TASK-BASED SPARSE CHOLESKY SOLVER ON TOP OF RUNTIME SYSTEM

Iain S. Duff, Jonathan D. Hogg and **Florent Lopez**

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Rutherford Appleton Laboratory
NLAFET Project

Objective

Solve $Ax = b$, where A is large and sparse, on modern architectures.

Using Direct Method: Sparse Cholesky factorization $A = LL^T$

- ▲ Numerically robust and general purpose
- ▼ High memory usage and computational cost

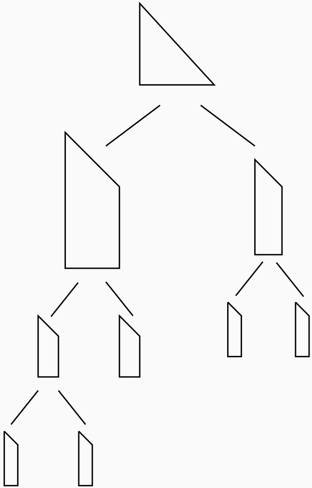
Exploiting modern platforms is challenging:

- Multicore processors and deep memory hierarchy.
- Heterogeneous e.g. CPU & GPU or Xeon Phi.
- Distributed-memory systems.

In numerical factorization of A the *elimination tree* expresses data dependencies in the factor L. Each node, referred to as *supernode*, is a dense lower trapezoidal submatrix of L.

The tree is traversed in a topological order, and each node is factorised using dense Cholesky algorithm.

Updates between node are handled using a supernodal scheme i.e. updates are applied directly to the target supernode.



Sparse Cholesky factorization

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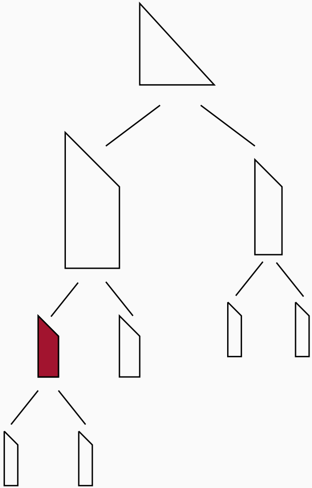

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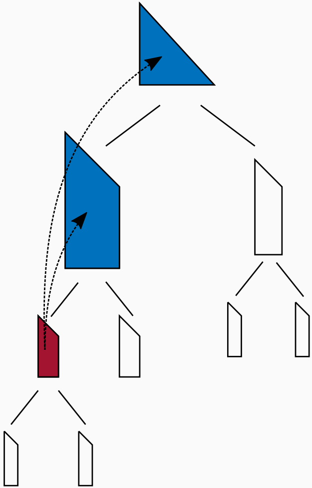
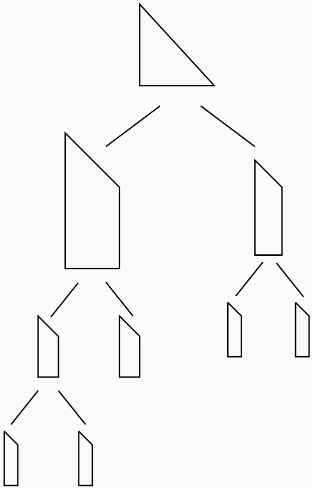


Sources of parallelism in the elimination tree:



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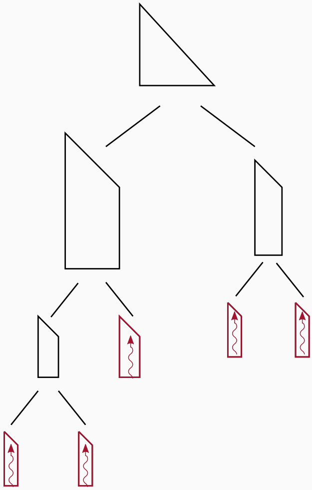
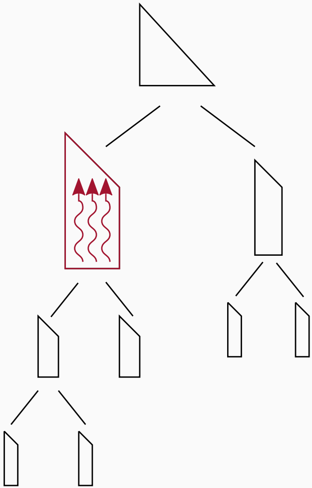
- Tree parallelism: Supernode in independent branches can be processed concurrently.



Sources of parallelism in the elimination tree:

- Tree parallelism: Supernode in independent branches can be processed concurrently.
- Node parallelism: When a supernode is large enough, it may be processed in parallel.



Task-based Sparse Cholesky factorization

```
forall nodes snode in post-order
   call alloc(snode) ! allocate data structures

   call init(snode) ! initianlize node structure
end do

forall nodes snode in post-order
  ! factorize node
   call factorize(snode) ! factorize block

   ! update ancestor nodes
   forall ancestors(snode) anode
     call update_btw(snode, anode)
   end do

  end do
end do
```

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forall nodes snode in post-order
   call alloc(snode) ! allocate data structures

   call init(snode) ! initianlize node structure
end do

forall nodes snode in post-order
  ! factorize node
  do k=1..n in snode
    call factorize(blk(k,k)) ! factorize block

    do i=k+1..m in snode
        call solve(blk(k,k), blk(i,k)) ! perform solve
    end do

    do j=k+1..n in snode
       do i=k+1..m in snode
          call update(blk(j,k), blk(i,k), blk(i,j))
       end do
    end do

    ! update ancestor nodes
    forall ancestors(snode) anode
      do j=k+1..p(anode) in snode
         do i=k+1..m in snode
            call update_btw(blk(j,k), blk(i,k), a_blk(rmap(i), cmap(j)))
         end do
      end do
    end do

  end do
end do
```

Sequential Task Flow (STF) programming model:

- Tasks are submitted to the runtime system following the sequential algorithm.
- The runtime analyses manipulated data and infers task dependencies in order to ensure the sequential consistency of the parallel code.
- The DAG is executed via a dynamic scheduling of the (ready) tasks on the architectures.
- The runtime may be capable of automatically handling the data transfer across the architecture.
- Superscalar analysis in processors: dependency detection between instructions in order to issue them in parallel.

The STF Sparse Cholesky Factorization

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         do i=k+1..m in snode
            call update_btw(blk(j,k), blk(i,k), a_blk(rmap(i), cmap(j)))
         end do
      end do
    end do

  end do
end do
```

```
forall nodes snode in post-order
   call alloc(snode) ! allocate data structures

   call submit(init, snode:W) ! initianlize node structure
end do

forall nodes snode in post-order
  ! factorize node
  do k=1..n in snode
    call submit(factorize, snode:R, blk(k,k):RW) ! factorize block

    do i=k+1..m in snode
        call submit(solve, blk(k,k):R, blk(i,k):RW) ! perform solve
    end do

    do j=k+1..n in snode
       do i=k+1..m in snode
          call submit(update, blk(j,k):R, blk(i,k):R, blk(i,j):RW)
       end do
    end do

    ! update ancestor nodes
    forall ancestors(snode) anode
      do j=k+1..p(anode) in snode
         do i=k+1..m in snode
            call submit(update_btw, blk(j,k):R, blk(i,k):R, a_blk(rmap(i), cmap(j)):RW)
         end do
      end do
    end do

  end do
end do
```

OpenMP 4.0

- **`task`** construct and **`depend`** clause (**`in`**, **`out`**, **`inout`**).
- No control on the scheduling policy.
- Shared-memory system only.

StarPU

- **`starpu_insert_task`** and data *handle* with access mode (`R`, `W`, `RW`).
- Full control on schduling policy with possibility to implement new one.
- API for distributed-memory systems.

Experiments

#	Matrix	Flops (10^9)	Application/description
1	Schmid/thermal2	18.6	Unstructured thermal FEM
2	Rothberg/gearbox	22.8	Aircraft flap actuator
3	DNVS/m_t1	23.4	Tubular joint
4	DNVS/thread	35.7	Threaded connector
5	DNVS/shipsec1	40.5	Ship section
6	GHS_psdef/crankseg_2	48.8	Linear static analysis
7	AMD/G3_circuit	67.3	Circuit simulation
8	Koutsovasilis/F1	228	AUDI engine crankshaft
9	Oberwolfach/boneS10	297	Bone micro-FEM
10	ND/nd12k	514	3D mesh problem
11	JGD Trefethen/Trefethen_20000	669	Integer matrix
12	ND/nd24k	2080	3D mesh problem
13	Oberwolfach/bone010	3910	Bone micro-FEM
14	GHS_psdef/audikw_1	5840	Automotive crankshaft

- Symmetric positive-definite matrices.
- Metis nested disection ordering.
- Machine: 2 x 14 cores E5-2695 v3 (Haswell) @ 2.30GHz.

#	spLLT				MA87	
	OpenMP (gnu)		StarPU		MA87	
	nb	facto (s)	nb	facto (s)	nb	facto (s)
1	512	1.801	1024	2.123	256	0.376
2	256	0.220	384	0.318	256	0.252
3	256	0.205	384	0.262	256	0.194
4	256	0.203	384	0.240	256	0.213
5	256	0.247	384	0.363	256	0.259
6	256	0.267	384	0.310	256	0.257
7	512	2.631	512	3.345	256	0.586
8	384	0.812	512	0.920	256	0.786
9	384	1.186	384	1.599	256	1.111
10	384	1.478	384	1.405	384	1.498
11	512	3.692	384	2.406	512	3.829
12	384	5.379	384	5.076	384	5.498
13	384	7.416	768	7.392	384	7.195
14	768	10.650	768	10.680	384	10.642

- OpenMP seems more efficient on smaller problems whereas StarPU gives better results on bigger problems.
- SpLLT and MA87 obtain similar performance except for two problems (Matrices #1 and #7) where the difference is relatively big.

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#	SpLLT				
	OpenMP		StarPU		MA87
	build (s)	facto (s)	build (s)	facto (s)	facto (s)
1	1.238	1.801	1.677	2.123	0.376
2	0.152	0.220	0.281	0.318	0.252
3	0.155	0.205	0.200	0.262	0.194
4	0.125	0.203	0.152	0.240	0.213
5	0.215	0.247	0.271	0.363	0.259
6	0.178	0.267	0.283	0.310	0.257
7	1.712	2.631	2.737	3.345	0.586
8	0.600	0.812	0.763	0.920	0.786
9	0.812	1.186	1.299	1.599	1.111
10	0.770	1.478	0.763	1.405	1.498
11	0.749	3.692	1.586	2.406	3.829
12	2.887	5.379	2.778	5.076	5.498
13	3.063	7.416	2.280	7.392	7.195
14	3.383	10.650	3.141	10.680	10.642

- In the STF model, depending on DAG size and granularity of tasks, the time spent for building the DAG might be important compared to the factorization time.

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	OpenMP		StarPU		MA87
	build (s)	facto (s)	build (s)	facto (s)	facto (s)
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5	0.215	0.247	0.271	0.363	0.259
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7	1.712	2.631	2.737	3.345	0.586
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Parametrized Task Graph (PTG) programming model:

- Uses a compact representation of the DAG which is problem size independent.
- The dataflow between tasks is explicitly encoded (i.e. task dependencies are explicitly given).
- The runtime handles the communications implicitly using the dataflow representation.
- Under some hypothesis, the dataflow information can be automatically extracted from the sequential code using a dedicated compiler: not in our case unfortunately.

#	spLLT				MA87	
	OpenMP/StarPU		PaRSEC		MA87	
	nb	facto (s)	nb	facto (s)	nb	facto (s)
1	512	1.801	384	0.610	256	0.376
2	256	0.220	384	0.300	256	0.252
3	256	0.205	256	0.286	256	0.194
4	256	0.203	384	0.284	256	0.213
5	256	0.247	256	0.327	256	0.259
6	256	0.267	256	0.368	256	0.257
7	512	2.631	384	1.072	256	0.586
8	384	0.812	512	1.058	256	0.786
9	384	1.186	384	1.345	256	1.111
10	384	1.405	512	1.879	384	1.498
11	384	2.406	384	3.673	512	3.829
12	384	5.076	768	6.333	384	5.498
13	768	7.392	384	7.061	384	7.195
14	768	10.650	1024	11.690	384	10.642

Conclusion

- The runtime-based solver SpLLT gives competitive results compared to the hand-tuned HSL code MA87.
- Both OpenMP and StarPU versions offer good performance but we have seen some limitations of the STF model.
- The PTG version also offer good performance and doesn't suffer from the same limitations as the STF code but there is still room for improvement.