

Ultrasound goes GPU: real-time simulation using CUDA

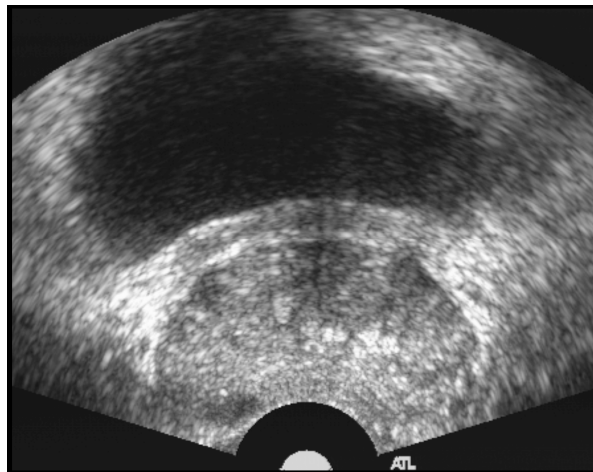
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Clinical Problem

- Despite increasing use of CT, MRI, etc. medical US remains widely in use because of low cost, non-invasiveness, real-time visual feedback, etc.
- Many procedures like US-guided needle insertion require a high degree of hand-eye coordination and extensive training.
- For ethical and patient safety reasons training on simulations is preferred.



Related Work

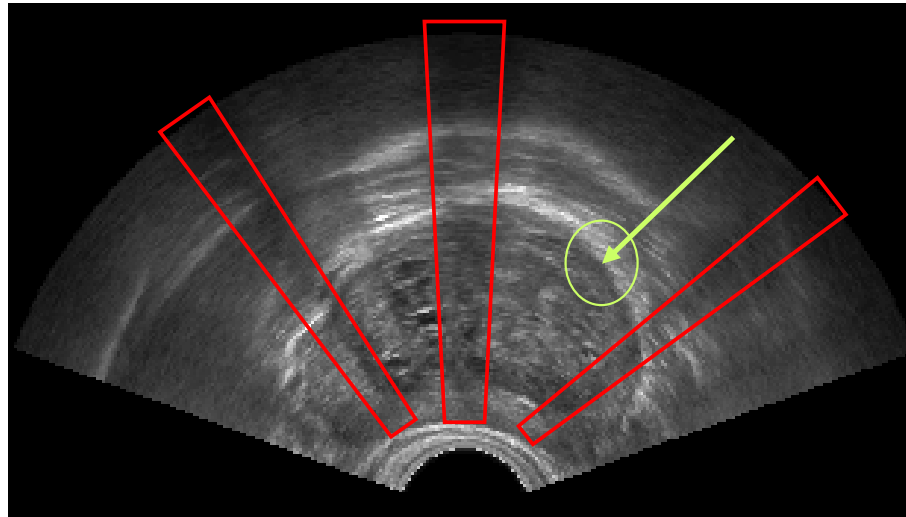
- Jensen 1996: exhaustive simulation of US imaging on the scatterer level
- Aiger and Cohen-Or 1998: **real-time** simulation by slicing 2D US images from 3D volume
- Hostettler et al. 2005: ray-tracing US waves, combined with CT textures
- Zhu et al. 2006: using synthetic 3D textures based on 2D US samples
- Wein et al. 2007: physically derived estimation of US reflection
- Shams et al. 2008: combination of US reflection (cf. Wein 2007) with scatter image (cf. Jensen 1996)

Common problem: computational effort, e.g. resolution is limited in favor of real-time simulation.

Idea: take advantage of modern graphics processors (GPU) and their capabilities for parallel processing

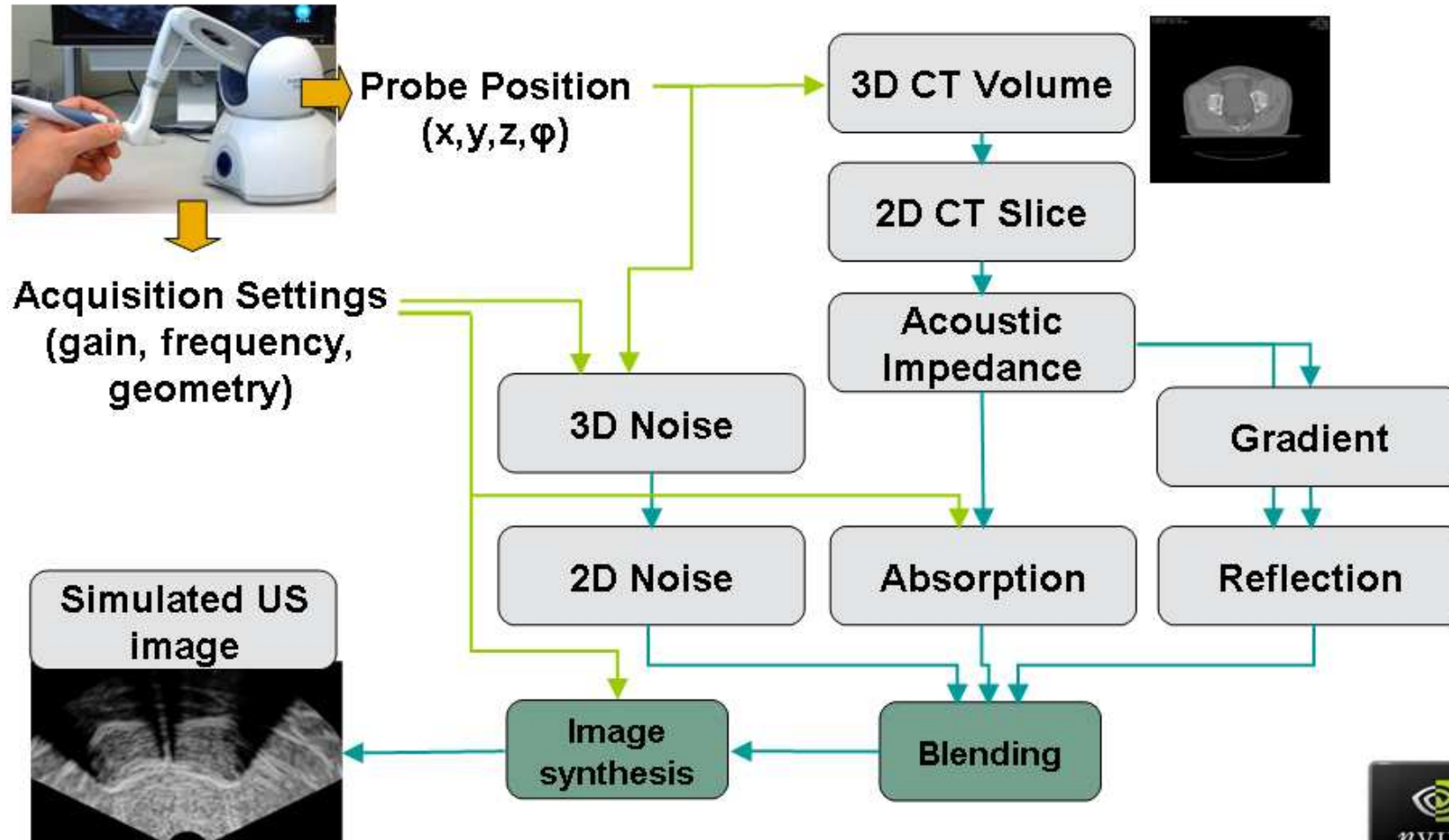
Goal: realistic simulation in real-time

Ultrasound Artifacts



- US reflection at tissue boundaries
- US attenuation in tissue, shadowing
- Speckle noise
- Radial blur

Implementation: Overview



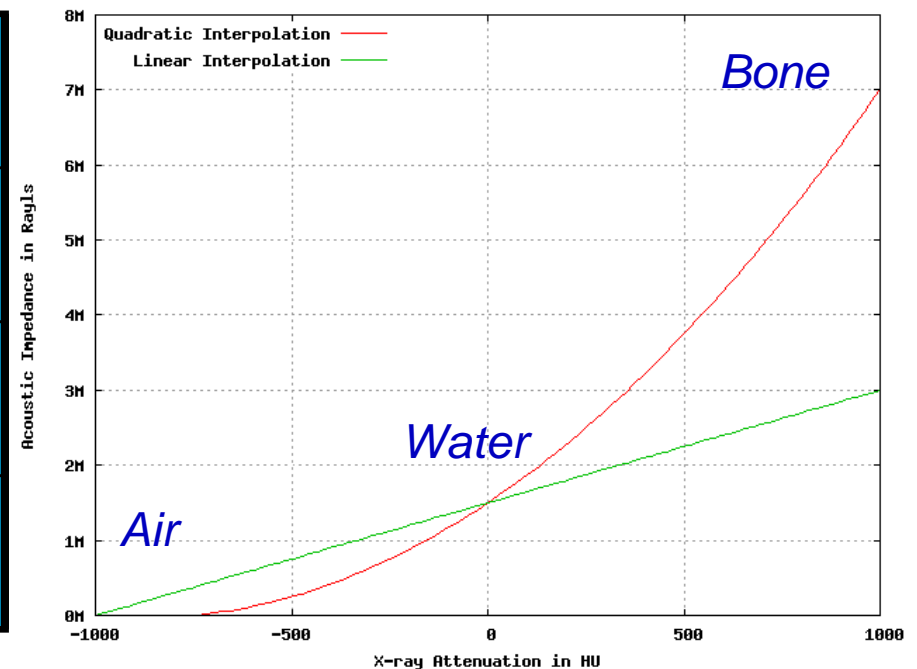
US Physics: Acoustic Impedance

- Estimation of acoustic impedance from CT values (Wein et al. 2007)
- Using quadratic instead of linear interpolation

$$Z = \rho \times c$$

ρ Density of the tissue
 c Speed of sound

	ρ [kg/m ³]	c [m/s]	Z [Rayl]	CT [HU]
Air	1.2	330	~400	-1000
Water	1000	1480	1.48 M	0
Bone	1800	4330	~7 M	1000



US Physics: Snell's Law

- Specular reflection:

$$\frac{I_r}{I_i} = \left(\frac{Z_2 \cdot \cos \theta_i - Z_1 \cdot \cos \theta_t}{Z_2 \cdot \cos \theta_i + Z_1 \cdot \cos \theta_t} \right)^2$$

- Simplification:

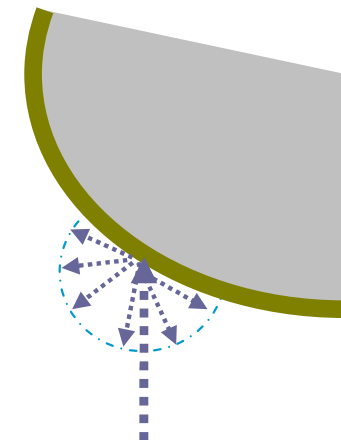
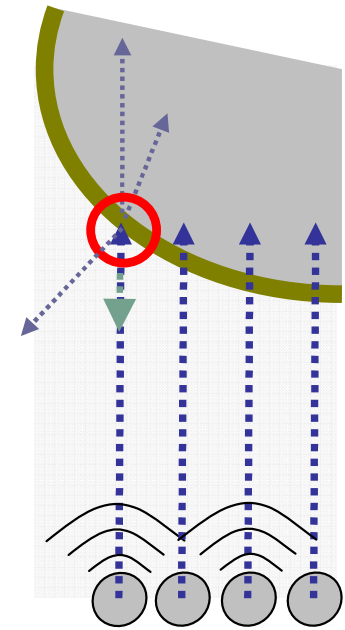
$$\theta_i \approx 0 \quad \frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

- Combination of specular and diffuse reflection:

$$\frac{I_r}{I_i} = \cos(\alpha)^n$$

- Using n=2:

$$\frac{I_r}{I_i}(x) = \left(\frac{d^T \cdot \nabla Z(x)}{2 \cdot Z(x)} \right)^2$$



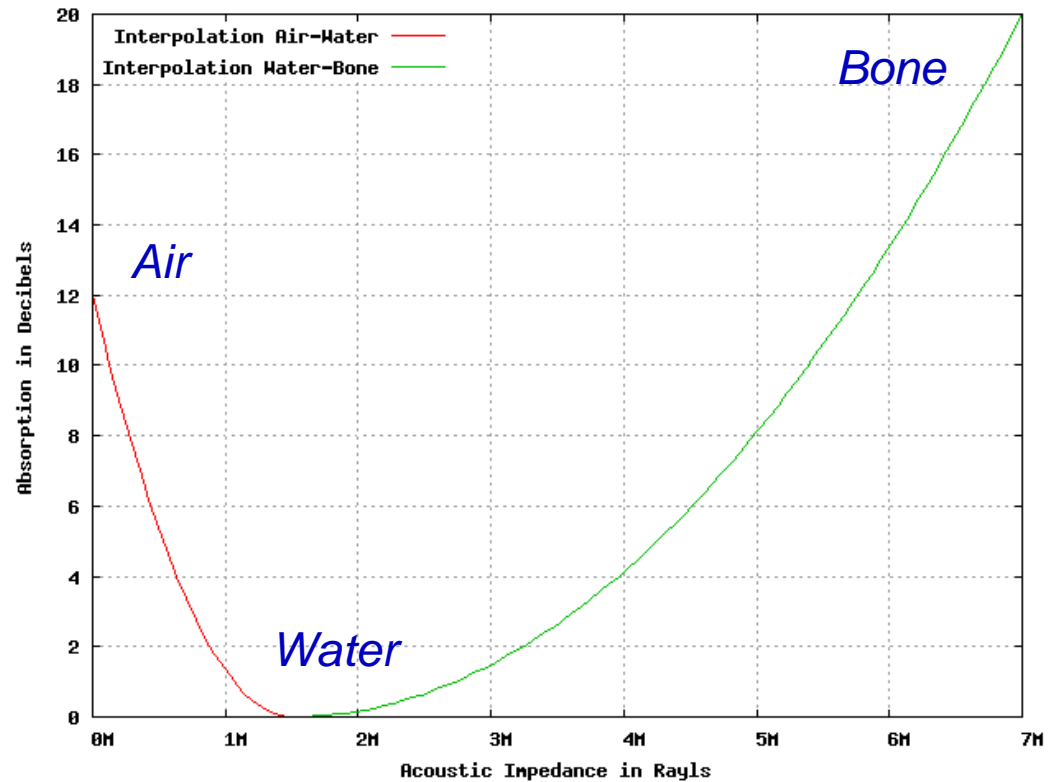
US Physics: Absorption

- Approx. 95-100% of attenuation due to absorption
- Exponential law, similar to X-ray attenuation:

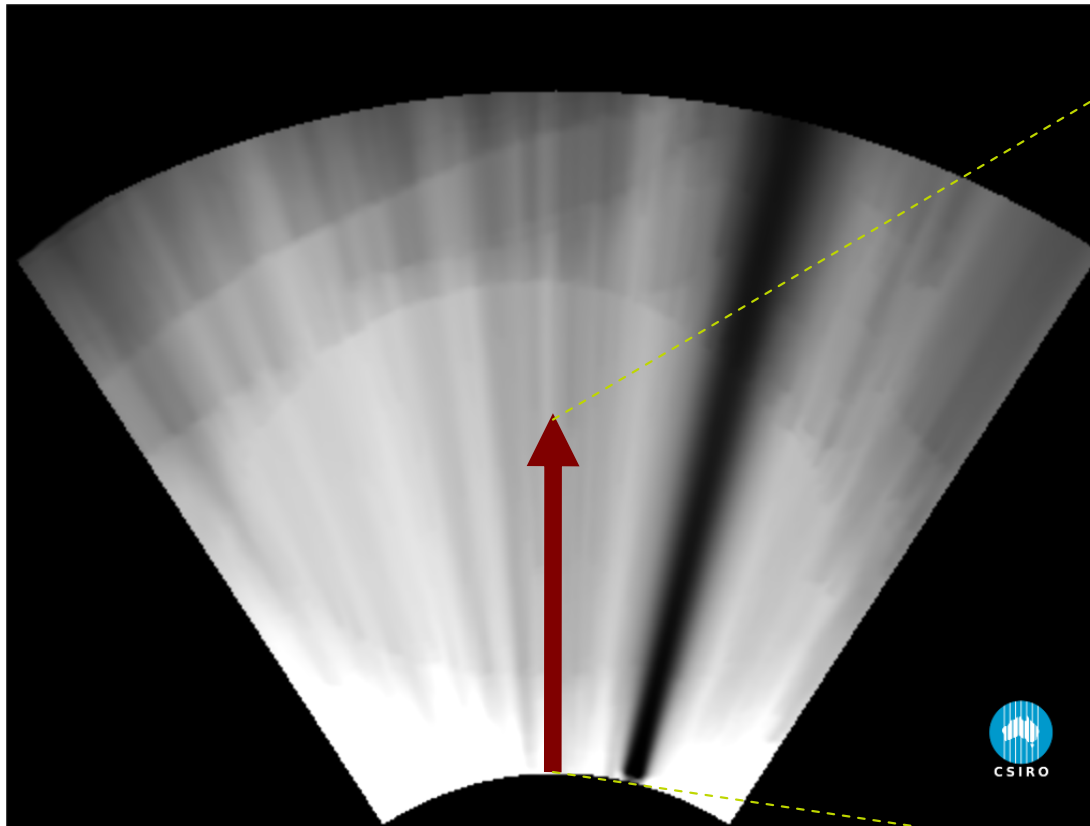
$$\frac{I}{I_0} = 10^{-\alpha \cdot d \cdot f / 10}$$

f US frequency

α attenuation coefficient

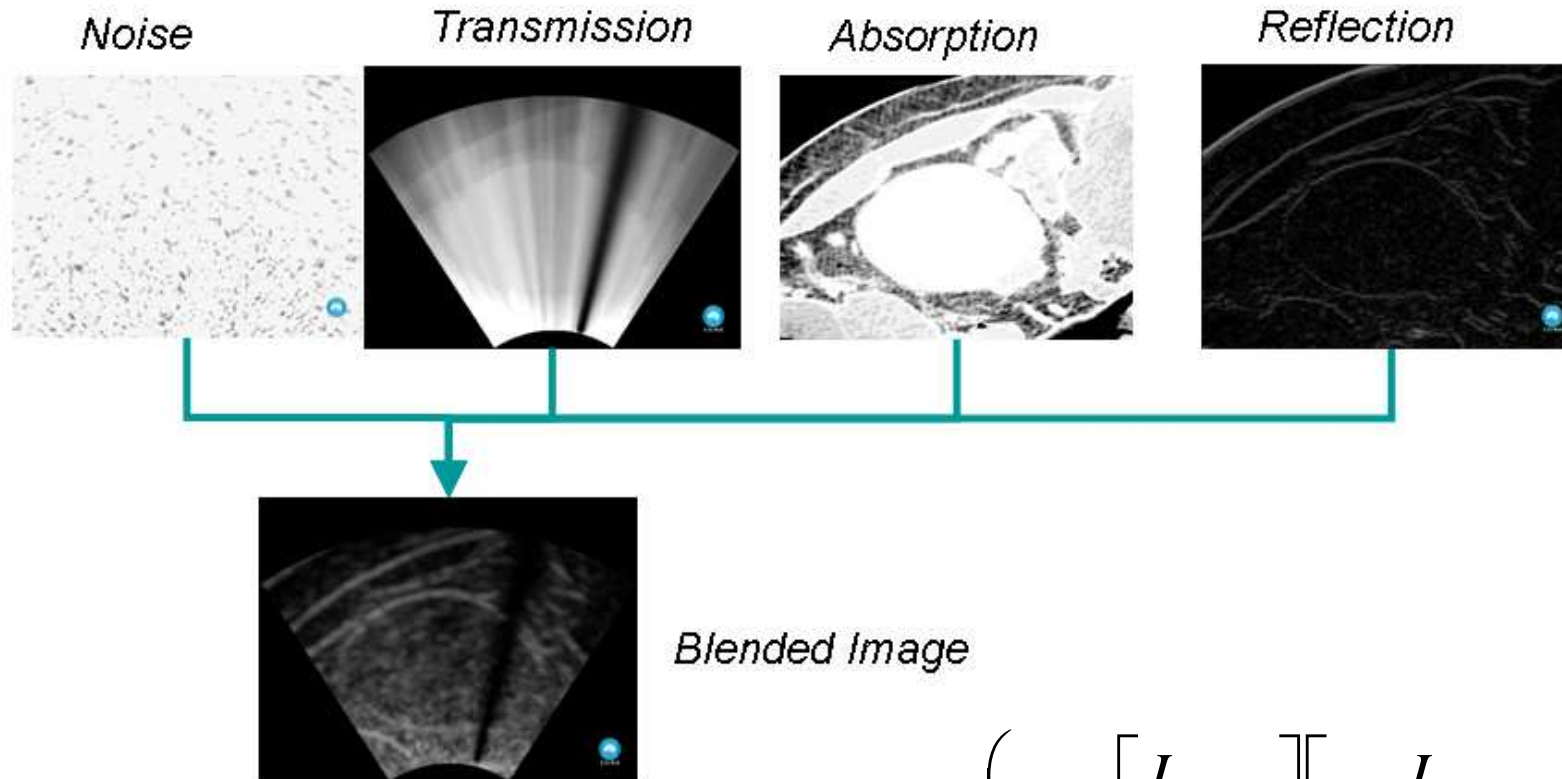


Transmitted Intensity



$$I_t(x) = I_0 \cdot \prod_{0 \leq k \leq x} \left[\underbrace{\frac{I_t(k)}{I_i}}_{\text{Transmission}} \cdot \left(1 - \underbrace{\frac{I_a(k, d)}{I_i}}_{\text{Absorption}} \right) \right]$$

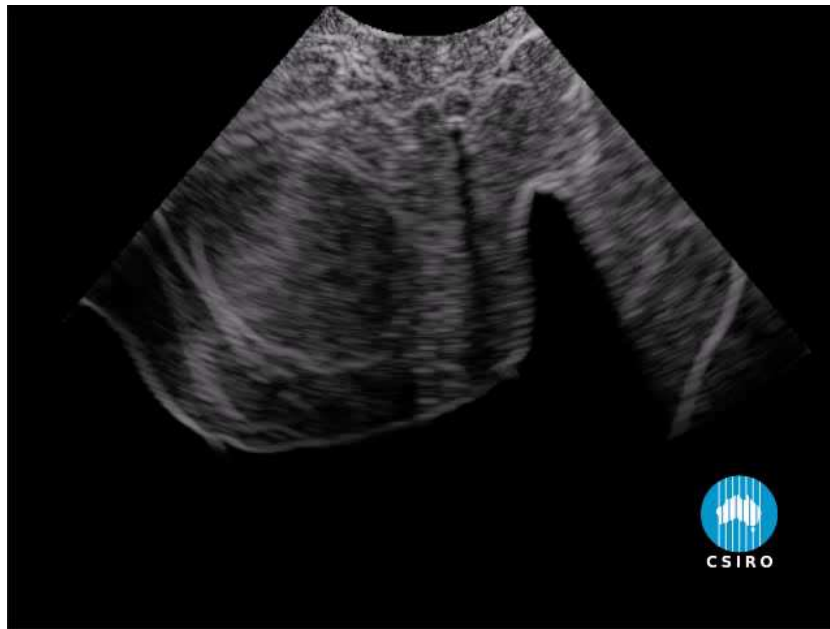
Reflected Intensity



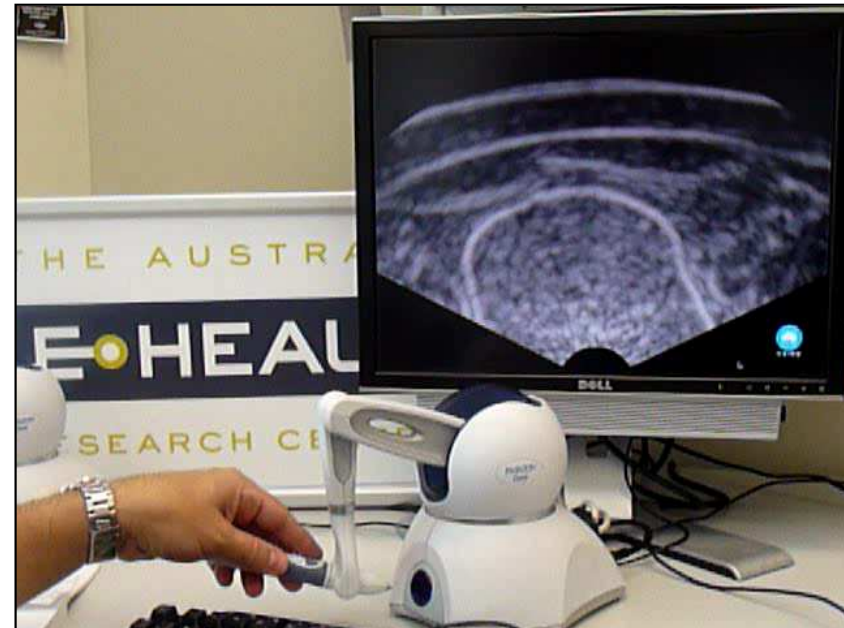
$$I_r(x) = I_0 \left(\prod_{0 \leq k \leq x} \left[\frac{I_t(k)}{I_i} \right] \left[1 - \frac{I_a(k, d)}{I_i} \right] \right)^2 \cdot R(x)$$

Transmission
Absorption
Reflection

Implementation: Real-time Simulation



Demo 1: Image quality



Demo 2: Interaction

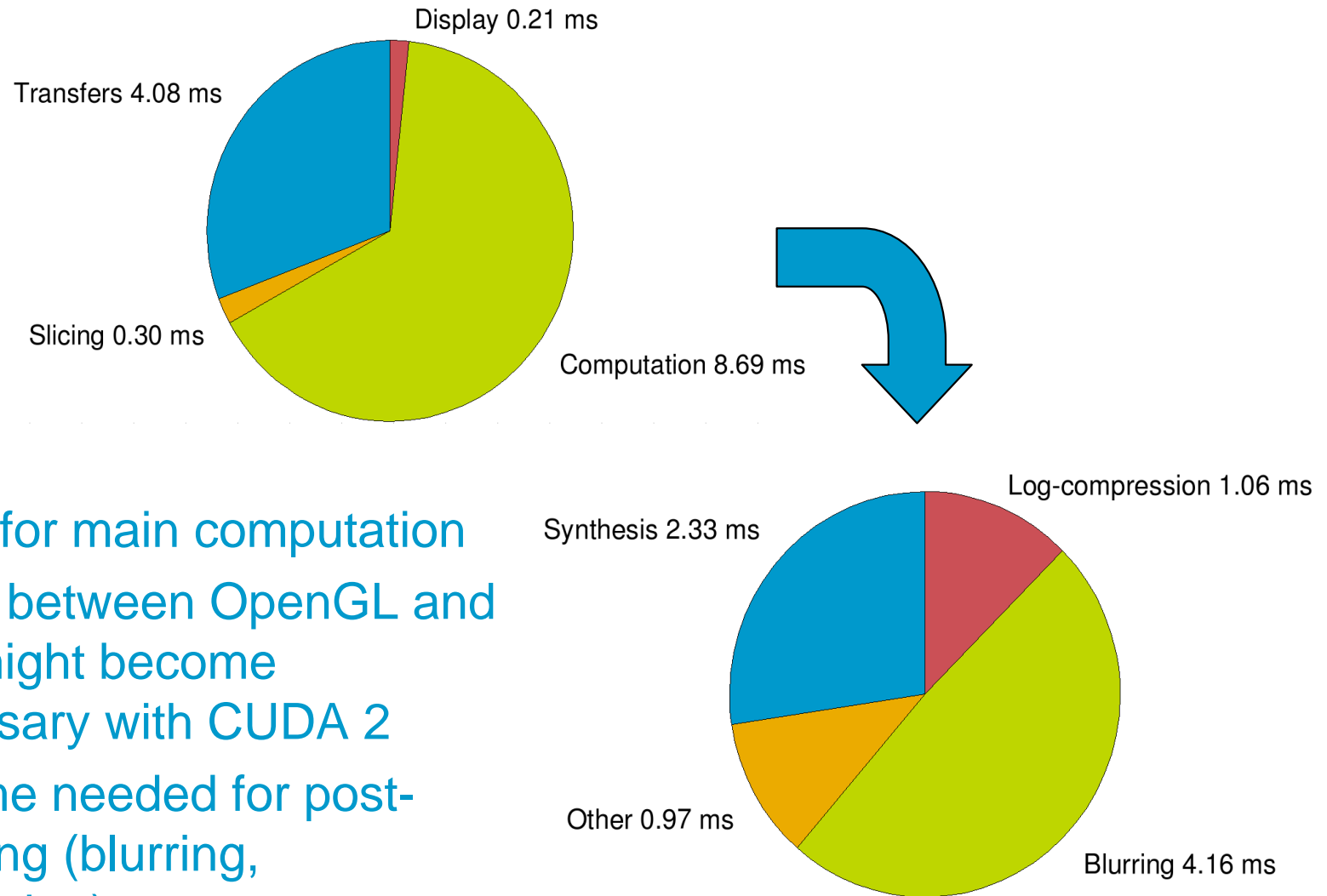
Implementation: Simulation Options

The screenshot displays three control panels for a simulation interface, overlaid on a grayscale ultrasound image. The background image shows a cross-section of a biological structure, possibly a vessel or organ, with varying echogenicity.

- Simulation properties:** This panel includes a 'Probe Type' section with radio buttons for 'Transrectal Probe' (selected) and 'Obstetric Probe'. Below are sliders for 'Frequency' (3.5 MHz), 'Intensity' (2.6 mW/cm²), and 'Radius' (9 mm). There are also checkboxes for 'Stick to Surface', 'Enable Fan Shape', 'Enable Stencil', 'Enable Noise', and 'Enable Blurring'. At the bottom, there are sliders for 'Axial Blur' (1.14 AU) and 'Lateral Blur' (1.02 AU).
- Display Options:** This panel features a 'Display Mode' section with checkboxes for 'Reflection Ratio', 'Absorption Ratio', 'Transmitted Intensity', 'Reflected Intensity' (checked), 'Probe Geometry', 'Acoustic Impedance', 'Gradient Magnitude', 'Original CT data', and 'Noise Only'. It also has an 'Inset Display' section with a checked 'Display 2-D Inset' and an 'Inset size' slider (1024 px). The 'Log-compression' section includes a 'Dyn. Range' slider (61 dB) and a checked 'Use Pre-defined Brightness' option.
- Time Gain Compensation:** This panel contains seven sliders labeled 'TGC 7' through 'TGC 0', each set to 0 dB. At the bottom, there are two empty rectangular input fields.

The CSIRO logo is visible in the bottom right corner of the simulation interface.

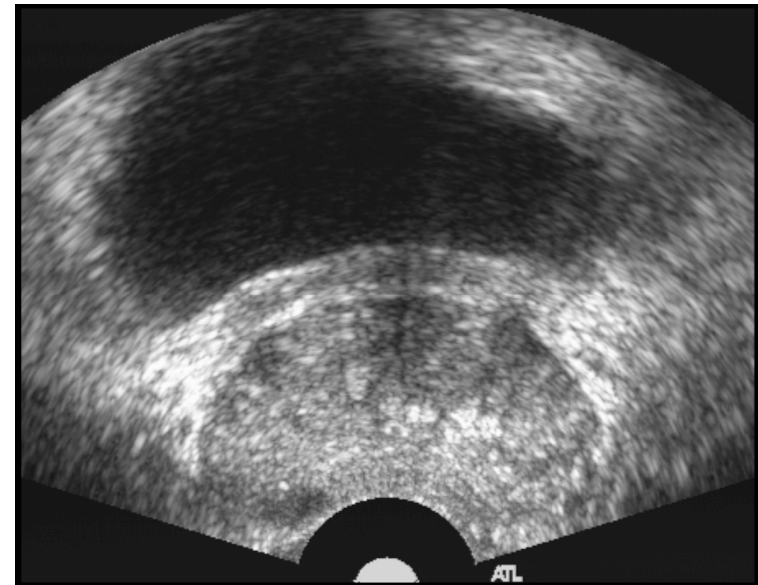
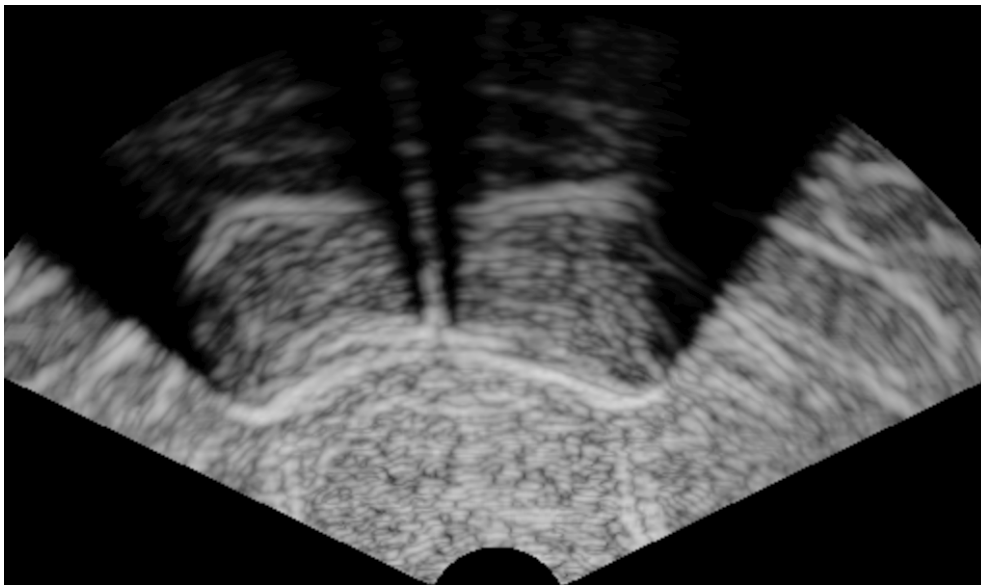
Results: Timing



- ~3.3 ms for main computation
- Transfer between OpenGL and CUDA might become unnecessary with CUDA 2
- Much time needed for post-processing (blurring, compression)

Results: Image Quality

- Comparison: simulated image (left), real image (right)
- Positive feedback from clinicians, collaboration for comparing and validating our results (Robarts Research, Canada)



Conclusion

- New physically plausible approach where computation is possible within the virtual US scan plane, i.e. using only one 2D slice from the original 3D CT volume
- No manual annotation or adjustment of the input data necessary
- Real-time simulation with „maximum“ resolution (i.e. same as CT data)
- Artifacts simulated: shadowing / attenuation, speckle noise, radial and lateral blurring
- All virtual acquisition parameters can be interactively changed: US frequency, US intensity, time-gain compensation, field geometry

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Thank you for your attention!

- Questions?