

TASK-BASED SPARSE CHOLESKY SOLVER ON TOP OF RUNTIME SYSTEM

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Rutherford Appleton Laboratory
NLAFET Project

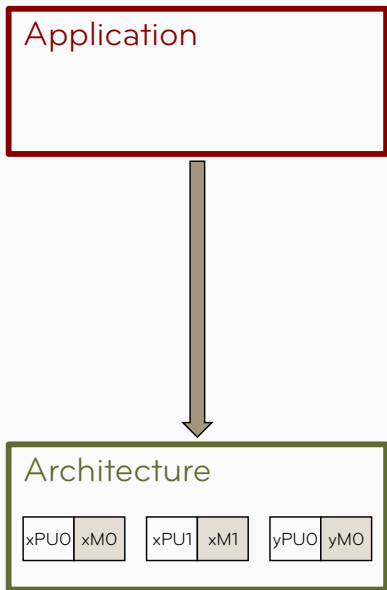
Solve $Ax = b$, where A is **large** and **sparse**, on modern architectures.

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

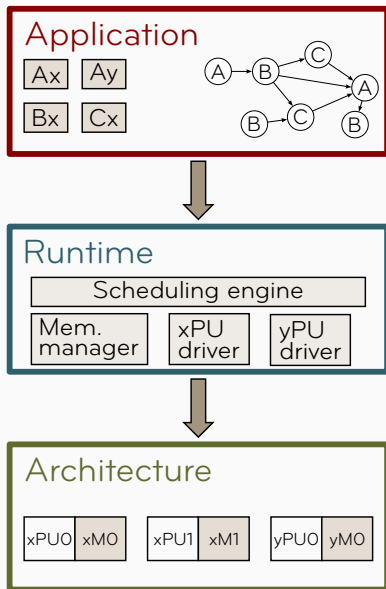
- ▲ Numerically robust and general purpose
- ▼ High memory usage and computational cost

Exploiting modern platforms is challenging:

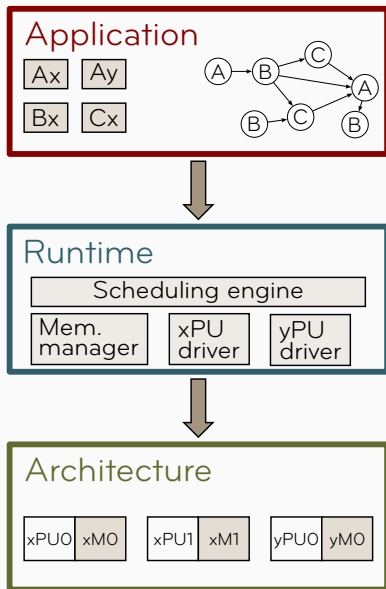
- **Multicore** processors and deep **memory hierarchy**.
- **Heterogeneous** e.g. CPU & GPU or Xeon Phi.
- **Distributed-memory** systems.



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 - requires a big programming effort.
 - is difficult to maintain and update.
 - is prone to (performance) portability issues.



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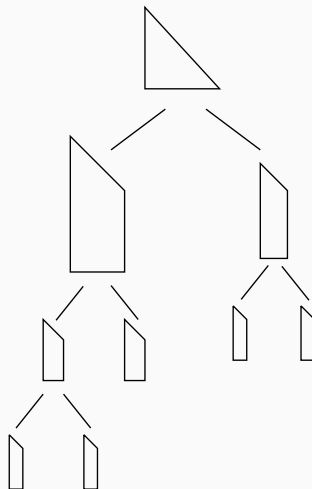
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 - requires a big programming effort.
 - is difficult to maintain and update.
 - is prone to (performance) portability issues.
- runtimes provide an abstraction layer that hides the architecture details.
- the workload is expressed as a DAG of tasks.

SPARSE CHOLESKY FACTORIZATION

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.

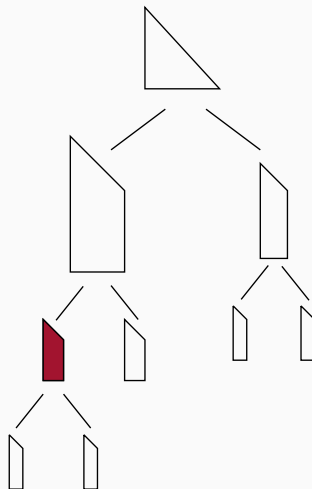


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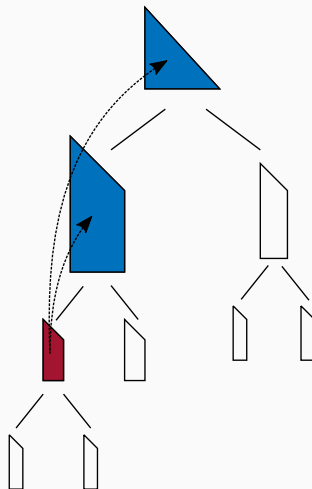


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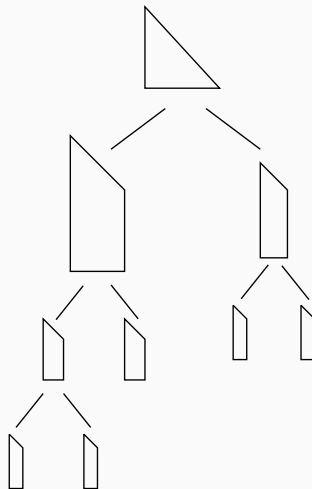
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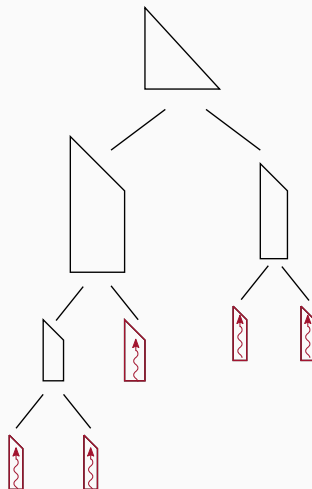


Sources of **parallelism** in the
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Sources of **parallelism** in the elimination tree:

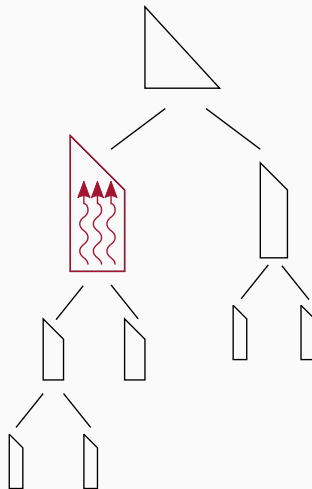
- **Tree parallelism**: Supernode in independent branches can be processed concurrently.



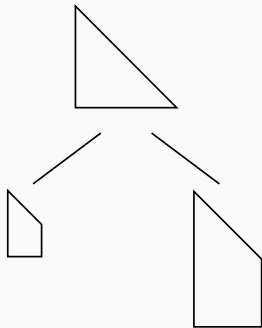
SPARSE CHOLESKY FACTORIZATION: PARALLELISM

Sources of **parallelism** in the elimination tree:

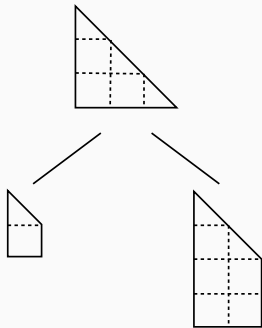
- **Tree parallelism**: Supernode in independent branches can be processed concurrently.
- **Node parallelism**: When a supernode is large enough, it may be processed in parallel.



TASK-BASED SPARSE CHOLESKY FACTORIZATION

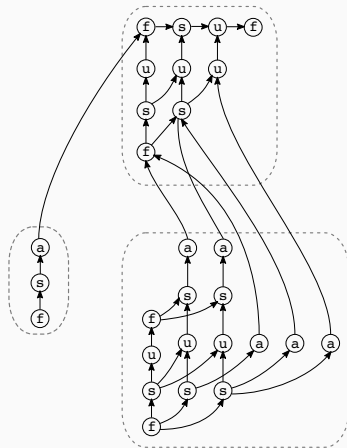
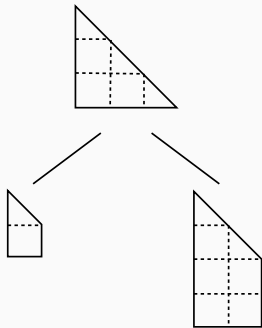


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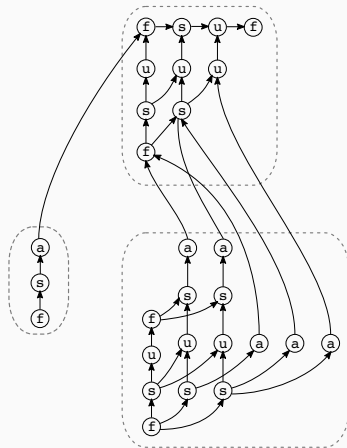
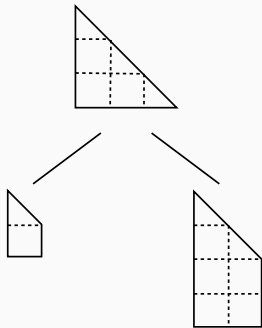
Supernodes are **partitioned** into square **blocks** ($nb \times nb$) on which operations are applied.

TASK-BASED SPARSE CHOLESKY FACTORIZATION



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Implemented in the HSL package [MA87](#).

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
  ! 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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        end do
      end do
    end do

  end do
end do
```

THE STF SPARSE CHOLESKY FACTORIZATION

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

  call submit(init, snode:W) ! initialize 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
call wait_for_all()
```

OpenMP 4.0

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

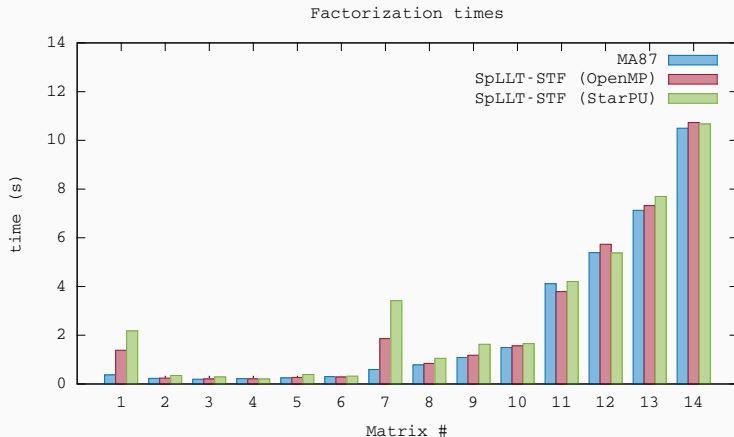
StarPU

- `starpup_insert_task` and data *handle* with access mode (`R`, `W`, `RW`).
- Full control on scheduling 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 dissection ordering.
- Machine: 2 x 14 cores E5-2695 v3 (Haswell) @ 2.30GHz.



- SpLLT and MA87 obtain similar performance most problems.
- In two cases (Matrices #1 and #7) the difference with MA87 is relatively big.

STF MODEL: LIMITATIONS

#	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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- 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.

Parametrized Task Graph (PTG) programming model:

- Uses a **compact representation** of the DAG (problem size independent).
- The dataflow between tasks is **explicitly** encoded (i.e. task dependencies are explicitly given to the runtime system).
- The runtime handles the communications implicitly using the dataflow representation.

PTG vs. **STF**

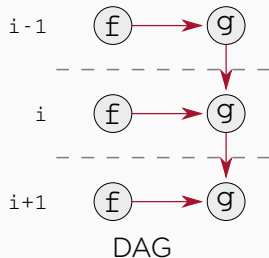
- ▲ In the PTG model, the DAG is **progressively** unrolled during the execution following the execution of tasks in a distributed way.
- ▼ Data-flow programming is much less intuitive than STF programming.

```
for (i = 1; i <= N; i++) {  
    x[i] = f(x[i]);  
    if (i > 1)  
        y[i] = g(x[i], y[i-1]);  
}
```

Simple sequential code

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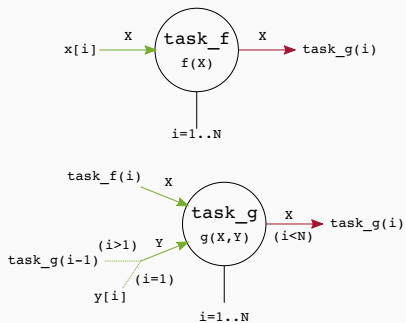
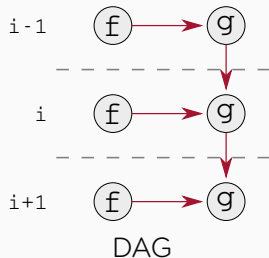


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3	256	0.205	256	0.286	256	0.194
4	256	0.203	384	0.284	256	0.213
5	256	0.247	256	0.327	256	0.259
6	256	0.267	256	0.368	256	0.257
7	512	2.631	384	1.072	256	0.586
8	384	0.812	512	1.058	256	0.786
9	384	1.186	384	1.345	256	1.111
10	384	1.405	512	1.879	384	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

- Competitive performance compared to MA87 and OpenMP/StarPU codes.
- Better performance on matrices # 1 and # 7 compared to STF-based implementations but still not as good as MA87.

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- 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 still not as efficient as MA87 in some cases.

- Run on **distributed-memory** systems: require to provide a data distribution to the runtime system.
- Run on **GPU** and **Xeon Phi** devices.
- Handle **indefinite** systems using pivoting techniques.