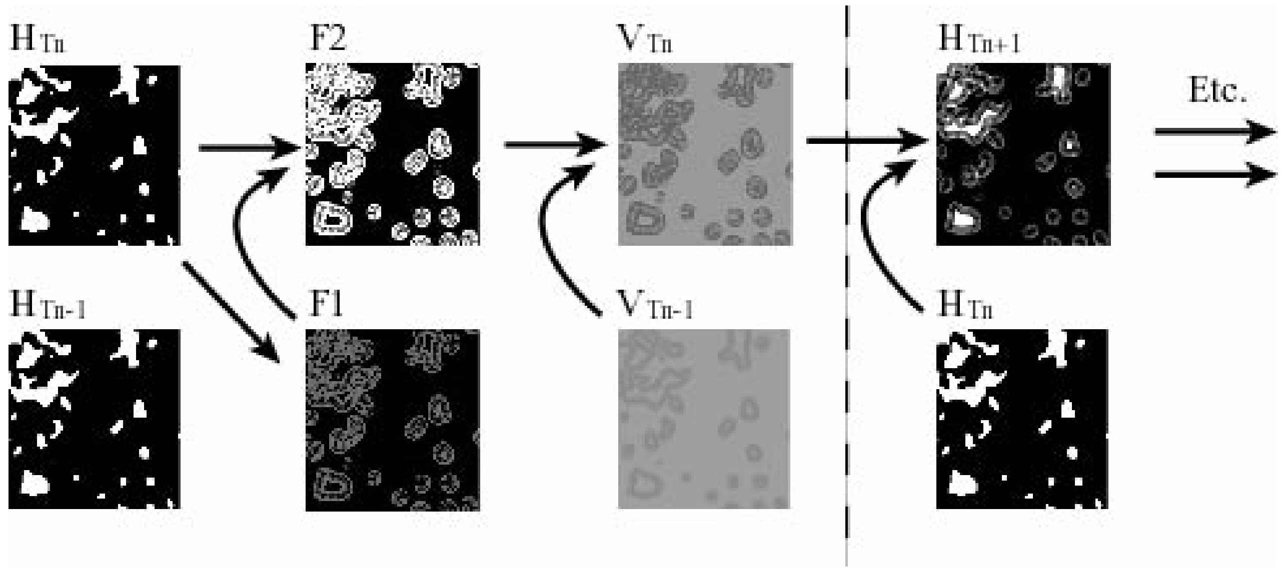
- Discretizing a 2D wave equation to a uniform grid gives equations which sample neighbors
  - Physics on a grid of points uses neighbor sampling
- Derivatives (slopes) in partial differential equations (PDEs) turn into neighbor sampling on a grid
- See [Lengyel] or [Gomez] for great derivations
- Textures + Neighbor Sampling are all we need
- Math is flexible – Use Intuition!
  - And a spring-mass system
  - The math is nearly identical to PDE derivation

Water Simulation Details

- **Height texels are connected to neighbors with springs**
- **Force acting on H0 from spring connecting H0 to H1**
  - $F = k * (H1 - H0)$
  - **k is spring strength constant**
  - **Always pulls H0 toward H1**
  - **H0, H1 are 8-bit color values**
- $F = k * (H1 + H2 + H3 + H4 - 4*H0)$
- $V' = V + c1 * F$
- $H0' = H0 + c2 * V'$
  - **c1, c2 are constants (mass,time)**

		H1	
	H4	H0	H2
		H3	

Water Simulation Details

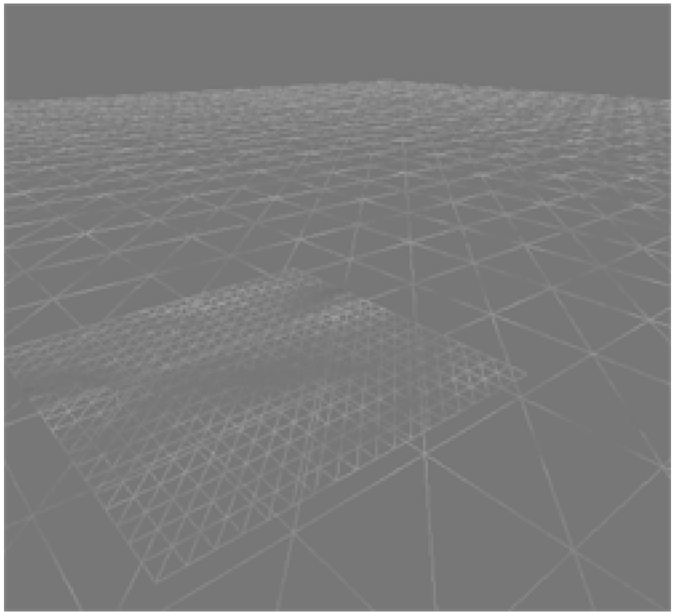


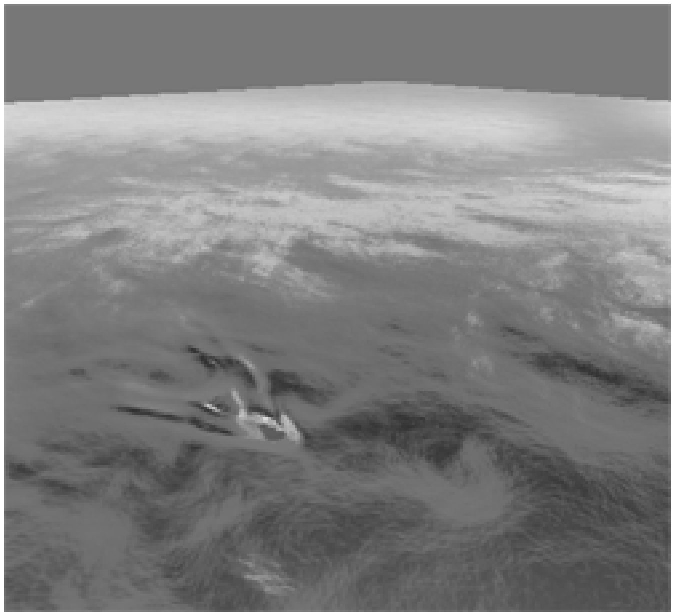
- Height current (HTn), previous (HTn-1)
- Force partial (F1), force total (F2)
- Velocity current (VTn), previous (VTn-1)
- Use 1 color channel for each

  F = red; V = green; H = blue and alpha

Water Simulation

- Local detail simulation coupled to tiled texture simulation
- 2 simulations using 256x256 textures





The Tricky Parts

- Procedural animation
  - Have to find the right rules
  - Stability
    - You can use cheesy hacks
    - Consistent behavior over time is all that matters
  - Learning curve for artistic control
    - But you can expose intuitive controls
- Precision
- Texture sample placement

Rules & Stability

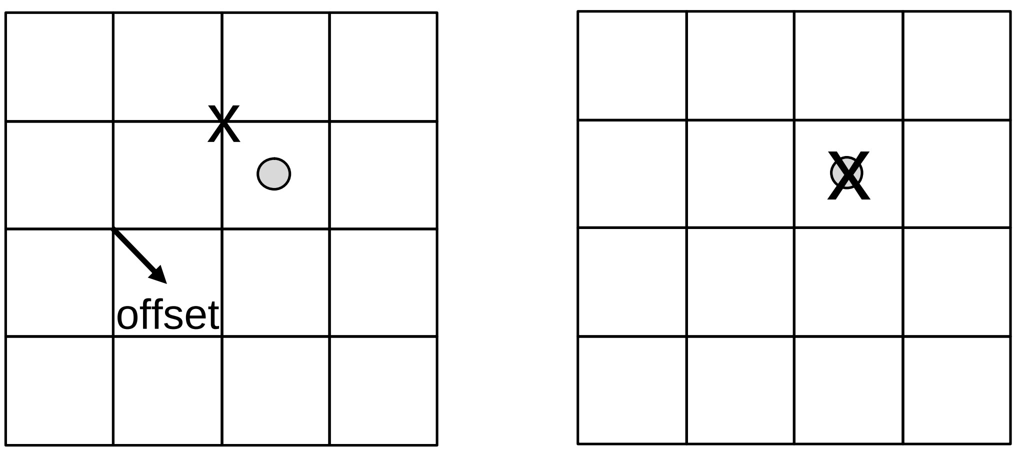
- The right rules
  - Lots of physical simulation literature
  - Good to adapt and simplify
  - Free public source code
- Stability
  - Tough using 8-bit values (2002 HW)
  - Damped + Driven system
    - Damped: looses energy, comes to rest
    - Driven: add just enough excitations to stay interesting
    - Not stable, but it looks and acts like it is!

Precision

- **A8R8G8B8 is good for many things**
- **Direct3D9 HW supports higher precision**
  - **32 bits per channel, floating point render targets**
- **High precision can be emulated using 2 or more 8-bit channels [Strzodka] [Rumpf]**
  - **Other ways for variable precision and fast ADD and SUB**
- **Can emulate 12, 15, 18, 21, 24, 27, 32 bits per component**
- **Encode, decode, add, subtract, multiply, arbitrary functions (from textures)**
- **NVIDIA volume fog demo**

Sample Placement

- **Subtle issue. Easy to deal with**
- **D3D and OpenGL sample differently**
  - **D3D samples from texel <u>corner</u>**
  - **OpenGL samples from texel <u>center</u>**
- **Can cause problems with bilinear sampling**
- **Solution: Add half-texel sized offset with D3D**



O = pixel rendered
tex coord = (2,1)
X = tex sample taken
from here

D3D   OpenGL

Let's Get Serious

- I've introduced the basics and some fast-and-loose approaches
- Mark will now present more rigorous solutions and sophisticated methods
- GPUs are ripe for complex, interesting physical simulation!

Lattice Computations

- Greg's been talking about them
- How far can we take them?
  - Anything we can describe with discrete PDE equations!
    - Discrete in space and time
  - Also other approximations

Approximate Methods

- Several different approximations
  - Cellular Automata (CA)
  - Coupled Map Lattice (CML)
  - Lattice-Boltzmann Methods (LBM)
- Greg talked about CA
  - I'll talk about CML

Coupled Map Lattice

- **Mapping:**
  - Continuous state → lattice nodes
- **Coupling:**
  - Nodes interact with each other to produce new state according to specified rules

Coupled Map Lattice

- CML introduced by Kaneko (1980s)
  - Used CML to study spatio-temporal chaos
  - Others adapted CML to physical simulation:
    - Boiling [Yanagita 1992]
    - Convection [Yanagita 1993]
    - Clouds [Yanagita 1997; Miyazaki 2001]
    - Chemical reaction-diffusion [Kapral '93]
    - Saltation (sand ripples / dunes) [Nishimori '93]
    - And more

CML vs. CA

- **CML extends cellular automata (CA)**

	CA	CML
SPACE	Discrete	Discrete
TIME	Discrete	Discrete
STATE	Discrete	Continuous

CML vs. CA

- Continuous state is more useful
  - Discrete: physical quantities difficult
    - Must filter over many nodes to get “real” values
  - Continuous: physical quantities easy
    - Real physical values at each node
    - Temperature, velocity, concentration, etc.

Rules?

- CML updated via simple, local rules
  - Simple: same rule applied at every cell (SIMD)
  - Local: cells updated according to some function of their neighbors' state

Example: Buoyancy

- Used in temperature-based boiling simulation
- At each cell:
  - If neighbors to left and right of cell are warmer, raise the cell's temperature
  - If neighbors are cooler, lower its temperature

CML Operations

- Implement operations as building blocks for use in multiple simulations
  - Diffusion
  - Buoyancy (2 types)
  - Latent Heat
  - Advection
  - Viscosity / Pressure
  - Gray-Scott Chemical Reaction
  - Boundary Conditions
  - User interaction (drawing)
  - Transfer function (color gradient)

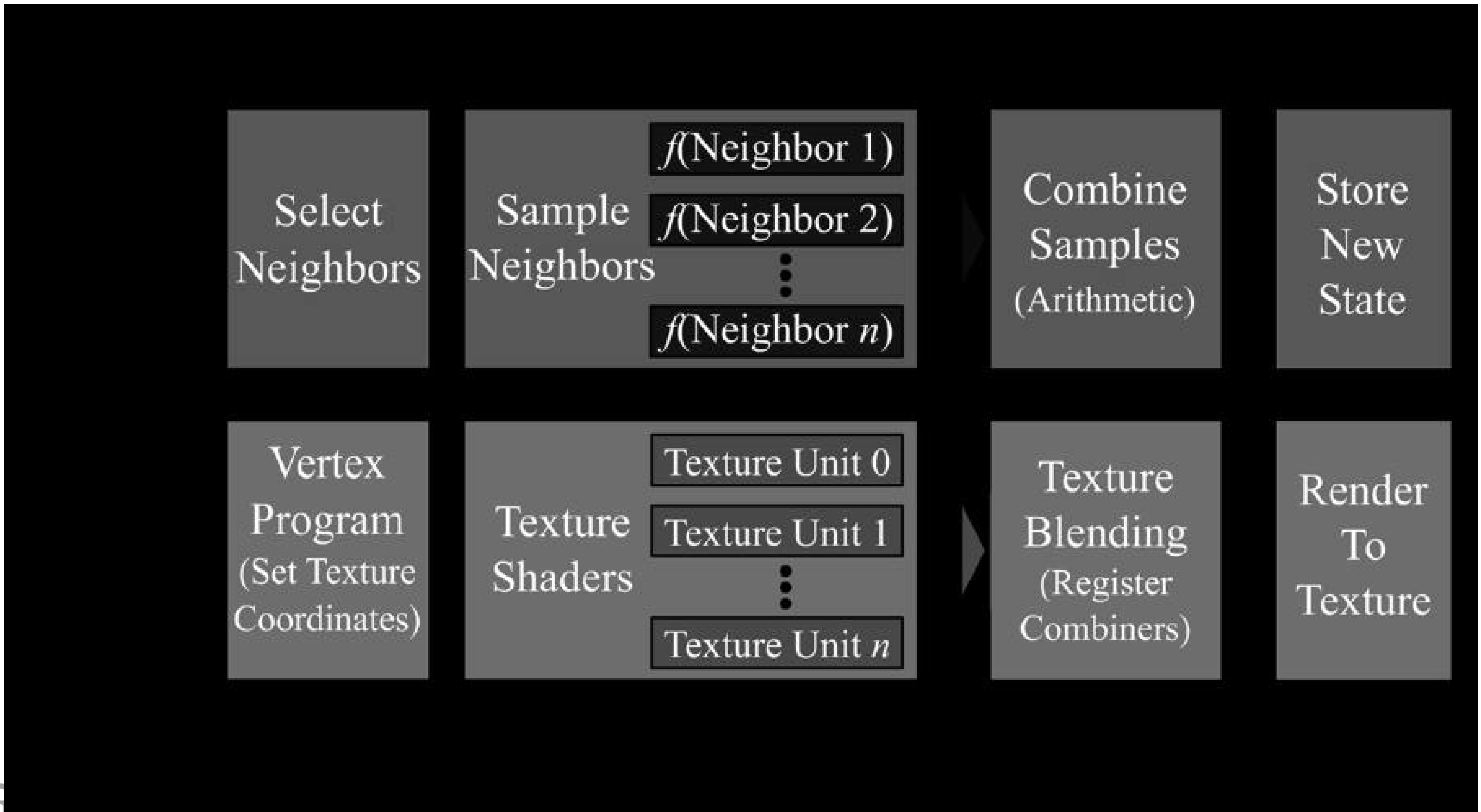
Anatomy of a CML operation

- **Neighbor Sampling**
  - Select and read values, v, of nearby cells
- **Computation on Neighbors**
  - Compute $f(v)$ for each sample (f can be arbitrary computation)
- **Combine new values (arithmetic)**
- **Store new values back in lattice**

Graphics Hardware

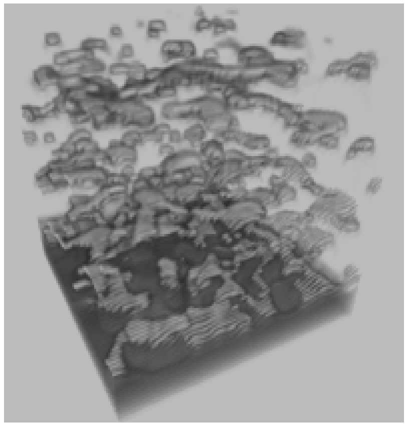
- **Why use it?**
  - Speed: up to 25x speedup in our sims
  - GPU perf. grows faster than CPU perf.
  - Cheap: GeForce 4 Ti 4200 < $130
  - Load balancing in complex applications
- **Why not use it?**
  - Low precision computation (not anymore!)
  - Difficult to program (not anymore!)

Hardware Implementation (GF4)

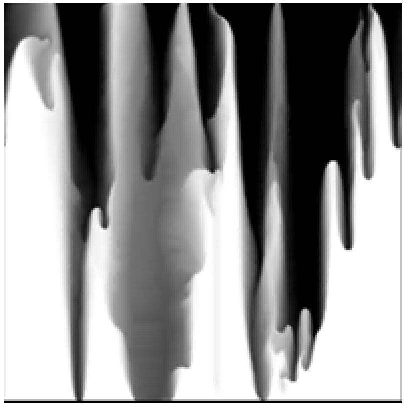


Example Simulations

- Implemented multiple simulations on GeForce 4 Ti.
- Examples:
  - Boiling (2D and 3D)

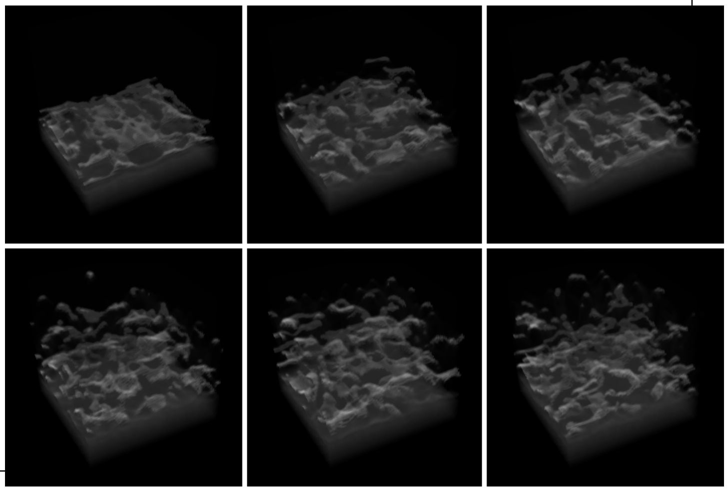


  - Rayleigh-Bénard Convection (2D)



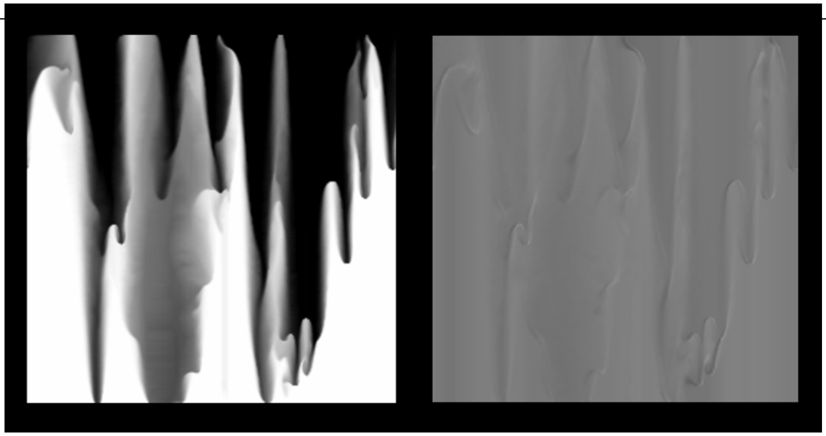
Boiling

- [Yanagita 1992]
- State = Temperature
- Three operations:
  - Diffusion, buoyancy, latent heat
  - 7 passes in 2D, 9 per 3D slice



Rayleigh-Bénard Convection

- [Yanagita & Kaneko 1993]
- State = temp. (scalar) + velocity (vector)
- Three operations (10 passes):
  - Diffusion, advection, and viscosity / pressure

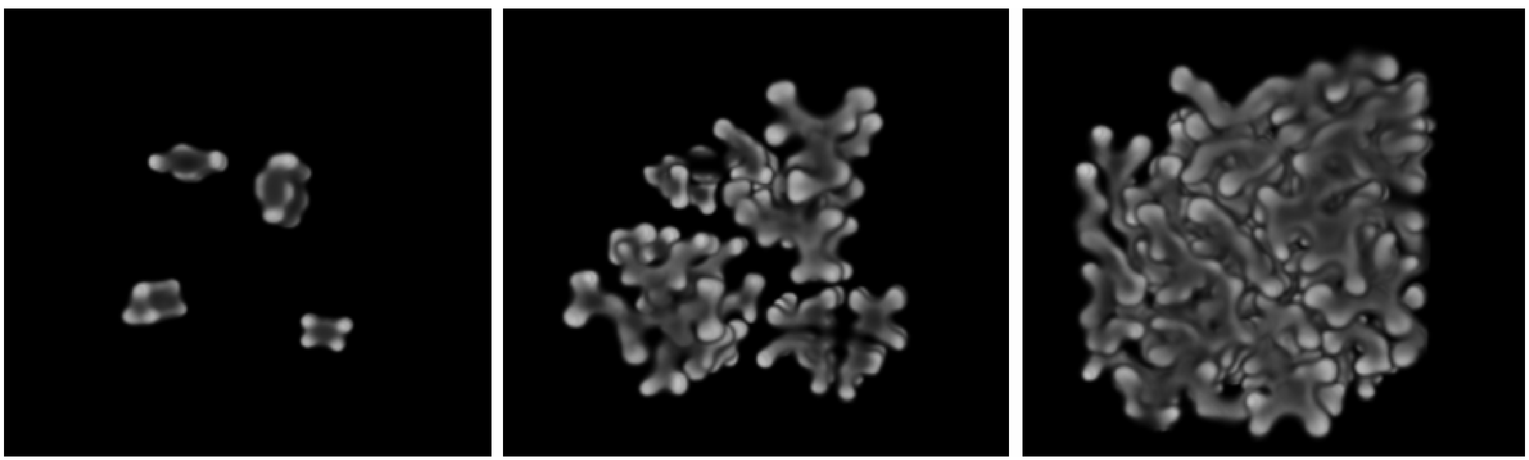


PDE Simulations

- Floating-point GPUs open up new possibilities
  - Less Ad Hoc methods: *real* PDEs
  - Must be able to discretize in space in time
- I'll discuss two examples:
  - Reaction Diffusion
  - Stable Fluids

Reaction-Diffusion

- Gray-Scott reaction-diffusion model [Pearson 1993]
- State = two scalar chemical concentrations
- Simple: just diffusion and reaction ops
- 2 passes in 2D, 3 per 3D slice



Gray-Scott PDEs

$$\frac{\partial U}{\partial t} = D_u \nabla^2 U - UV^2 + F(1-U),$$

$$\frac{\partial V}{\partial t} = D_v \nabla^2 V + UV^2 - (F+k)V$$

Diffusion **Reaction**

Stable Fluids

- Solution of Navier-Stokes fluid flow eqs.
  - Stable for large time steps
    - Means you can run it fast!
  - [Stam 1999], [Fedkiw et al 2001]
- Can be implemented on latest GPUs

Navier-Stokes Equations

- **Describe fluid flow over time**

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \cdot \nabla)\mathbf{u} - \frac{1}{r}\nabla p - n\nabla^2\mathbf{u} + \mathbf{f}$$

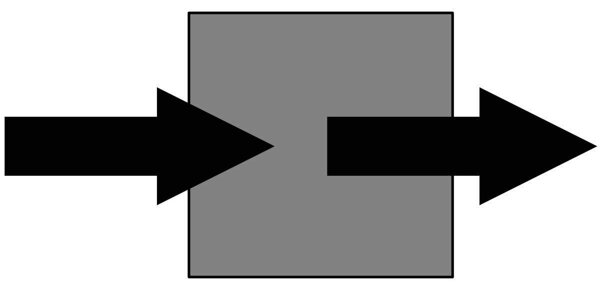
Advection — Pressure Gradient — Diffusion (viscosity) — External Force

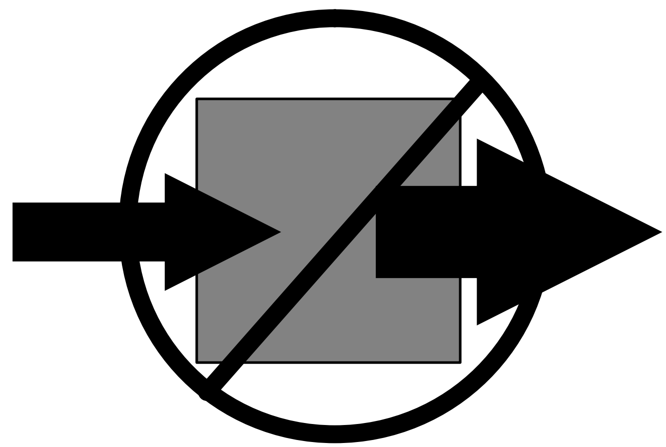
$$\nabla \cdot \mathbf{u} = 0$$

← Velocity is divergence-free

Divergence-Free?

- In any element of fluid, the velocity *into* the element must be balanced by velocity *out* of the element
  - No sources or sinks
- Ensures mass conservation





Stable Fluids Implementation

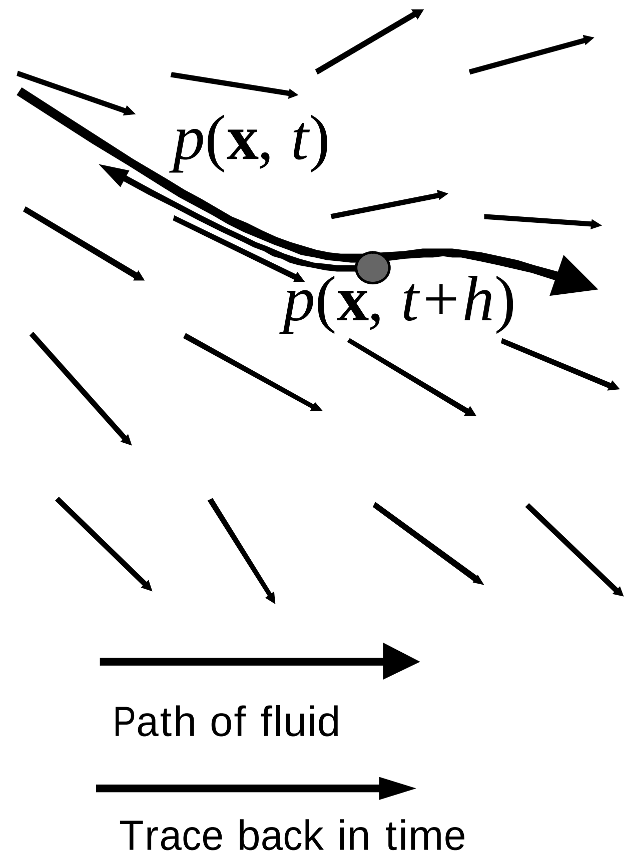
4 Basic Steps:

1. Add force to velocity field
   - Gravity, user interaction forces, etc.
     - Simple fragment program – scale force by dt, add to velocity.
2. Advect
   - Velocity and other quantities get carried along by velocity field
3. Diffuse
   - Viscous fluids only
   - Implementation very similar to step 4
4. Remove divergence

Advection

- **At each time step. Fluid "particles" moved by fluid velocity**
- **Want velocity at position $\mathbf{x}$ at new time $t + h$**
- **Follow velocity field *back* in time from $\mathbf{x}$**
  - **Like tracing particles!**
  - **Easy to implement in a fragment program:**

$$\mathbf{u}(\mathbf{x}, t+h) = \mathbf{u}(\mathbf{x} - h\mathbf{u}(\mathbf{x}, t), t)$$



Simplify the Divergence Problem

- Stam uses the ***Helmholtz-Hodge decomposition:***
  - Any vector field $\mathbf{w}$ can be decomposed into this form:

$$\mathbf{w} = \mathbf{u} + \nabla p$$

    - Where $\mathbf{u}$ has zero divergence, and p is a scalar field
- If we dot both sides of above with ∇ , we get

$$\nabla \cdot \mathbf{w} = \nabla^2 p \qquad \text{(Since } \nabla \cdot \mathbf{u} = 0 \text{)}$$

- Solve for p, then $\mathbf{u}$ is just $\mathbf{u} = \mathbf{w} - \nabla p$

Poisson-Pressure Solution

- It turns out that $\nabla^2 p = \nabla \cdot \mathbf{w}$ is a ***Poisson Eq.***
  - p **is the pressure of the fluid**
  - $\mathbf{w}$ **is the velocity after steps 1-3 (divergence [1] 0)**
- **So, just solve this *Poisson-Pressure* eq. for p, and subtract ∇p from the velocity after step 3 to get divergence free velocity**
- **The viscosity term is similar – also a Poisson equation – so we can use the same solution technique**

How do I solve it?

- **Discretize the equation, solve using an iterative matrix solver (relaxation)**
  - **Jacobi, Gauss-Seidel, SOR, Conjugate Gradient, etc.**
    - **On the GPU, Jacobi is easy, the rest are tricky**
    - **I use Jacobi iteration (several iterations usually enough)**
  - **Since the matrix is sparse, it boils down to repeated evaluation of:**

$$q_{i,j}^{n+1} = \frac{1}{4}\Big(q_{i+1,j}^{n} + q_{i-1,j}^{n} + q_{i,j+1}^{n} + q_{i,j-1}^{n} - d^2(\nabla \cdot \mathbf{w})\Big),$$

$$\nabla \cdot \mathbf{w} = \frac{1}{2d}(u_{i+1,j} - u_{i-1,j} + v_{i,j+1} - v_{i,j-1})$$

δ	**=** grid spacing
u, v	= components of $\mathbf{w}$
i, j	= grid coordinates
n	= solution iteration

Stable Fluids

- See Jos Stam's talk here at GDC for details.
  – His papers are also very clear.

- GPU fluids demo (source code available)

Hardware Limitations

- Precision, precision, precision!
  - 8 or 9 bits is far from enough
    - You have to be tricky on GeForce 4, Radeon 8500, etc.
    - Solved on GeForce FX, Radeon 9700
  - Diffusion is very susceptible to precision problems
    - Many natural phenomena are diffusive!
  - High dynamic range simulations very susceptible
    - Convection, reaction-diffusion, fluids
    - Not boiling – relatively small range of values

Future Work

- Explore simulation techniques / issues on graphics hardware
  - Other PDE solution techniques
  - More complex simulations
  - High dynamic range simulations
  - Easy to use framework for lattice simulations
- Applications:
  - Interactive environments, games
  - Scientific Computation
  - Dynamic painting / modeling applications
  - Dynamic procedural texture synthesis
  - Dynamic procedural *model* synthesis
  - ...

General Purpose GPUs

- A growing trend: GPGPU
  - In both academia and industry
- GPUs are capable parallel processors
  - Useful for more than just graphics!
- A catalog of recent GPGPU research:
  - http://www.cs.unc.edu/~harrism/gpgpu
  - A large variety of applications:
    - Physical simulation, solving sparse linear systems, image processing, computer vision, neural networks, scene reconstruction, computational geometry, large matrix-matrix multiplication, voronoi diagrams, motion planning, collision detection…

Conclusion

GPUs are a capable, efficient, and flexible platform for physically-based visual simulation

Go add cool dynamic phenomena to your games!

UNC Acknowledgements

- NVIDIA Developer Relations
- Sponsors:
  - NVIDIA Corporation
  - US National Institutes of Health
  - US Office of Naval Research
  - US Department of Energy ASCI program
  - US National Science Foundation

For More Information

- http://www.cs.unc.edu/~harrism/cml
- http://www.cs.unc.edu/~harrism/gpgpu
- http://developer.nvidia.com
- Email harrism@cs.unc.edu
- Email gjames@nvidia.com

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