Kronecker Algebra for Static Analysis of Barriers in Ada

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Outline

1. Preliminaries and Modelling

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- matrices out of $\mathcal{M} = \{M = (m_{i,j}) \,|\, m_{i,j} \in \mathcal{L}\}$ only.

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  - set of nodes V,
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  - so-called *entry* node $n_e \in V$
- sets V and E constructed out of the elements of $\langle \mathcal{T}, \mathcal{S}, \mathcal{L} \rangle$.

Kronecker Product

Given an m-by-n matrix A and a p-by-q matrix B, their *Kronecker product* $A \otimes B$ is an mp-by-nq block matrix defined by

$$A \otimes B = \begin{pmatrix} a_{1,1} \cdot B & \cdots & a_{1,n} \cdot B \\ \vdots & \ddots & \vdots \\ a_{m,1} \cdot B & \cdots & a_{m,n} \cdot B \end{pmatrix}.$$

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Given two automata, the Kronecker product synchronously executes them (lock-step).

Kronecker Sum

Given a matrix A of order m and a matrix B of order n, their *Kronecker sum* $A \oplus B$ is a matrix of order mn defined by

$$A \oplus B = A \otimes I_n + I_m \otimes B$$

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- Kronecker sum calculates all possible interleavings of two concurrently executing automata
- even if the automata contain conditionals and loops.

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Given an m-by-n matrix A and a p-by-q matrix B, we call $A \oslash_L B$ their selective Kronecker product. For all $l \in L \subseteq \mathcal{L}$ let
$A \oslash_L B = (a_{i,j}) \oslash_L (b_{r,s}) = (c_{t,u})$, where

$$c_{(i-1)\cdot p+r,(j-1)\cdot q+s} = \begin{cases} l & \text{if } a_{i,j} = b_{r,s} = l,\ l \in L, \\ 0 & \text{otherwise.} \end{cases}$$

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Selective Kronecker product ensures that, e.g., a semaphore p-call in the left operand is paired with the p-operation in the right operand and not with any other operation in the right operand. In practice, we usually constrain $L \subseteq \mathcal{L}_S$.

Filtered Matrix

We call M_L a *filtered matrix* and define it as a matrix of order $o(M)$ containing entries of $L \subseteq \mathcal{L}$ of $M = (m_{i,j})$ and zeros elsewhere:

$$M_L = (m_{L;i,j}), \text{ where } m_{L;i,j} = \begin{cases} m_{i,j} & \text{if } m_{i,j} \in L, \\ 0 & \text{otherwise.} \end{cases}$$

System Model

The adjacency matrix representing program $\mathcal{P}$ is referred to as P (= CPG).

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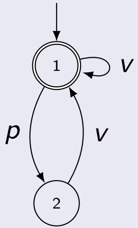
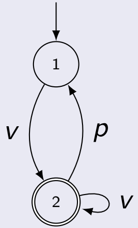
$$P = T \oslash_{\mathcal{L}_\mathrm{S}} S + T_{\mathcal{L}_\mathrm{V}} \otimes I_{o(S)}.$$

Examples



Initially Unlocked Binary Semaphore



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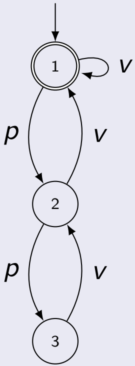
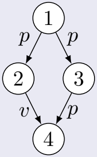


Counting Semaphore

Examples



(a) CFG

$$\begin{pmatrix} 0 & p & p & 0 \\ 0 & 0 & 0 & v \\ 0 & 0 & 0 & p \\ 0 & 0 & 0 & 0 \end{pmatrix} \oslash_{\{p,v\}} \begin{pmatrix} v & p \\ v & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & p & 0 & p & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & v & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & v & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & p \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

(b) Matrices

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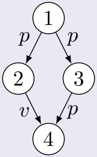

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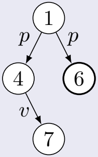

self-deadlock at node 6

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- The number of threads can vary at runtime for *dynamic barriers*.

Barriers in Ada (Annex D)

```
package Ada.Synchronous_Barriers is
    pragma Preelaborate(Synchronous_Barriers);
    subtype Barrier_Limit is Positive range 1 .. implementation-defined;
    type Synchronous_Barrier (Release_Threshold : Barrier_Limit) is limited private;
    procedure Wait_For_Release (The_Barrier : in out Synchronous_Barrier;
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Java has static and dynamic barriers (reusable and non-reuseable)

In this paper: only static barriers

Implementation of Barriers

Reusable Barrier Solution using Semaphores

```
mutex.wait()                 # ps
    count += 1               # i
    if count == n:
        turnstile2.wait()    # pb2, lock the second
        turnstile.signal()   # vb1, unlock the first
    else # empty             # T1.a; T2.e
mutex.signal()               # vs

turnstile.wait()             # pb1, first turnstile
turnstile.signal()           # vb1

# critical point             # T1.b; T2.f

mutex.wait()                 # ps
    count -= 1               # d
    if count == 0:
        turnstile.wait()     # pb1, lock the first
        turnstile2.signal()  # vb2, unlock the second
    else # empty             # T1.c; T2.g
mutex.signal()               # vs

turnstile2.wait()            # pb2, second turnstile
turnstile2.signal()          # vb2
```

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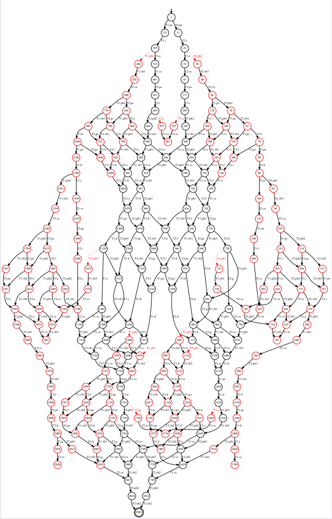

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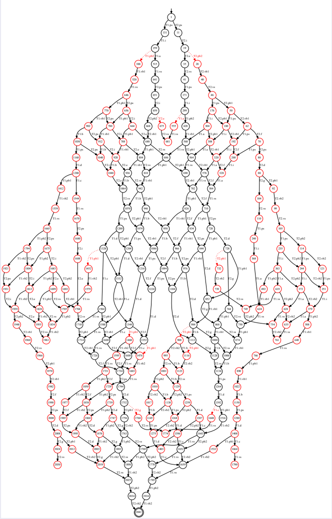

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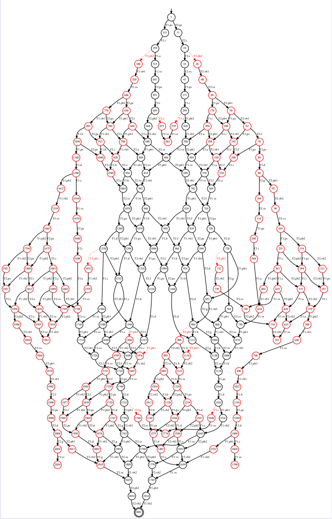

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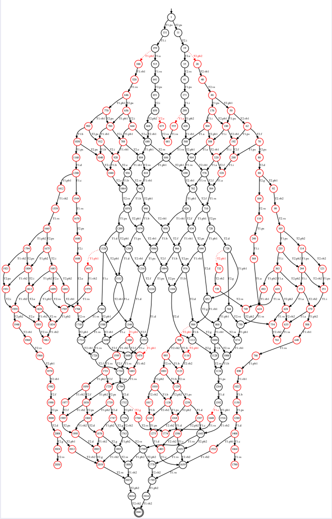

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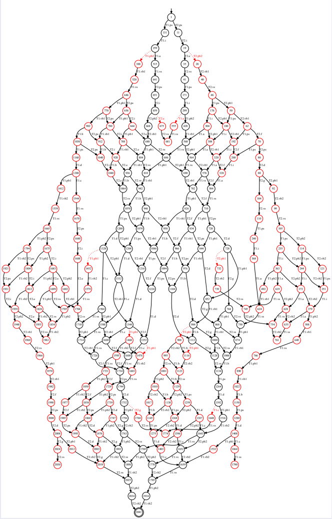

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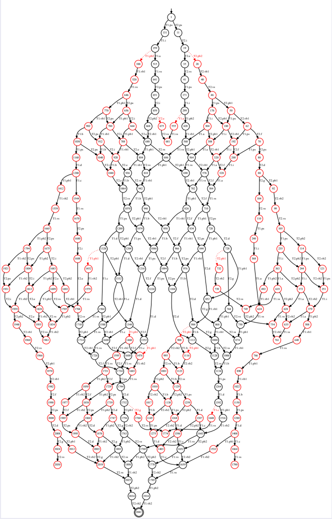

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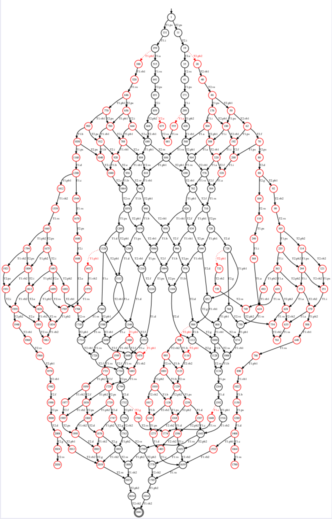

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- All potential deadlock nodes are unreachable.
- Implementation using three semaphores is correct.
- Advanced approaches like symbolic analysis are needed.

Implementation of Barriers

Non-Reusable Barrier Solution using Semaphores

```
# rendezvous

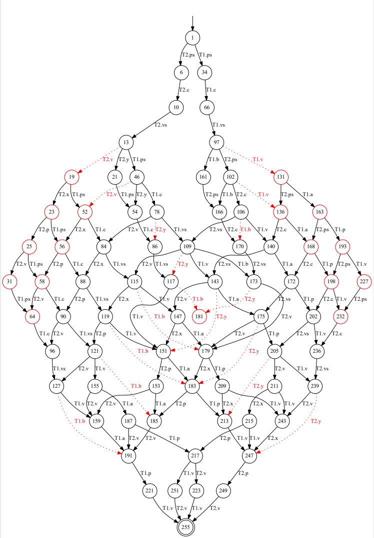
mutex.wait()                       # ps
    count = count + 1              # c
mutex.signal()                     # vs

if count == n: barrier.signal()    # T1.v, T1.a; T2.v, T2.x
else # empty                       # T1.b; T2.y

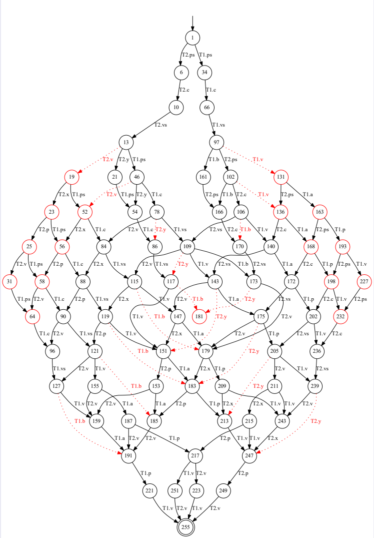
barrier.wait()                     # p
barrier.signal()                   # v

# critical point
```

Non-Reusable Barrier Solution using Semaphores



Non-Reusable Barrier Solution using Semaphores



- Again there are dead paths (the corresponding edges are dotted).

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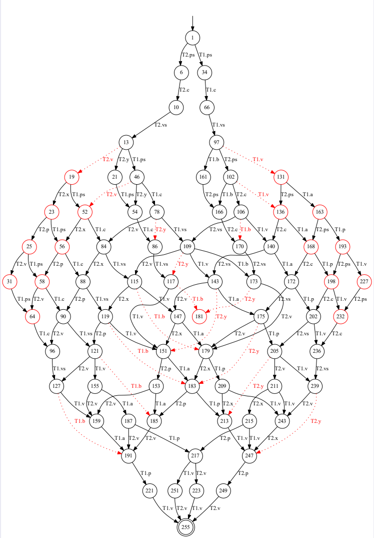
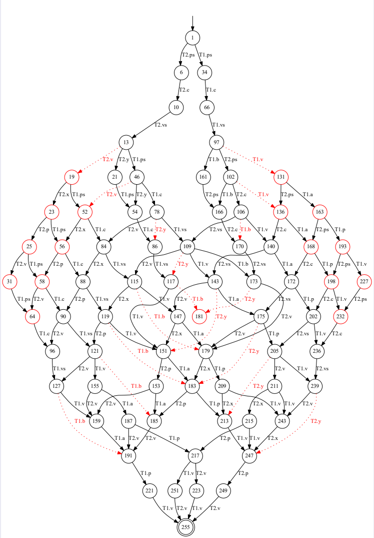


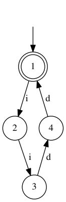
- Again there are dead paths (the corresponding edges are dotted).
- Deadlock node (node 181).

Non-Reusable Barrier Solution using Semaphores

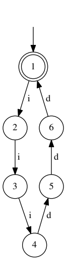


- Again there are dead paths (the corresponding edges are dotted).
- Deadlock node (node 181).
- Paths to node 181 are dead paths.

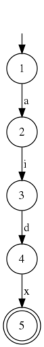
Barrier Synchronization Object



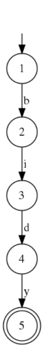
size 2
barrier object



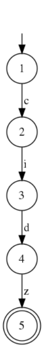
size 3
barrier object



user
thread 1

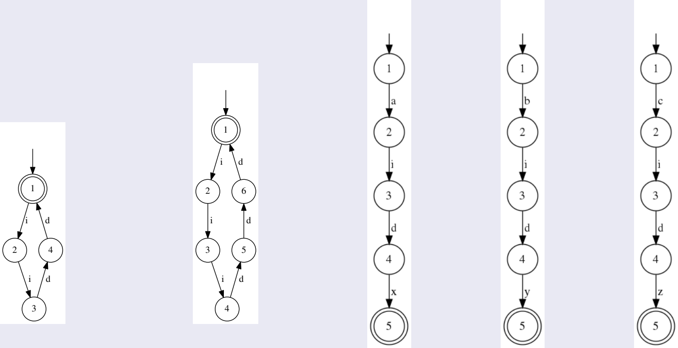


user
thread 2



user
thread 3

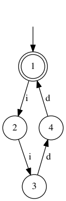
Barrier Synchronization Object



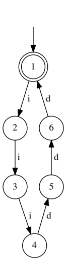
size 2 barrier object | size 3 barrier object | user thread 1 | user thread 2 | user thread 3

- models "semantics of barriers" instead of "implementation"

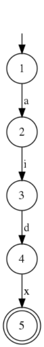
Barrier Synchronization Object



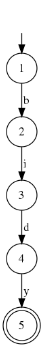
size 2
barrier object



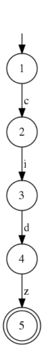
size 3
barrier object



user
thread 1



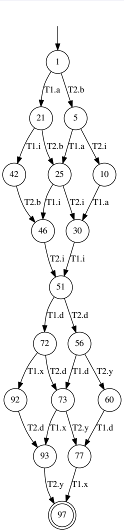
user
thread 2



user
thread 3

- models “semantics of barriers” instead of “implementation”
- cannot verify implementation

Barrier Synchronization Object – Example: Two threads



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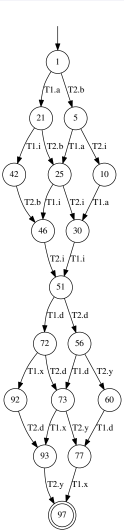

- free of deadlocks

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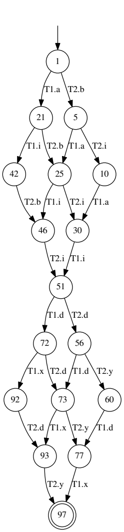
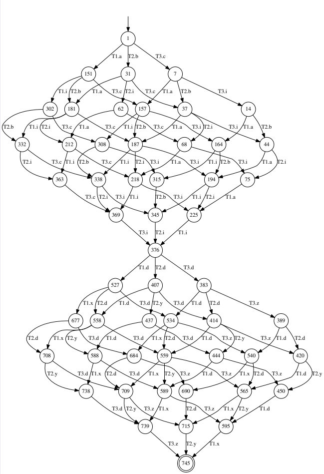


- free of deadlocks
- no need for value sensitive analysis

Barrier Synchronization Object – Example: Three threads



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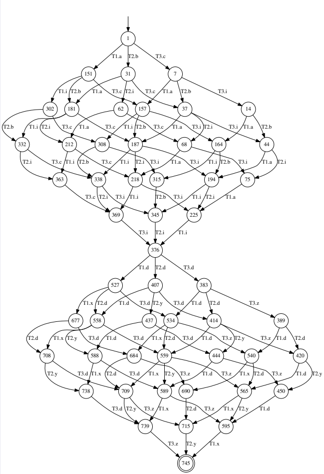

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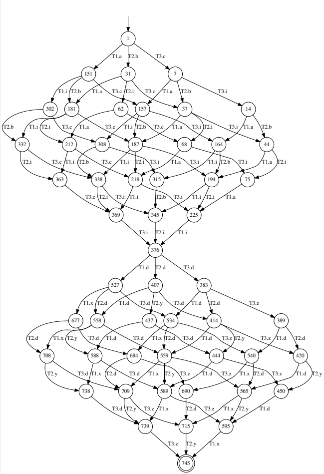

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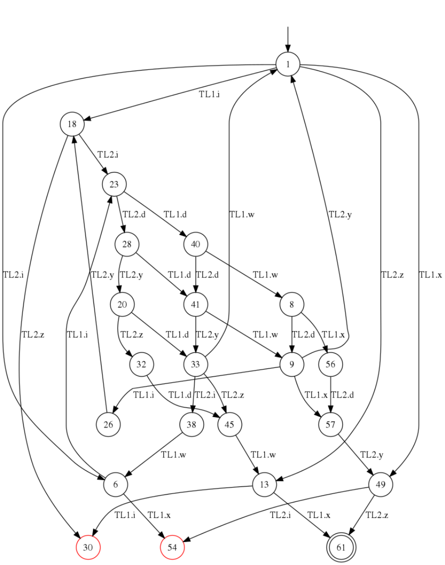
Barrier Synchronization Object – Example with Loops



- Each task contains a loop and a `Wait_For_Release` inside the loop.

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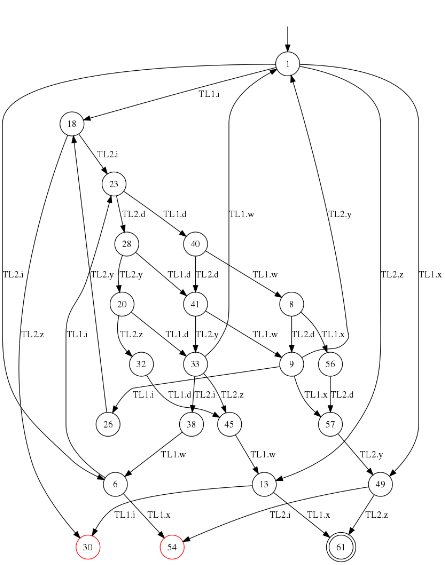

- Each task contains a loop and a `Wait_For_Release` inside the loop.
- If the number of loop iterations is the same in both tasks, the final node 61 is reached; otherwise, the program stalls at nodes 30 or 54.

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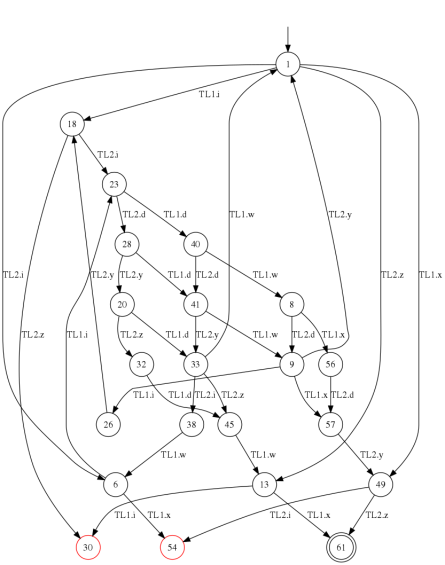

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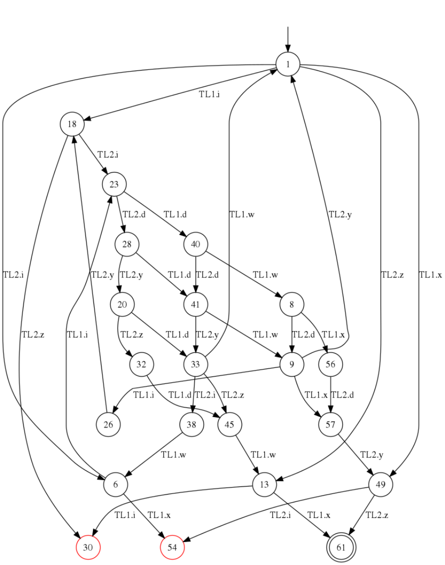

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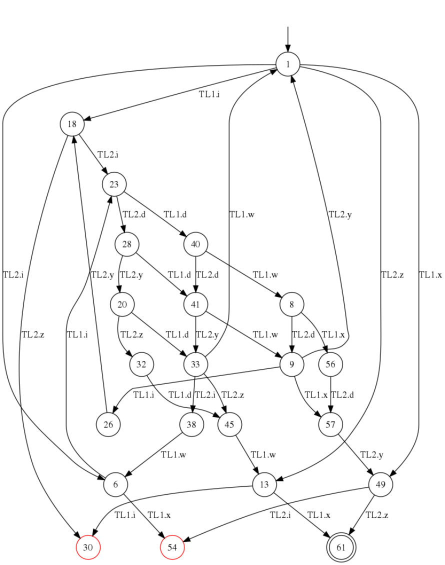

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- The number of loop iterations cannot be calculated by the Kronecker approach.
- For this purpose e.g. some sort of symbolic analysis is needed.
- In the simplest case, only lower and upper bounds of for-loops have to be compared.

Conclusions

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- Compared our novel barrier synchronization primitive with a barrier implementation based on semaphores.
- Implementations using semaphores require advanced techniques to find dead paths.
- Our barrier construct can be analyzed by static analysis only.
- Need advanced techniques for programs containing loops or conditional statements.