PARALLEM: massively Parallel Landscape Evolution Modelling

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The University of Sheffield

A. Stephen McGough, Darrel Maddy
J. Wainwright, S. Liang, M. Rapoportas, A. Trueman,
R. Grey, G. Kumar Vinod, and James Bell
Outline

• What is Landscape Evolution Modelling (LEM)
• Parallelization of LEM
• Preliminary Results
• The Current Situation
• Future Directions
Landscape Evolution Modeling

• Landscapes change over time due to water/weathering
  • Physical and Chemical Weathering require water to break down material
  • Higher energy flowing water both Erodes and Transports material until decreasing energy conditions result in Deposition of material

• These processes take a long time
  • Many glacial-Interglacial Cycles
    • Cycles are ~100ka for last 800ka, prior to 800ka cycles were ~40ka in length

• We want to use retrodiction to work out how the landscape has changed
Landscape Evolution Modeling

• Use a simulation to model how the landscape changes
  • 3D Landscape is discretized as a regular 2D grid (x, y) with cell values representing surface heights (z) derived from a digital elevation model (DEM)
    • Cells can be 10m x 10m or larger
Landscape Evolution Modeling (simplified)
Each iteration of the simulation:

- How much material will be removed?
- How much material will be deposited?

• Each step is ‘fairly’ fast...
• But we want to do lots of them 120K to 1M years
• On landscapes of 6-56M cells
• If we could simulate 1 year in 1 minute this would take 83 – 694 days!
  • assuming 1 year = 1 iteration
  • may need more

Sequential version is much slower than this…

How much material will be removed? How much material will be deposited?
Execution analysis of Sequential LEM

• We started from an existing sequential LEM
  • 51x100 cells for just 120K years took 72 hours
    • estimate for 25M cells 64,000 years
  • This was non-optimal code
    • Reduced execution time from 72 to 4.7 hours
    • 64,000 years down to 300 years

• But this is still not enough for our needs
Execution analysis of Sequential LEM

• Performance Analysis:
• ~74% of time spent routing and accumulating
• Need orders of magnitude speedup
  • So focus was on flow routing / accumulation
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Parallel Flow Routing

• Each cell can be done independently of all others
  • SFD
    • 100% flow in the direction of steepest decent
      (normally lowest neighbour)
  • MFD
    • Flow is proportioned between all lower neighbours
    • Proportional to slope to each neighbours

• Almost linear speed-up
  • Problems with code divergence
    • CUDA Warps split when code contains a fork

Single flow direction vs multiple flow direction
MFD is ‘better’ but much more computationally demanding
Parallel Accumulation: Correct Flow

- Iterate:
  - Do not compute a cell until it has no incorrect cells flowing into it
  - Sum all inputs and add self
  - All cells can work independently of each other
    - Some restriction on updates not happening immediately

Flow Routing

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Accumulation

Correct

Cell values are not normally 1, but the initial rainfall on the cell
Not the whole story...

- Sinks and Plateaus
  - Can’t work out flow routing on sinks and plateaus
  - Need to ‘fake’ a flow routing
    - Fill a sink until it can flow out
      - Turn it into a plateau
    - Fake flow directions on a plateau to the outlet
Parallel Plateau routing

• Need to find the outflow of a plateau and flow all water to it
• A common solution is to use a breadth first search algorithm
  • Parallel implementation
  • Though result does look ‘unnatural’
  • Alternative patterns are possible – but acceptable
• We are investigating alternative solutions
Sink filling

• Dealing with a single sink is (relatively) simple
  • Fill sink until we end up with a plateau (lake)
• But what if we have multiple nested sinks?
Nested Sink filling

• Implemented parallel version of the sink filling algorithm proposed by Arger et al [2003]
  • Identify each sink (parallel)
  • Determine which cells flow into this sink - watershed (parallel)
  • Determine the lowest cell joining each pair of sinks (parallel/sequential)
  • Work out how high cells in each sink need to be raised to allow all cells to flow out of the DEM (sequential)
• Fill all sink cells to this height (parallel)
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Results: Performance

• Overall performance
Results: Performance

• Flow Direction
  • Including sink & plateau solution
Results: Performance

• Flow Accumulation
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The Current Simulation

- Core Model now extended with processes
  - Most only affect individual cells (weathering, vegetation)
  - Some have cross DEM effects (mass movement) but can use same process as before
The Current Simulation

- Actively running landscape models on K40/K80 GPGPUs
- Taking ~7 weeks to run our model (MFD)
  - Leading to interesting results
  - Not seen as models have traditionally been much smaller
  - Taking ~4 weeks for SFD
- Currently running on just 1 GPGPU
  - Running multiple models simultaneously
  - Now have a multi-GPGPU code for running flow accumulation
    - Designed to ‘sweep’ over the landscape

Upper Thames Valley + 120K
Multi-GPU: Attempt 1

- Flow direction can be done without problems
- Flow accumulation requires communication
- Perform each flow direction as one kernel call
  - No branching
  - Communication easier between cards
Multi-GPU: Attempt 1

**Whole Simulation**

- **5m Active Cells (Kepler K40/K80)**
- **20m Active Cells (Kepler K40/K80)**
- **5m Active Cells (Pascal Titan XP)**
- **5m Active Cells Sequential (CPU)**

**Flow Accumulation**

- **Compute**
- **Transfer**

Wallclock runtime (nanoseconds) vs. GPU Count

Wallclock runtime (seconds) vs. GPU Count
Problem: Landscape Cutting with SFD
Comparing ‘cut in’ between SFD and MFD
Problem: Algorithm Slow-down

- Correct flow algorithm requires all input cells to be correct before progressing
- Becomes a problem for rivers

![Correct flow completion profile](chart.png)
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Process Improvements

- Smaller cells lead to greater depth of erosion
  - Rivers are currently only one cell wide
  - Make rivers wider (multi-cell)
- Modification of process algorithms to allow for lateral erosion

One potential PhD position to work on this
Summary

• Able to show 2+ orders of magnitude speedup in PARALLEM
• Significant potential for further speedup
  • Optimization of the processes
  • Remove sequentialization of correct flow
• The use of GPGPUs has allowed us to redress the execution restriction which has prevented us doing MFD – leading to ‘better’ landscapes

We Are recruiting:
- 2 PostDoc (Machine Learning)
- Always looking for good PhD Candidates

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