Algorithms re-engineering as a fundamental step towards exploitable hybrid computing for engineering simulations

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Algorithmic Re-Engineering for Modern Non-Conventional Processing Units
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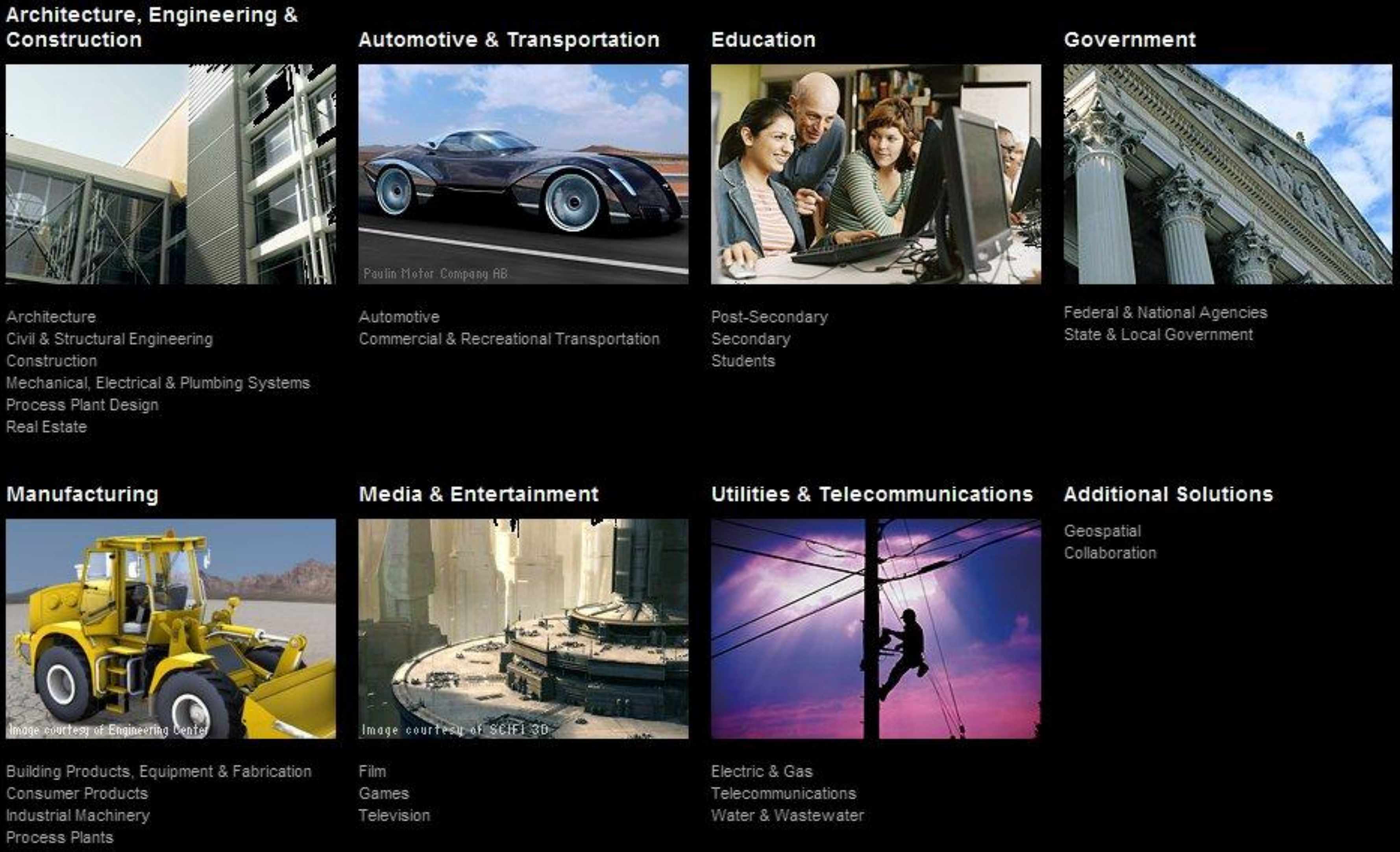
Agenda

- About Autodesk
- Simulation for Engineering trend in computing requirements
- Traditional approach to accelerators exploitation
- A more modern approach
- A new approach

Autodesk: a leading ISV in digital prototyping



Architecture, Engineering & Construction

Architecture
Civil & Structural Engineering
Construction
Mechanical, Electrical & Plumbing Systems
Process Plant Design
Real Estate

Automotive & Transportation

Paulin Motor Company AB

Automotive
Commercial & Recreational Transportation

Education

Post-Secondary
Secondary
Students

Government

Federal & National Agencies
State & Local Government

Manufacturing

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Building Products, Equipment & Fabrication
Consumer Products
Industrial Machinery
Process Plants

Media & Entertainment

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Film
Games
Television

Utilities & Telecommunications

Electric & Gas
Telecommunications
Water & Wastewater

Additional Solutions

Geospatial
Collaboration

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- Research activities:
  - User interfaces
  - Environment & ergonomics
  - Simulation & graphics
  - High performance computing
  - Technology transfer

- High performance computing research group created in 2009

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Simulation for Engineering trend in computing requirements

- Never-ending quest for efficiency and cost reduction
- Projects sustainability is becoming increasingly important
- Multidisciplinary, multidimensional analysis and simulations are required
- Design increasingly affected by simulation

Simulation for Engineering trend in computing requirements

1. From reduced complexity models to full models
2. From single-system to multi-system models
3. From individual simulations to multiple combined simulations
4. From simulation to optimization

Simulation for Engineering trend in computing requirements

- From reduced complexity models to full models
  - Simulation scalability issues
  - Overall simulation performance
  - Huge datasets directly from CAD and other sources

Simulation for Engineering trend in computing requirements

- From single-system to multi-system models
  - To reduce simulation time systems models are often reduced to small combinations of parts
  - The next barrier to increasing simulation accuracy involves modeling all the individual parts of a system and have them interact continuously in the simulation environment

Simulation for Engineering trend in computing requirements

- From individual simulations to multiple heterogeneous simulations
  - Simulations for the various dimensions/disciplines of a system are often conducted in isolation by individual experts
  - Only a combination of parameterized heterogeneous simulations can provide a comprehensive view on a project, essential to take informed decisions quickly and effectively

Simulation for Engineering trend in computing requirements

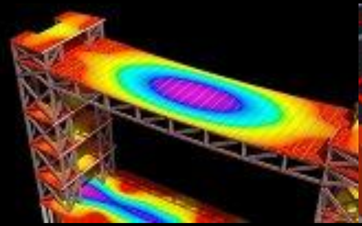
- From simulation to optimization
  - Simulation offers the analysis of a specific parameterized model
  - Increasing the efficiency and cost effectiveness of engineering projects involves finding the best combination of thousands of parameters
  - Faster and more precise simulations lead to faster convergence to optimal parameters

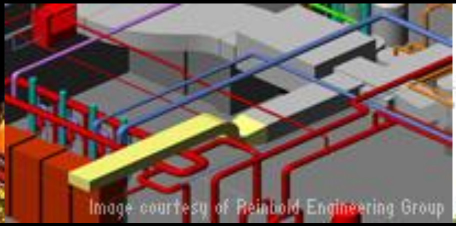
Requirements

- The size of future engineering simulation efforts requires enormous amount of computing power
- We need new methods for distributing simulations over numerous computing systems
- We need new methods for employing dedicated accelerators to reduce the simulations time and cost, and ultimately improve the overall projects efficiency

Example: Building Simulation and beyond

- Multiple simulation disciplines/dimensions:
  - – Simulation for design
  - – Simulation for structural integrity
  - – Simulation for infrastructure
  - – Simulation for green efficiency/lifecycle management





Example: Building Simulation and beyond

- So far these simulations have been conducted by domain experts in almost complete isolation, they need to be combined to achieve optimal results
- From a single building to a single block, to a city, to a region, the situation just gets worse

Example: Building Simulation for efficiency/lifecycle management

- Some example simulation components:
  - Ray tracing (sun exposure to maximize daylight exposure, heating and cooling issues)
  - CFD (HVAC to optimize air flow, temperature control and minimize related costs)
  - FEA (structural analysis, minimize bill of materials while ensuring tolerances)
  - Energy consumption/carbon footprint analysis
- Each of these simulations have both constraints and variables, which can be adjusted within certain boundaries

Example: Building Simulation for efficiency/lifecycle management

- The current state of the art is a set of separate simulations, with user-directed or brute-force choice of parameters to identify sets of "good" solutions
- Optimization techniques can reduce the simulations iterations, but the computing requirements are still very large

Simulation cost breakdown

- Simulation software development cost factors:
  - Code research and development cost: requirement to reduce time to market while exploiting performance improvement, software technology reuse
  - Code maintenance and porting cost: requirement to define “portable” algorithms, reducing the time to exploit new platforms and accelerators

Simulation cost breakdown

- Simulation software usage cost factors:
  - Required overall performance (time to answer)
  - Required overall precision (level of detail/optimization)
  - Software efficiency (tuning)
  - Hardware platform/s efficiency
  - Energy cost (running costs per simulation/optimization process)

How do non-conventional processing units and accelerators fit in all this?

Traditional approach to Accelerators exploitation

- So far accelerators have shown vast performance and efficiency improvements for extremely data parallel problems
- Non trivially-parallel algorithms still pose problems
- SaS business model emerging as new large market
- Hard to justify including accelerators into computing clouds/clusters for mainstream SaS usage due to development, maintenance and IT costs

Traditional approach to Accelerators exploitation

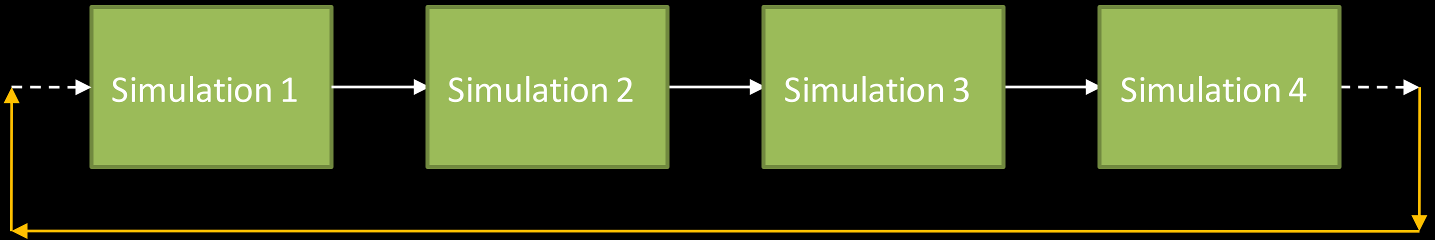
- Different architectural constraints require ad-hoc re-architecture tuning strategies
  - Programming languages/Instruction sets
  - Problem partitioning
  - Data layout
  - Memory hierarchy
- Parallel patterns and libraries contain solution to individual problems, but often their composition into applications often suffers badly from Amdahl's law

Traditional approach to Accelerators exploitation

- OpenCL and similar languages are powerful tools, but do not scale to accommodate very large algorithms, especially on accelerators
- Additional software infrastructure is often required to "glue" different parts of algorithms to avoid incurring in big performance penalties
- Even stream-oriented languages don't solve all problems: balancing heterogeneous software/hardware pipelines is hard to model, it is often a trial and error process

Traditional approach to Accelerators exploitation

- Example engineering simulation scenario:



Simulation 1

Simulation 2

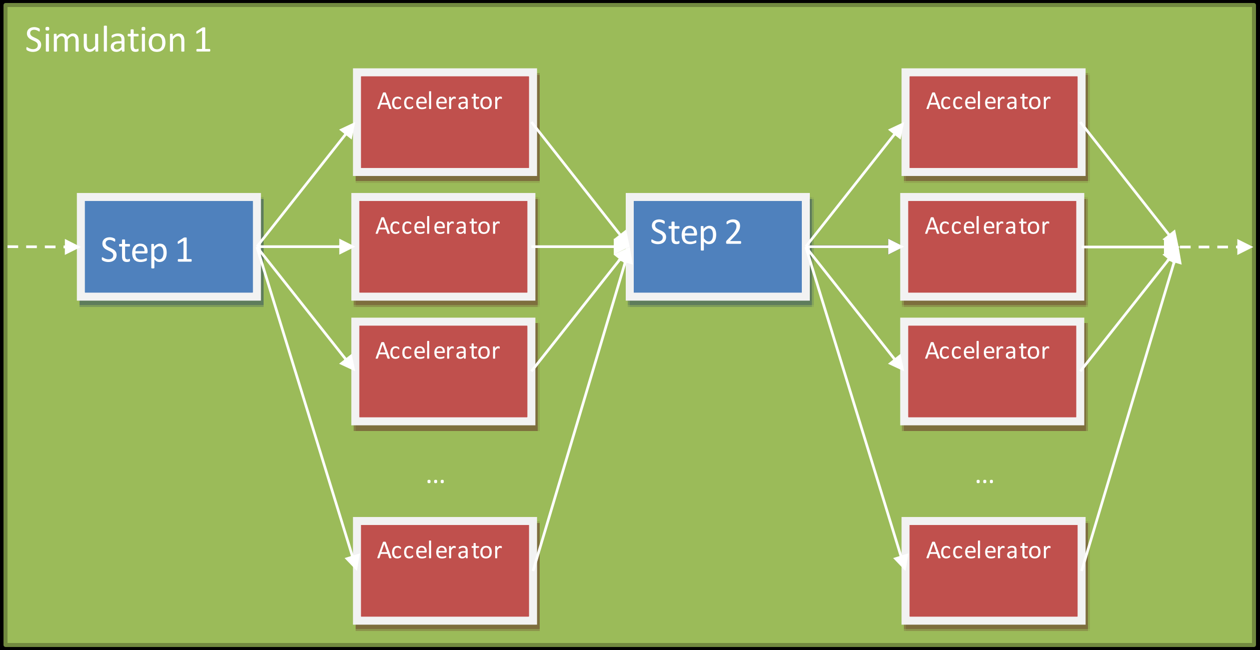
Simulation 3

Simulation 4

Iterate thousands to millions of times

Traditional approach to Accelerators exploitation

- Example engineering simulation scenario:



Simulation 1

Step 1

Accelerator

Accelerator

Accelerator

…

Accelerator

Step 2

Accelerator

Accelerator

Accelerator

…

Accelerator

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Traditional approach to Accelerators exploitation

- Simulations executed serially due to data dependencies
- Granularity is extremely coarse
- DGEMM et al. too coarse if present in large sequences
- Amdahl law hits hard at all synchronization points
- Intermediate resources (hosts) in the hierarchy are mostly unused and execute serial code or idle
- Difficult to model/predict all bottlenecks, especially due to the variability of computing systems

A more modern approach

Declarative language

+

Scalable task-based distributed software platform

A more modern approach

- Simulations are re-engineered into declarative, composable directed graphs; expressions of predefined libraries of small, computing intensive tasks (graph nodes) and data marshalling (graph edges)
- Task and data "core" libraries are written and optimized for CPUs and accelerators to provide implementations for the set of low-level tasks and data marshalling facilities
- Data dependency analysis is one of the fundamental techniques that enable optimizing compilers

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A more modern approach

- Budimlic et al. [CPC09] show that splitting macro tasks (Cholesky factorization) to create finer-grained dependency graphs results in better usage of resources and better performance due to the different order of scheduling
- This shows the potential for emergent behavior in complex systems where hot-spots are difficult to predict
- Increased granularity improves portability reuse and interoperability between heterogeneous systems

A more modern approach

- **Higher-level descriptive languages**: some frameworks exist, some have visual editing environments, more to appear
- **Large dependency graph analysis and integrated multi-level scheduling**: a few frameworks exist (Intel Concurrent Collections, etc.), more to appear

A more modern approach, limitations

- Dependency graph partitioning, processing and distribution is not new, but the solution space for optimal distribution is too large to be treated with traditional heuristics, especially on heterogeneous systems
- Complexity is much higher than classic "shop" problem: tasks do not execute in constant time even on similar platforms due to differences in memory architecture, cache sizes, number of cores, etc...

A more modern approach, limitations

- Task scheduling is lightweight and typically faster than context switch but not free
- Processing very large dependency graphs composed of hundreds of thousands of fine-grained tasks can bring even the best systems and task schedulers to their knees
- The overhead of scheduling the tasks could be so large to overshadow the benefits of parallelism

A new approach

Declarative language

+

Scalable task-based distributed software platform

+

Dynamic compilation

+

Iterative, feedback-directed task aggregation, scheduling and data transfer optimization

A new approach

- **Dynamic compilation:**
  - Dynamic, variable tasks granularity without "locking" algorithms implementations to a specific architecture
  - Reduce scheduling overhead by smart aggregation of tasks
  - Reduce tasks I/O overhead by collapsing data marshalling between tasks whenever possible
  - Additional potential for performance improvement due to further target-specific compilation optimizations

A new approach

- **Platform specific dynamic compilation, task aggregation, data marshalling collapsing**:
  - CPU: imperative language "core" tasks library, dynamic generation of object code kernels by LLVM dynamic compilation
  - Data parallel accelerator: OpenCL "core" tasks library, dynamic generation of kernels by dynamic OpenCL compilation, block size parameters
  - FPGA: VHDL/other languages "core" tasks library, dynamic generation of synthesizable kernels by dynamic compilation and synthesis

A new approach

- **Iterative, feedback-directed task aggregation, scheduling and data transfer optimization:**
  - Better chances of overcoming Amdahl's law and exploiting emerging non conventional architectures by dynamically assigning tasks to the most appropriate computing resources while minimizing overhead
  - All computing resources are treated as such, thereby actively contributing to the graph evaluation (no host-accelerator relationship limitation)

A new approach

- **Dynamic compilation**: very few frameworks exist (LLVM, etc.), more to appear
- **Iterative, heterogeneous task assignment and scheduling optimization**: extremely few frameworks exist, *Autodesk Research working on this*

A new approach

- **Our approach to Iterative, feedback-directed task aggregation, scheduling and data transfer optimization**: *Consider the scheduling optimization as a black-box non-linear constrained numerical optimization problem, use gradient-less function minimization techniques*

A new approach

- Energy function examples: total wall clock, total used memory, total data communication, etc.
- Function parameters: tasks aggregation flags based on dependency constraints, tasks assignment flags based on available "core" tasks and data marshalling libraries
- Soft constraints examples: scheduling or assignments hints
- Hard constraints examples: accelerator/s memory usage, FPGA/s gates used
- Minimization techniques: GA, Simulated annealing, Pattern search

A new approach

- Fixed platform (embedded systems, games consoles, mobile phones, etc.): algorithms can be distributed in a pre-evaluated aggregation and scheduling configuration
- Variable platform (personal computers, etc.): algorithms are iteratively optimized at runtime on the target system

A new approach

- Recent, ongoing research project
- No measurable results to date
- We are writing a prototype based on Intel Concurrent Collections/TBB + OpenCL
- Testing will be conducted initially on ad-hoc synthetic benchmarks

Questions?

Thank you.

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