Implementing Wave Particles for Real-time Water Waves with Object Interaction

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Outline

- Introduction to Wave Particles
- Wave Particle Iteration
- Rendering the Height Field
- Wave Generation
- Forces on Objects
- The Overall System
Wave Particles

- Fluid surface
Wave Particles

- Wave particle
Wave Particles

- Bump
Wave Particles

- Dent
Wave Particles

- Wavefront
Wave Particles

- Wave particles
Wave Particles

- Bumps
Wave Particles

- Wavefront
Wave Particles

- Expanding wavefront
Wave Particles

- Subdivision
Wave Particles

- Subdivision
Wave Particles

- Subdivision
**Boundaries**

- **Boundary collision**
  - Waves reflect
  - Wave particles bounce back

- **No boundaries**
  - Infinite ocean!
  - Wave particles continue on
Wave Particles

- Wave particles
  - Collectively represent wavefronts
  - DO NOT interact
  - Move independently
  - Reflect independently
  - Subdivide independently
    - into smaller wave particles
    - Die when too small
Water Waves

transverse waves

longitudinal waves

water waves
Wave Particles

- Vertical deviation
  - cosine based
Wave Particles

- Horizontal deviation
  - sine based
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Wave Particle Iteration

- Wave Particle Properties
  - 2D position
  - 2D direction (not velocity)
  - Amplitude
  - Dispersion angle
  - Age
Wave Particle Iteration

- **Iteration**
  - Wave Particle Properties
    - 2D position
    - 2D direction
    - Amplitude
    - Dispersion angle
    - Age

- **Reflection**

- **Subdivision**

**Iteration**: numerical integration on CPU / GPU / **Neither!**
Wave Particle Iteration

Neither?

position $x_0$ @ time $t_0$
direction $u$

constant wave speed $v$

$\mathbf{x}_1 = \mathbf{x}_0 + u (t_1 - t_0) v$

position $\mathbf{x}_1$ @ time $t_1$
Wave Particle Iteration

- Wave Particle Properties
  - 2D position
  - 2D birth position
  - 2D direction
  - Amplitude
  - Dispersion angle
  - Age  Birth time

- Iteration
- Reflection
- Subdivision
Wave Particle Iteration

- Reflection

boundary

birth position

new birth position
Wave Particle Iteration

- Subdivision

birth position

dispersion angle
Wave Particle Iteration

- Time table of events

<table>
<thead>
<tr>
<th>subdivision</th>
<th>wave particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>t1</td>
<td>particle1</td>
</tr>
<tr>
<td>t2</td>
<td>particle2</td>
</tr>
<tr>
<td>t3</td>
<td>particle3</td>
</tr>
<tr>
<td>t4</td>
<td></td>
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<tr>
<td>t5</td>
<td></td>
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<tr>
<td>t6</td>
<td></td>
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<tr>
<td>t7</td>
<td></td>
</tr>
<tr>
<td>t8</td>
<td>particle6</td>
</tr>
<tr>
<td>t9</td>
<td>particle8</td>
</tr>
<tr>
<td>...</td>
<td>particle9</td>
</tr>
</tbody>
</table>

x marks an event at that time.
## Wave Particle Iteration

- **Time table of events**

|   | t1 | t2 | t3 | t4 | t5 | t6 | t7 | t8 | t9 | ...
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

- **Reflection**
  - t3: particle4
  - t7: particle5
  - t8: particle7

- **Wave particles**
Wave Particle Iteration

- Time table of events

<table>
<thead>
<tr>
<th>subdivision</th>
<th>wave particles</th>
<th>reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>t1</td>
<td>particle1</td>
<td>t1</td>
</tr>
<tr>
<td>t2</td>
<td>particle2</td>
<td>t2</td>
</tr>
<tr>
<td>t3</td>
<td>particle3</td>
<td>t3</td>
</tr>
<tr>
<td>t4</td>
<td>particle4</td>
<td>t4</td>
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<tr>
<td>t5</td>
<td>particle5</td>
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<tr>
<td>t6</td>
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<tr>
<td>t7</td>
<td>particle7</td>
<td>t7</td>
</tr>
<tr>
<td>t8</td>
<td>particle8</td>
<td>t8</td>
</tr>
<tr>
<td>t9</td>
<td>particle9</td>
<td>t9</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Wave Particle Iteration

- When creating
  - Find subdivision time
  - Find reflection time
  - If (reflection time < subdivision time)
    - Place in reflection list at the reflection time
  - Else
    - Place in subdivision list at the subdivision time

- After subdivision or reflection
  - Place in the next list
Wave Particle Iteration

- Killing wave particles
  - Right before subdivision
  - Check amplitude
    - If below threshold, KILL
    - Otherwise, subdivide

- Damping
  - Optional
  - Keep birth amplitude
  - \[ \text{amplitude} = \text{amplitude}_{\text{birth}} \exp(\text{damping}(\text{time} - \text{time}_{\text{birth}})) \]
Wave Particle Iteration

- **Summary**
  - No numerical integration
  - Event handling only
    - Visits for subdivision or reflection
  - On CPU
  - Can be on a separate thread
  - Use pre-allocated arrays

**Note:** Early subdivision is OK
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Rendering the Height Field

- Render to height field texture

Wave Particles → Height Field
Height Field

- Surface attached to camera
Rendering the Height Field

- Point rendering method
  - Approximate
  - FAST
Rendering the Height Field

- Draw wave particles as points
Rendering the Height Field

- Antialiased points
  (Hardware antialiasing can be SLOW!)
Rendering the Height Field

- X-Filter
Rendering the Height Field

- Y-Filter
Rendering the Height Field

- Horizontal deviation
  - Render points
  - Write direction x amplitude
  - X-Filter
    - Compute x-deviation from x-direction
    - Filter y-direction
  - Y-Filter
    - Compute y-deviation from y-direction
    - Filter x-deviation
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Wave Generation

- Each time step
  - Compute object motion
  - Generate waves
Wave Generation

- For each face
  - Find the velocity of the face
  - Find the area inside the fluid
  - Find the volume of fluid moved by the face (*wave effect*)
    - Pushed
    - Pulled

face velocity
Wave Generation
Wave Generation

- Steps
  1. Render low-resolution silhouette (in water)
Wave Generation

Steps

2. Render object faces as points
   - Write wave effect (direct/indirect)
Wave Generation

Steps

3. Find silhouette boundaries
Wave Generation

Steps

4. Distribute indirect wave effects to silhouette boundaries
Steps

5. Generate waves
   (a) direct waves
   (b) indirect waves
Wave Generation

- How to distribute wave effects
- How to find wave direction
- How to find dispersion angle
Wave Generation

- Silhouette Pyramid
Outline

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Forces on Objects

- Static forces
  - Buoyant force

- Dynamic forces
  - Drag force
  - Lift force
Forces on Objects

- Buoyant force

Procedure:
- Render object from top view with additive blending
- For each fragment
  - Write + depth if backface
  - Write − depth if frontface
Forces on Objects

- Drag and lift forces on each face
  - Can be on GPU
  - Render each face as a point
  - Distribute the computation between
    - Vertex shader
    - Fragment shader

- While computing forces
  - Compute wave effect!
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The Overall System

The main thread

- **Simulation**
  - Advance time
  - Render force texture
  - Apply forces
  - Render wave generation texture
  - Generate waves
  - Render height field

- **Frame Render**

Rigid body thread

- Rigid body simulation

Wave particle thread

- Create waves
- Wave particle iteration
  - Subdivision
  - Reflection

New wave buffer
Thank you!

- **Acknowledgements**

- **Wave particles web-page:**

- **“Wave Particles” paper presentation**
  - Fluids paper session, Thursday ~11:20 am