Task-Oriented Programming: Task-Graph Enhancements and Validation

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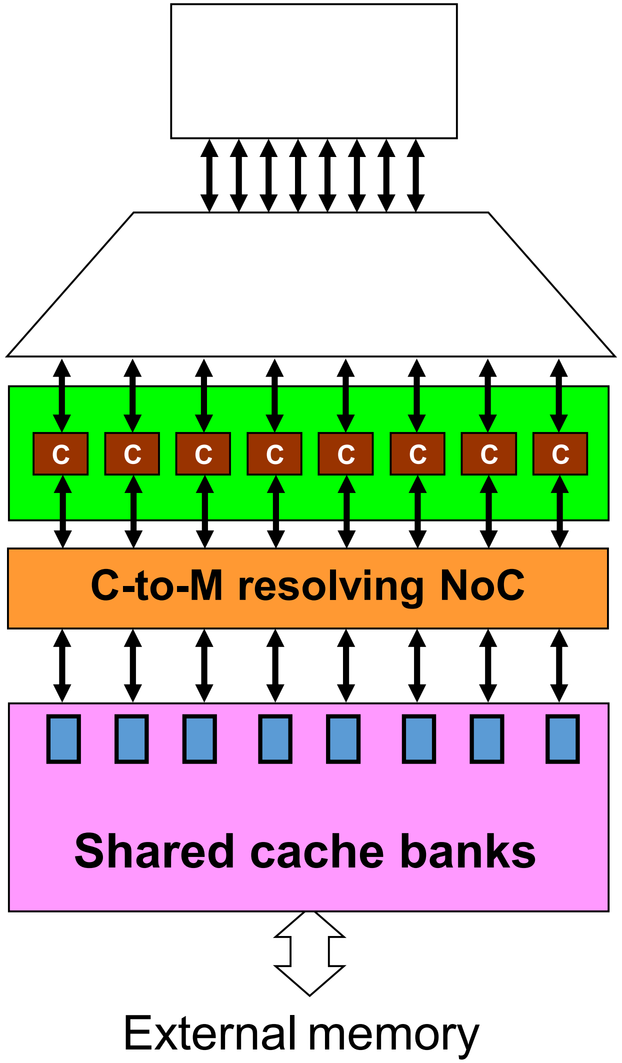
The Hypercore Architecture

Nimrod Bayer + Ran Ginosar; later Plurality Ltd.; now adopted and adapted by Ramon Chips and incorporated in the RC-64 satellite-born accelerator.

HyperCore: Memory Architecture



NO PRIVATE MEMORY

⇒

Any core is equally effective on any task

⇒ Dramatically simpler programming

Numerous memory banks and "anti-local" address-to-bank mapping

Low-latency (~1 cycle each way), high-bandwidth combinational NOC

⇒

No memory communication bottleneck

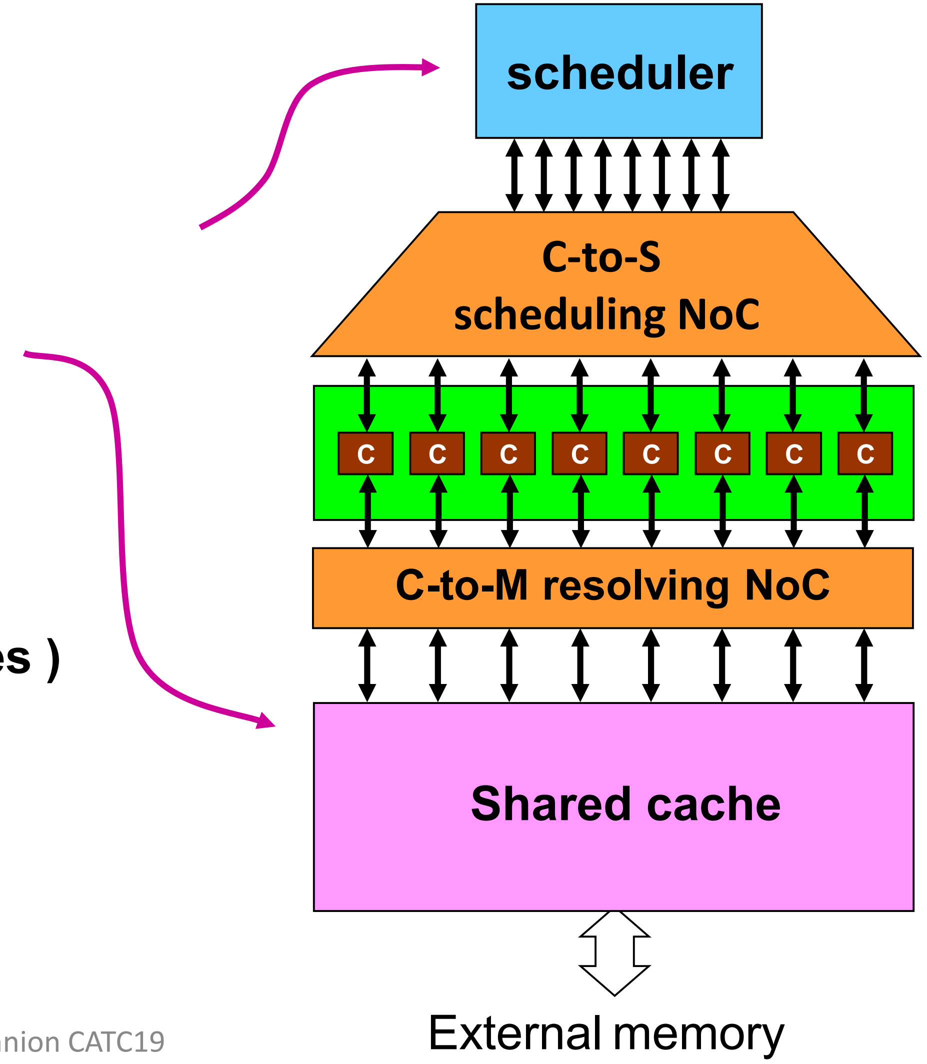
Resembles a PRAM machine

Programming Model: Task-Oriented Programming

- Programmer or tool identify possible parallelism
- Compile into
  - task-dependency graph
  - task codes
- Task graph loaded into scheduler
- Tasks loaded into memory

Task template:

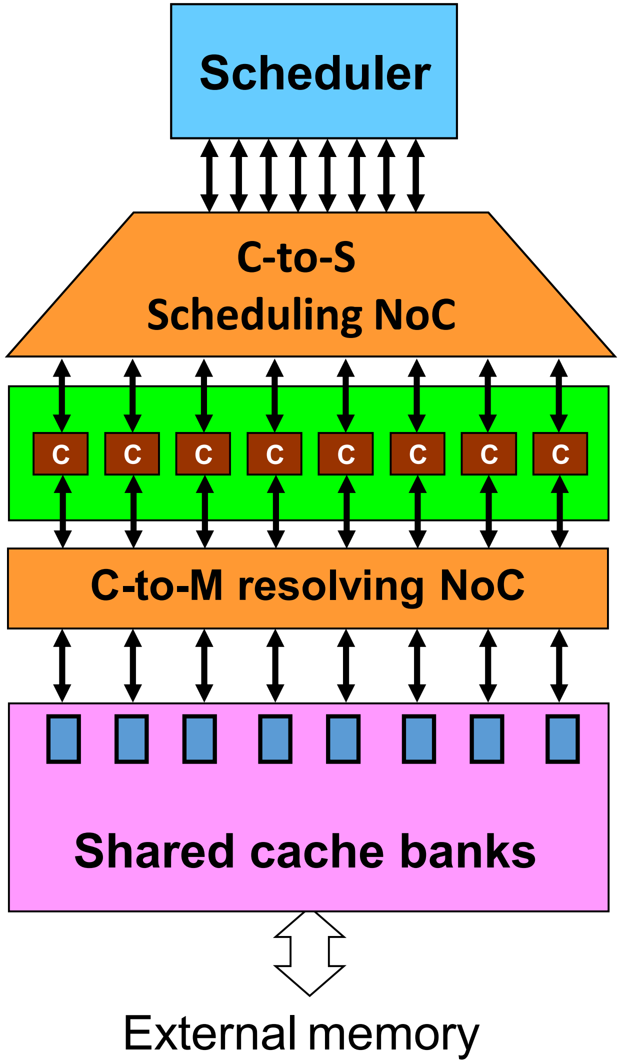
```
⎧ Regular       ⎫
⎨ Duplicable    ⎬ task xxx( dependencies )
⎩ Dummy (F/J)   ⎭
{
        … INSTANCE ….
        …..
}
```



Task Types

- Regular task:
  - A single piece of sequential code
  - Can return True/False to scheduler
  - Execution of a dependent task may be conditioned upon the return value
- Duplicable task:
  - Multiple instances of same code running on different data (fixed stride)
  - Any subset may be executed concurrently
  - No return flag (other than completion)
  - Handled as a single vertex in the task graph
    (any number of instances may be dispatched simultaneously; task completed when all are done)
- Dummy task (Fork/Join):
  - No core allocated
  - Used to represent more complex dependencies.

HyperCore: Task Scheduling



Low latency parallel scheduling (task dispatching)

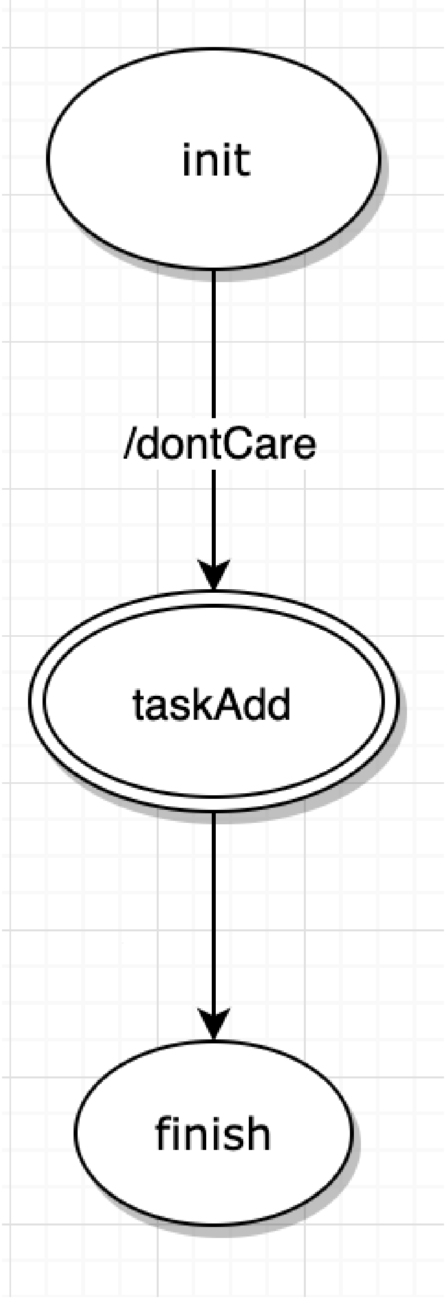
Multiple instances of a duplicable task may be run concurrently and can be dispatched simultaneously.

⇒ **Enables efficient exploitation of fine grain parallelism that is often readily available but cannot be exploited due to prohibitive data movement and/or task dispatching overhead!**

Program Example – Adding Two Vectors

- SET_QUOTA is a runtime function that sets the number of instances to run
- INSTANCE_NUMBER will get the values [0…length-1]

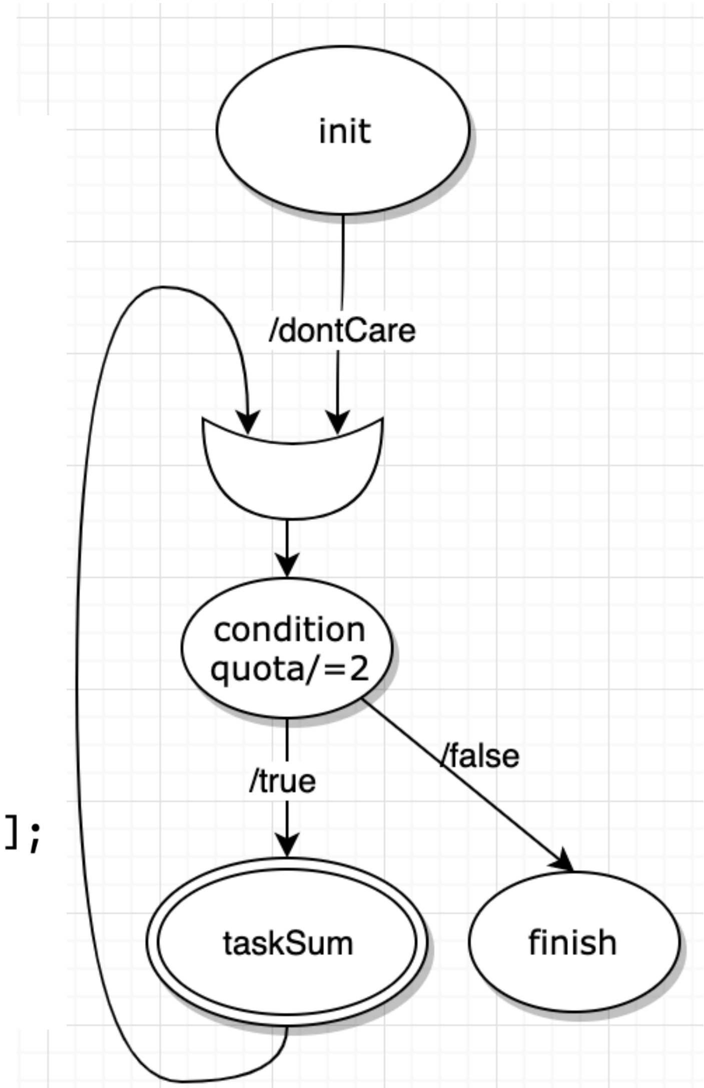
```
Task code
void init(void){
    SET_QUOTA(taskAdd,length);
}
void taskAdd(void){
    int id=INSTANCE_NUMBER;
    c[id]=a[id]+b[id];
}
void finish(void){
}
```



Example: Reduce (Task-Oriented)

- Sum of a vector
- Multiple calls to SET_QUOTA are allowed, the last value before triggering the task is relevant

```
void init(void){
}
void condition(void){
    if(length<=1){
        return false;
    }
    length/=2;
    SET_QUOTA(taskSum,length);
    return true;
}
void taskSum(void){
    int id=INSTANCE_NUMBER;
    arr[id] = arr[id] + arr[id + length];
}
void finish(void){
}
```

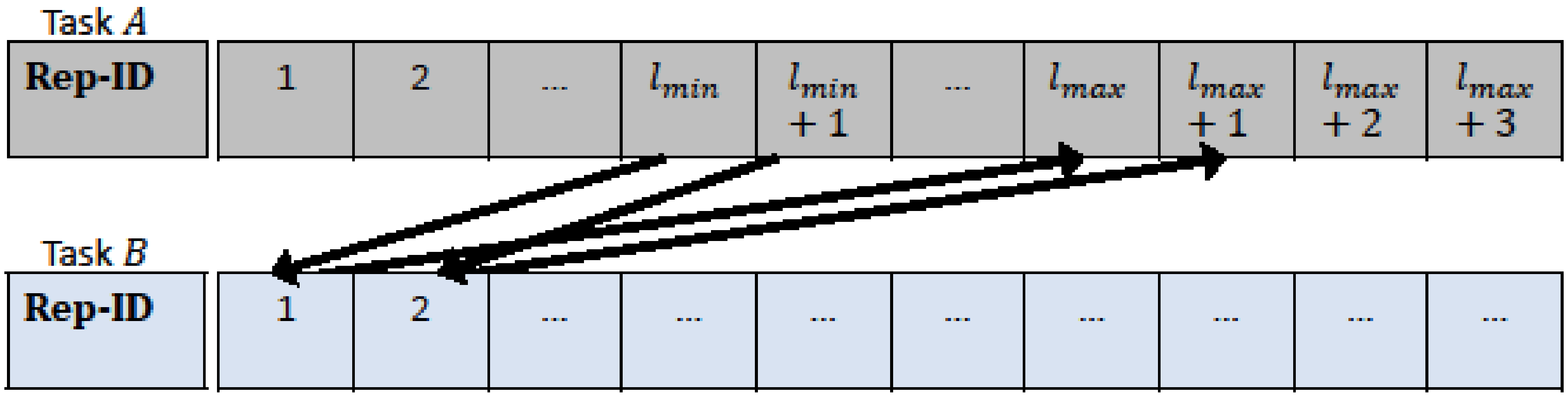


Architecture Benefits

- Any core can do any task equally well on short notice
  - scales automatically (code is agnostic to number of cores)
  - easy accommodation of core failure
- Many-bank shared cache + fast C-to-M NoC
  - low latency
  - No cache coherence issues
  - No communication bottleneck accessing shared memory
- Fast scheduling of tasks to free cores (many at once)
  - enables efficient exploitation of fine grain data parallelism
  - impossible in other architectures due to:
    - task scheduling overhead
    - data locality
- Programming model:
  - intuitive to programmers
  - easy for automatic parallelizing compiler

Shortcomings

- Limited precedence constraints, especially among duplicable tasks
  - Reason: “all or none” → serialization among such tasks
    → cache inefficiency when they share data and the cache cannot hold all of it
  - Solution: permit staggered lockstep with some slack



- **Programming model exposure: accidental omission of edges in the ask graph leads to unpredictable execution results.**

Our Goals:

- Ensure program correctness (verification that there are no data races among tasks that may execute concurrently)
  - No false approvals, but a low false rejection rate is permissible

- Aspirations:
  - Correctness + low false alarm rate without overly restricting the programmer
  - Support the extended precedence relationships among duplicable tasks
  - Scalability to a very large number of tasks.

Data Race Criterion

- A data race between two tasks exists iff both touch the same memory address, and at least one of them writes to it.
  W-W W-R R-W R-R

- Given the memory footprints of two tasks, the computational complexity of testing is O(M), where M is the size of the footprint.

Main Components

- **Given the task graph, determine concurrently-runnable tasks**
- Determine task footprints
  - Program code analysis (source code or at any compilation stage)
  - Run task and record footprint
- **Compare footprints of concurrently runnable tasks to check for data races**

Determining Memory Footprints

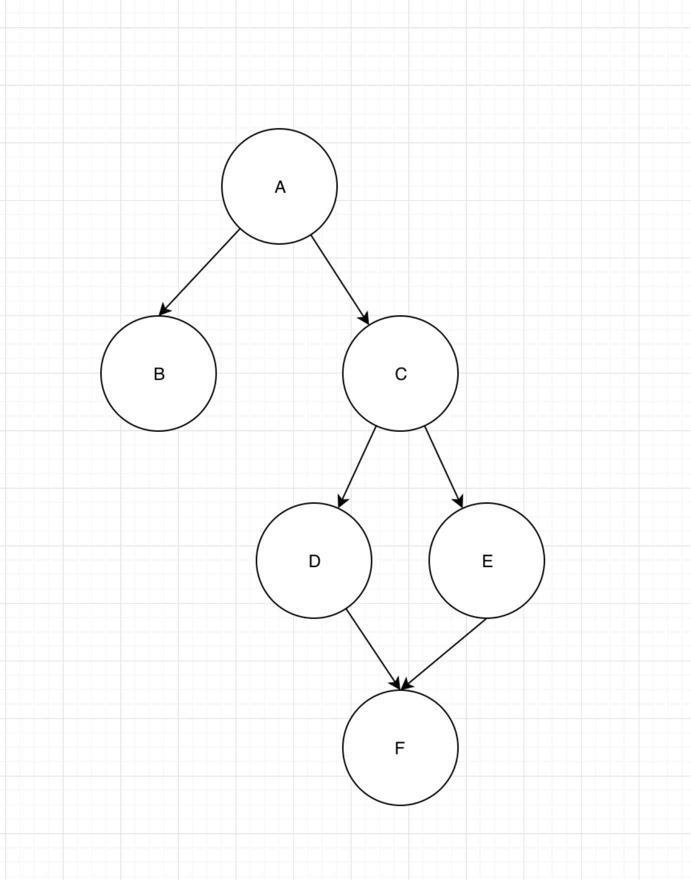
- Two approaches:
  - Examination of the code
    - Offline code examination, but
    - May limit programming flexibility (use of pointers, etc.) due to address ambiguity
  - Run the tasks and compare the actual (data) memory footprints of concurrently runnable tasks
    - Requires code instrumentation or some other mechanism
    - Insensitive to addressing mode
    - Limitation: true only for specific run.
  - Also: combining the two

- Observation: determining that two tasks access the same address does not necessarily require knowing the actual address
  (E.g., a shared variable with same name)

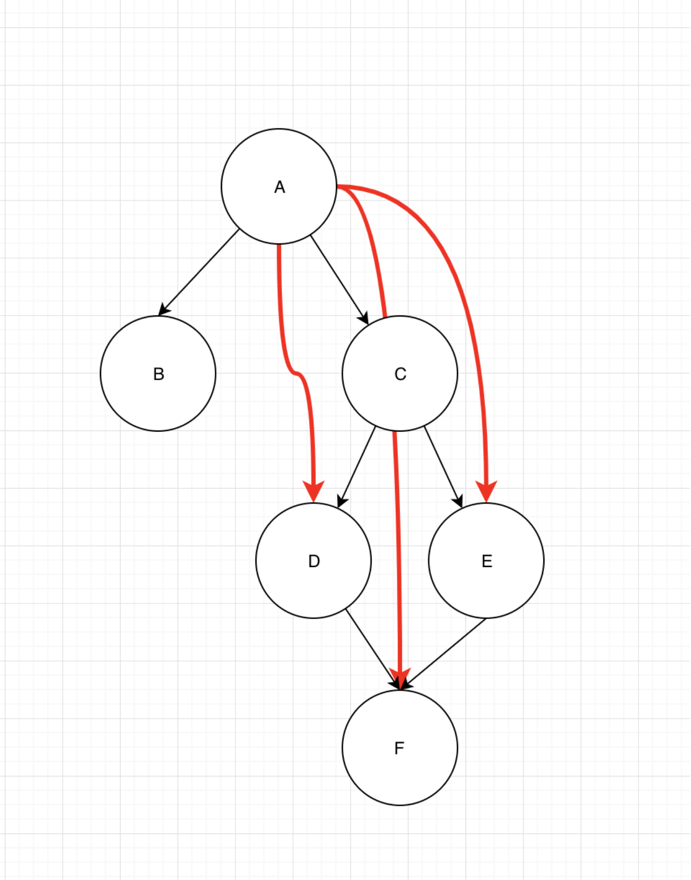
Determining Concurrently Runnable Tasks

- Given: task graph G(T,D) (a directed graph)
  - T: tasks
  - D: dependences
- Derive G_{TC}(T,D), the transitive closure of G.
- Derive the ***Independence Graph*** G_{Ind}=G_{TC}(T,D’):
  there is an edge between two tasks iff they are runnable concurrently

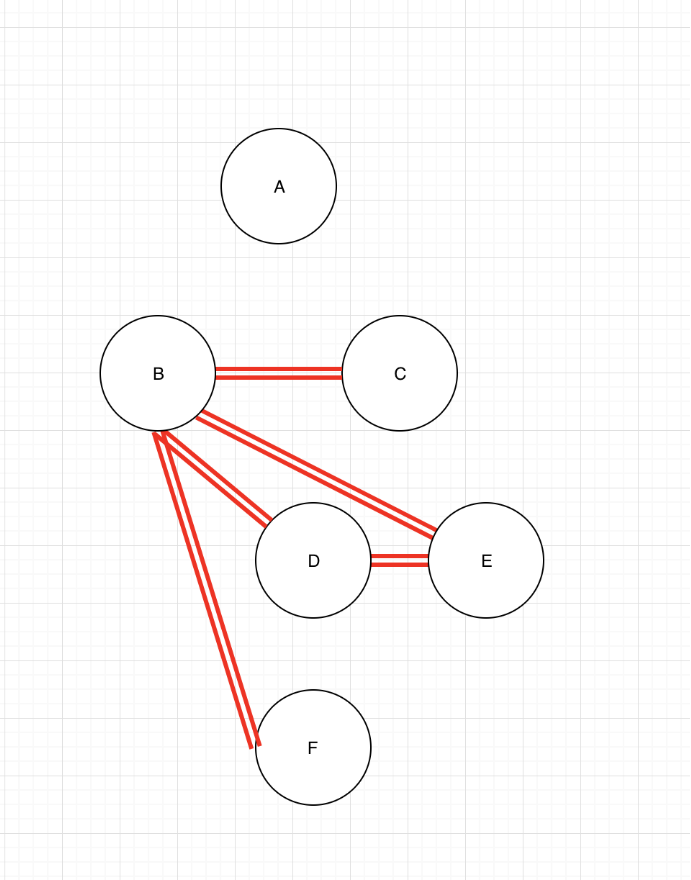
Example: Constructing the Independence Graph



G - Dependency Graph



G_{TC} - Transitive Closure



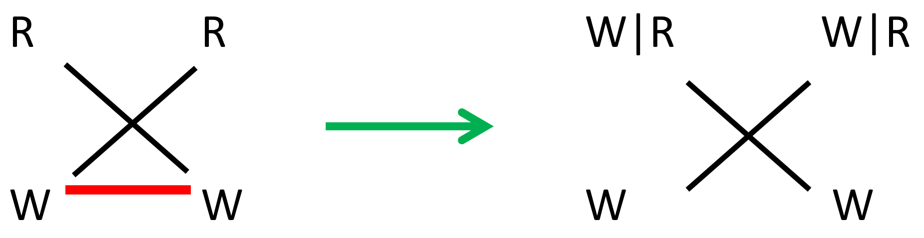
G_{ind} - Independence Graph

Checking for Races (Given the Memory Footprints)

- Requirement: for any two tasks A and B s.t. $(A,B) \in D'$, check for a race
- If done in a straightforward manner, $O(T^2 \cdot M)$

Useful Observations

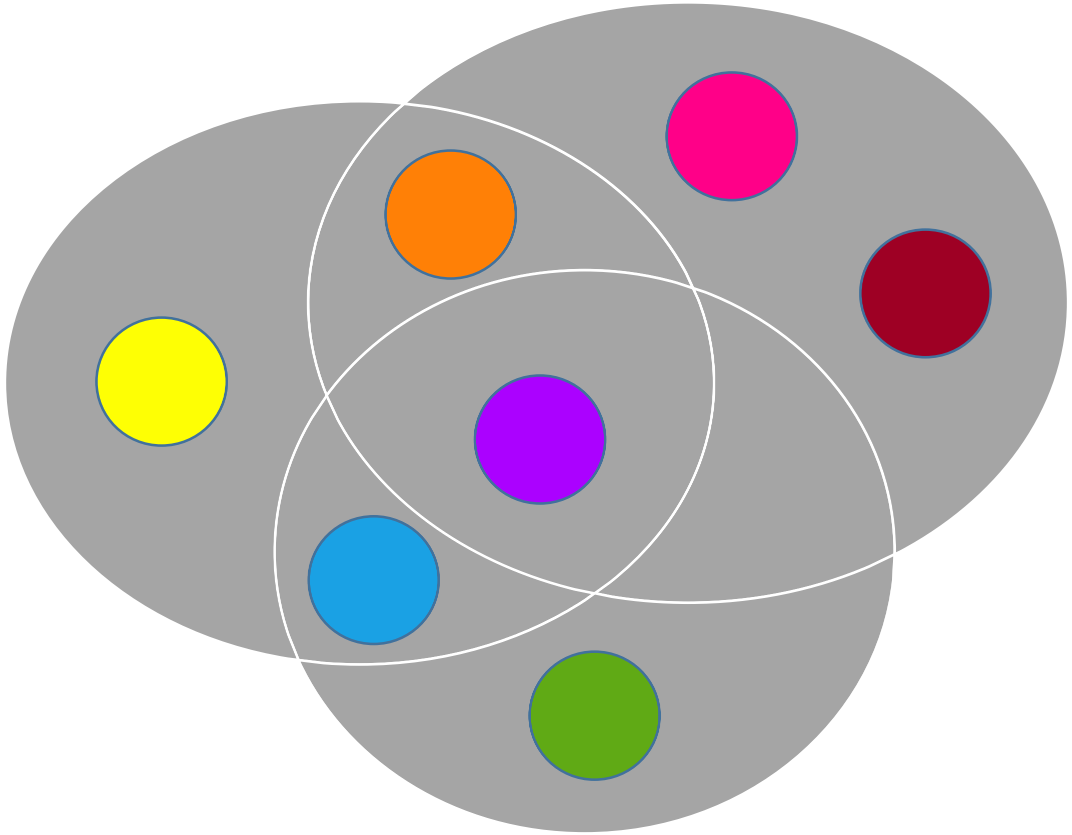
- Determining that two tasks access the same address does not necessarily require knowing the actual address
- If there is a race between tasks A and task B, there is also a race between A and the union of (memory footprints) of B and any other tasks.
- If there is a race between the union of one subset of tasks and that of another subset, then there is a race between at least one member of the first and at least one member of the other
- For a set of *n* concurrently runnable tasks (a clique in G_{Ind}), can check in $O(n \cdot M)$
- If we keep a W footprint and a W|R footprint, then 2 tests suffice instead of 3.

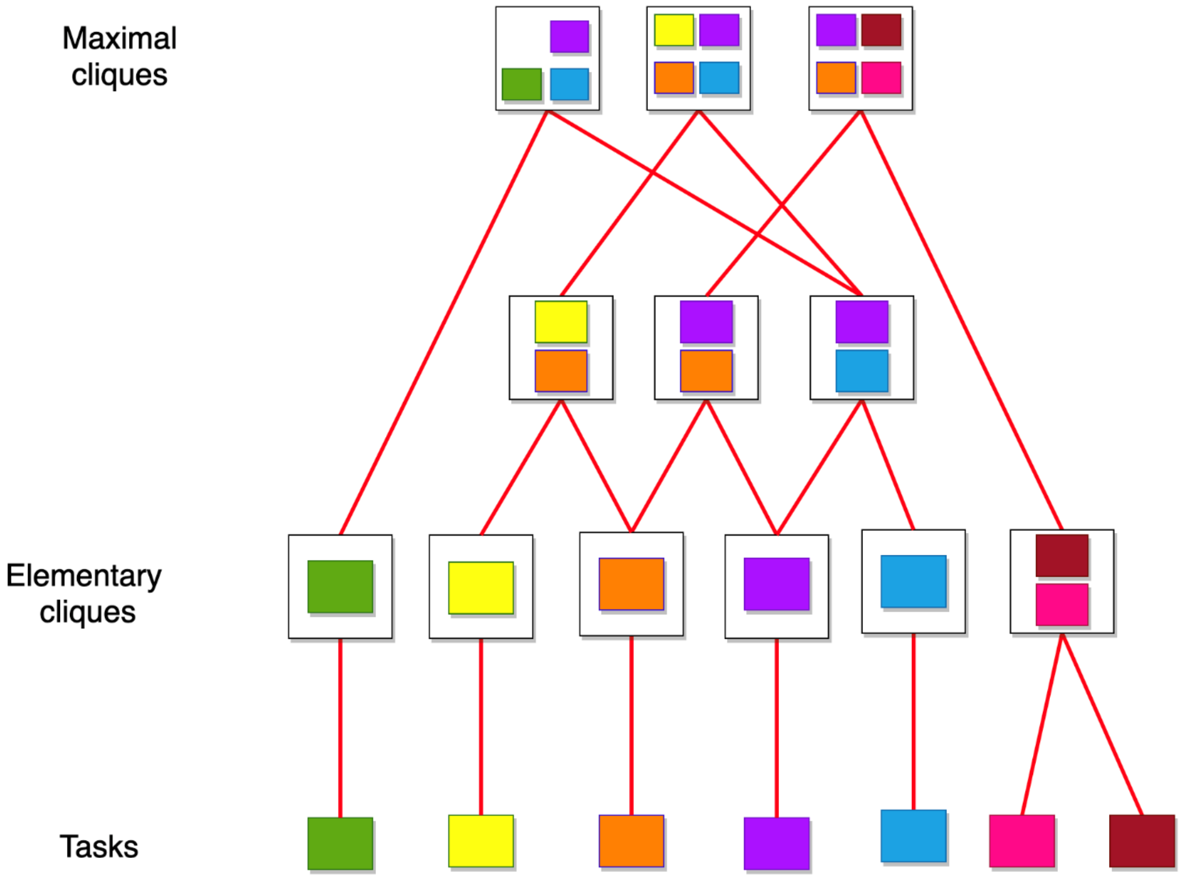


Using Cliques in the Independence Graph

- Find all maximal cliques (maximal subsets of concurrently-runnable tasks)
- Derive all intersections of maximal cliques.
- Partition the result into elementary cliques (cliques whose member tasks all belong to the same subset of maximal cliques).
- For Each elementary clique, carry out the test among the member tasks:
  - Iteratively scan the tasks, checking each tasks against the cumulative union of the footprints
  - Keep the cumulative footprint for future use
- For each non-elementary clique, carry out the test among its member elementary cliques, similarly storing cumulative footprints along the way.
- Proceed until all cliques have been covered.

Example: Clique-Based Race Detection





Complexity of Footprint Comparisons(Crude approximation)

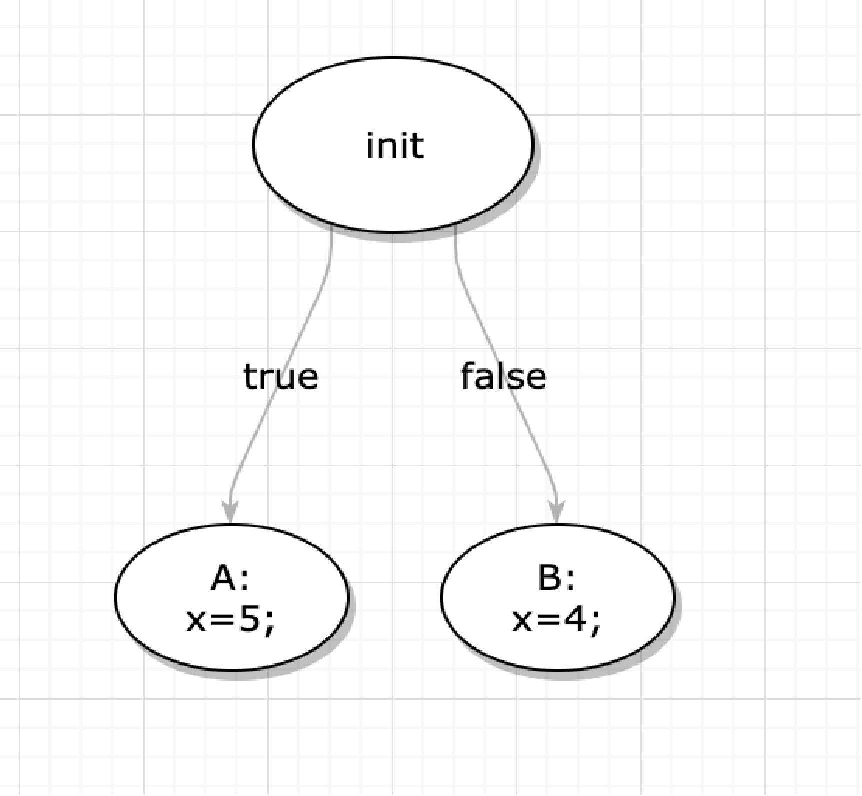
- E - Number of elementary cliques
- R - ~ mean number of maximal cliques including any given elementary clique. ("Reuse factor")
- M - ~ Memory footprint (approximation: that of a union of tasks equals that of a single task)
- T - Number of tasks

	Straightforward	Direct Maximal Cliques	Incremental
Computational	$M \cdot T^2$	$M \cdot T \cdot R$	$M \cdot (T+E \cdot R)$
Memory	$M \cdot T$	$M \cdot T$	$M \cdot (Max(T, E+))$
Time	logM	logM·(Height of clique tree)	logM·(Height of clique tree)

Finding the Source of a Detected Race

- Find the smallest colliding cliques
- Use group testing for further partitioning.

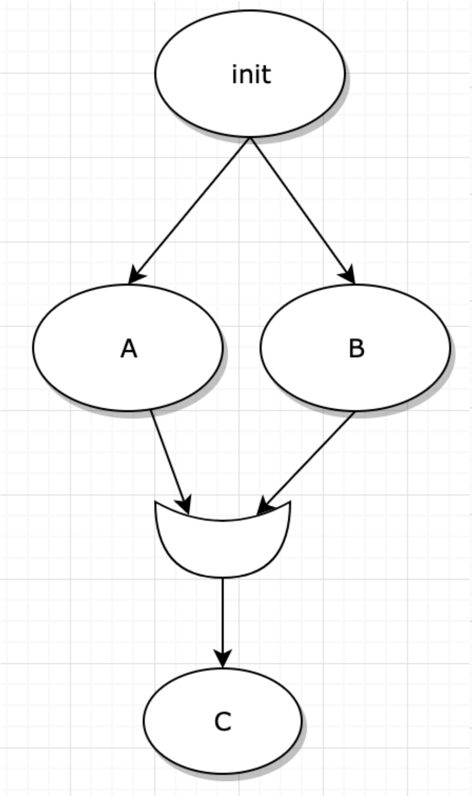
Complication: Mutex Among Tasks

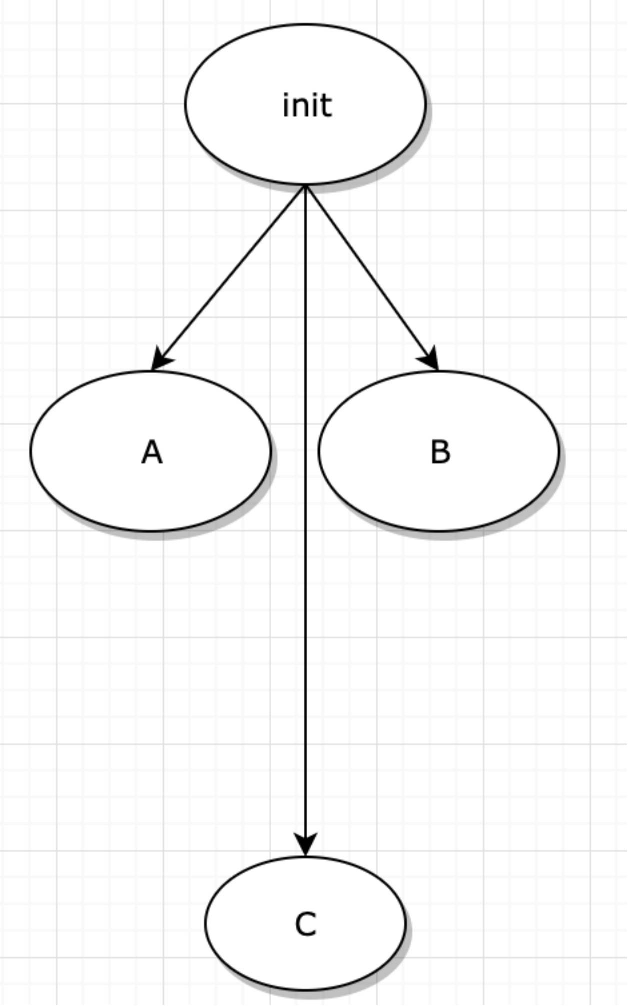


- Tasks conditioned upon the return value of their predecessor:
- All possible memory accesses inside a task are treated as if they actually occurred
- If we do not take into account the mutex between A an we may get a false race detection
- Solution: in T_{TC}
  - Insert an edge between the mutex tasks
  - Insert an edge between each node in the subtree below A and every node in the subtree below B → no edges between mutually exclusive tasks in G_{ind} → will not check for races → no false race detection.

Complication: OR dependency

- Edge between A and C in the task map doesn't apply they cannot run concurrently
- For example, A and B start running, B finishes before A.
- When B has finished task C become runnable, and start running.
- Tasks A and C are now running concurrently.
- Solution: remove edges crossing OR junction
- Lowering the false positives rate: add dependency between C and the Most recent common ancestor of A and B





Intra-Task Complications

- Example:

```
Task A:
If(cond){
      X=5;
}else{
      y=5;
}
```

```
Task B:
If(!cond){
      X=4;
}else{
      y=4;
}
```

- No mutex between tasks, but mutex between writes to the same address.
- Again, ignoring the control path may result in a false race detection
- Approaches:
  - deeper analysis from the outset or
  - detailed exploration upon detection
- No false race detection if using actual program traces.

Conclusions

- An interesting problem with a real motivation
- We have a path to detecting and locating races
- Work required on program memory-access analysis

- Will be happy to hear ideas on:
  - program analysis
  - tips on using the Clang static analyzer
  - optimal clique combining

Thank You