形式化方法导引

第 5 章 模型检测

5.1 应用 – 5.1.4 NuSMV

黄文超

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⟶ 教学课程 ⟶ 形式化方法导引

NuSMV (sometimes called simply SMV): A language for

- describing models
- specifying LTL / CTL formulas, etc.
- check the validity of the formulas on the models

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  LTLSPEC
    G(request -> F status=busy)
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NuSMV v.s. C, Java...

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  - main
- Differences
  - state transition
  - specification
  - non-deterministic
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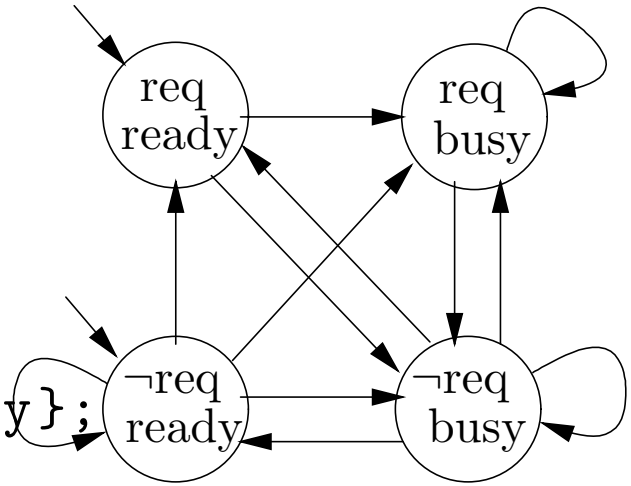

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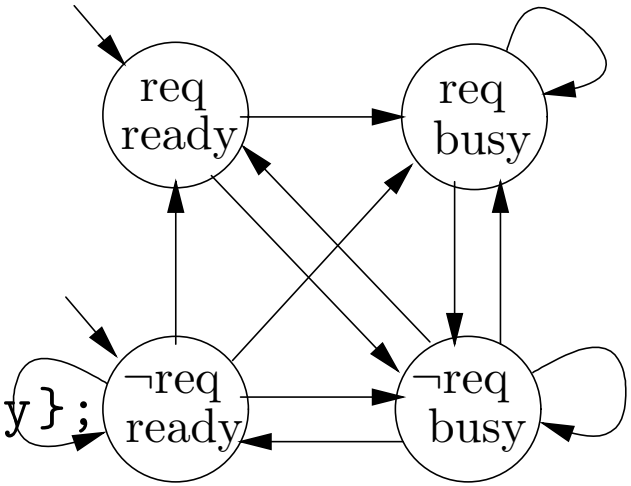

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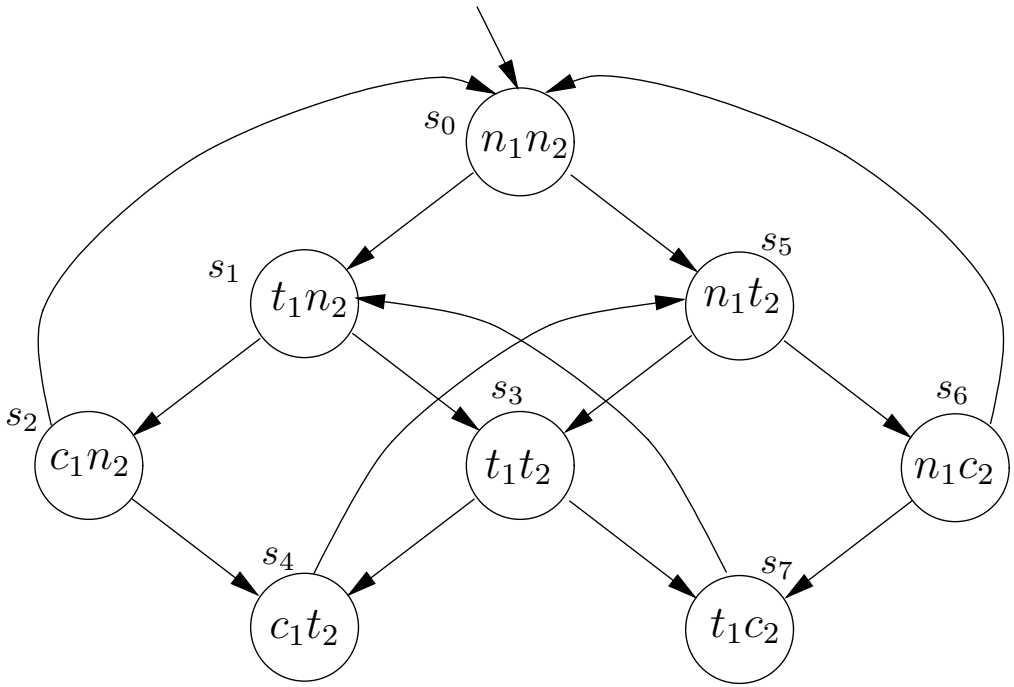

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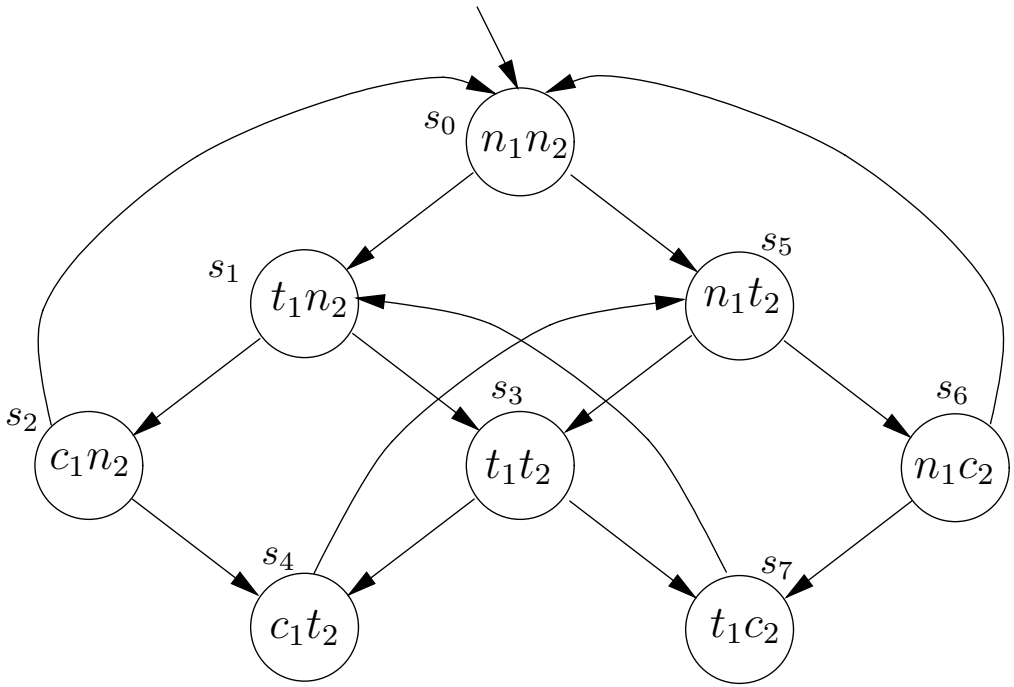

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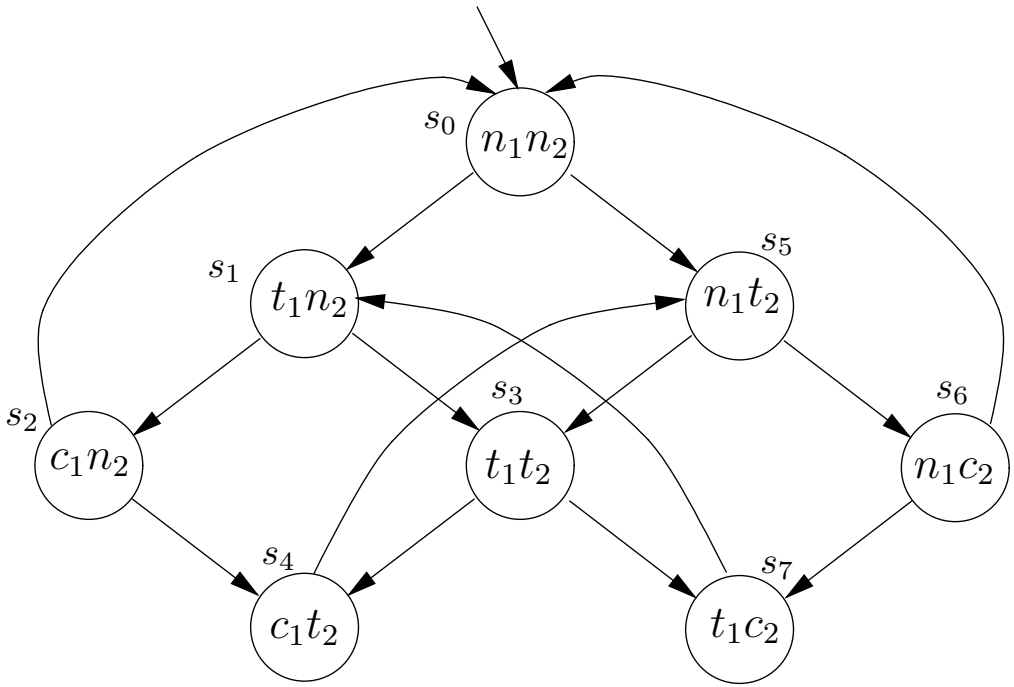

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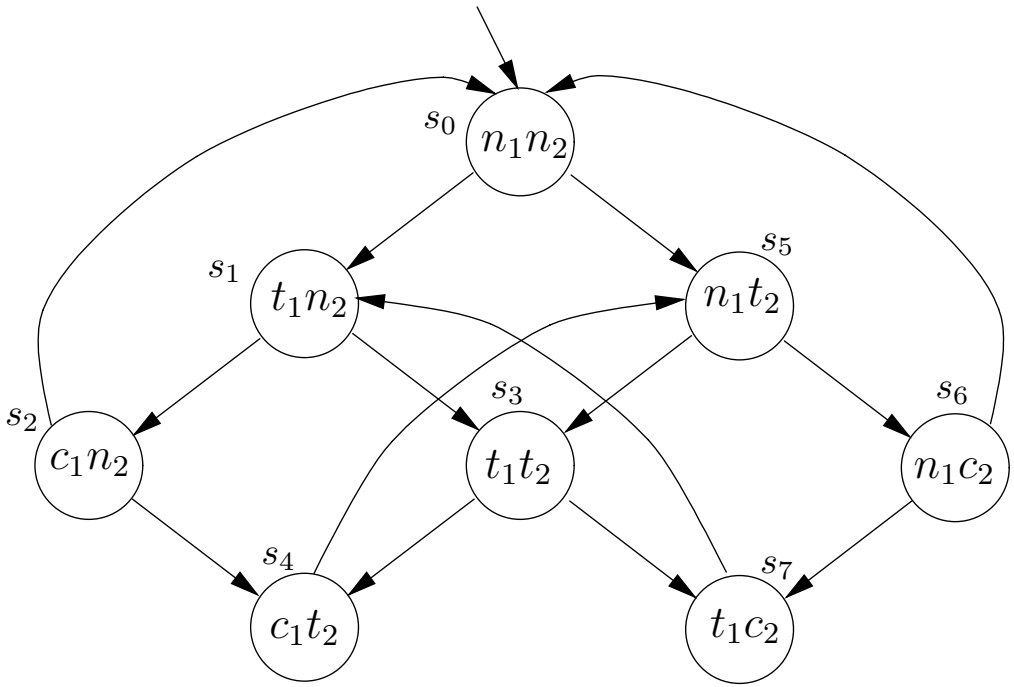

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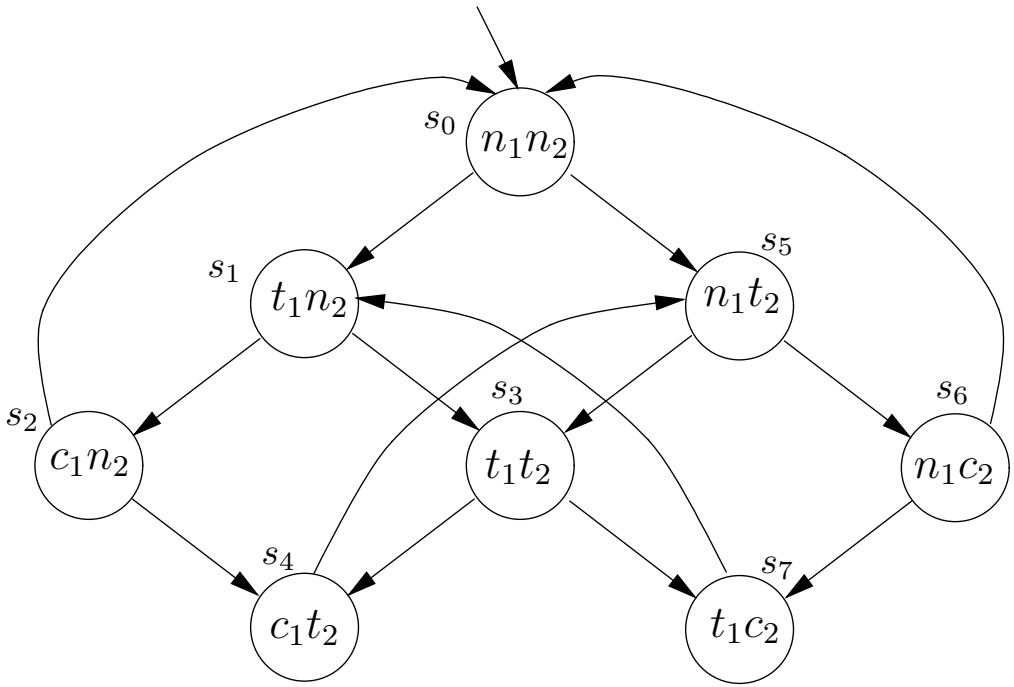

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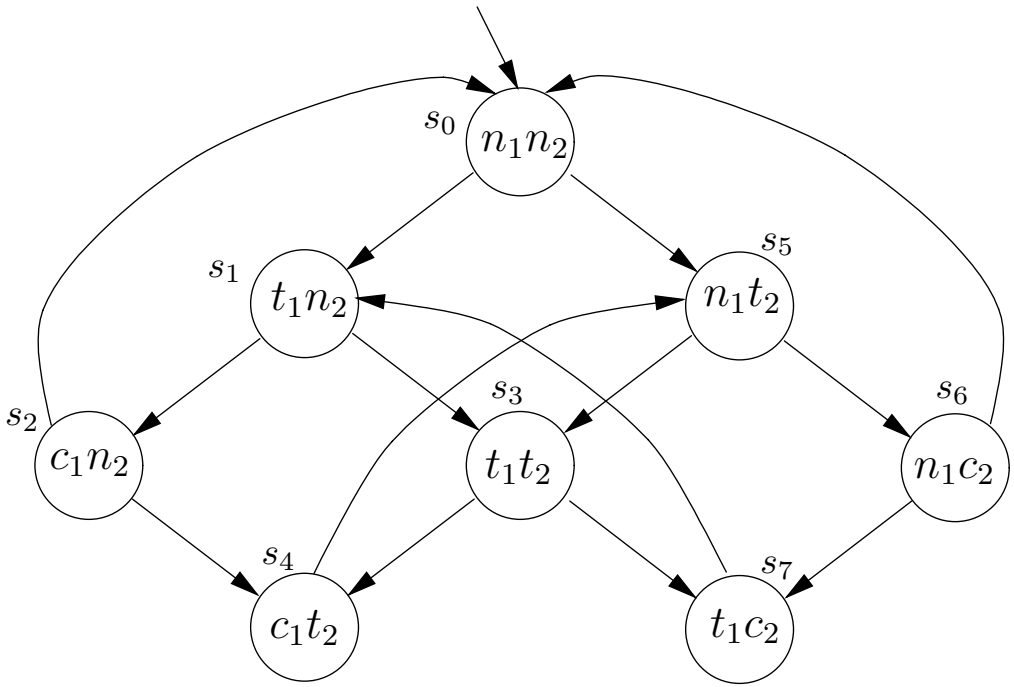

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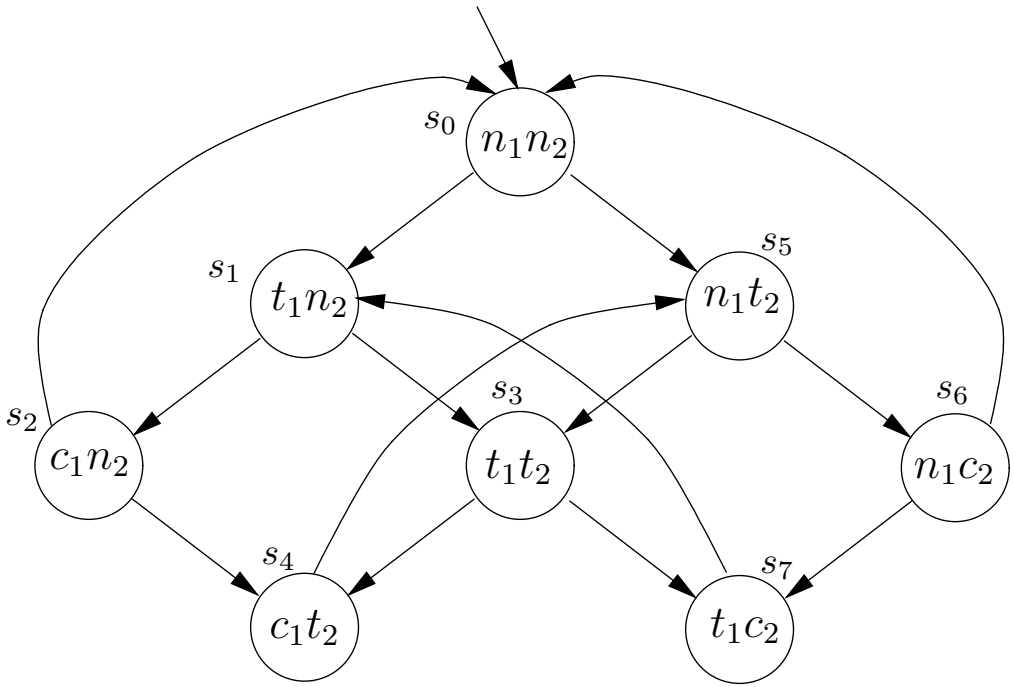

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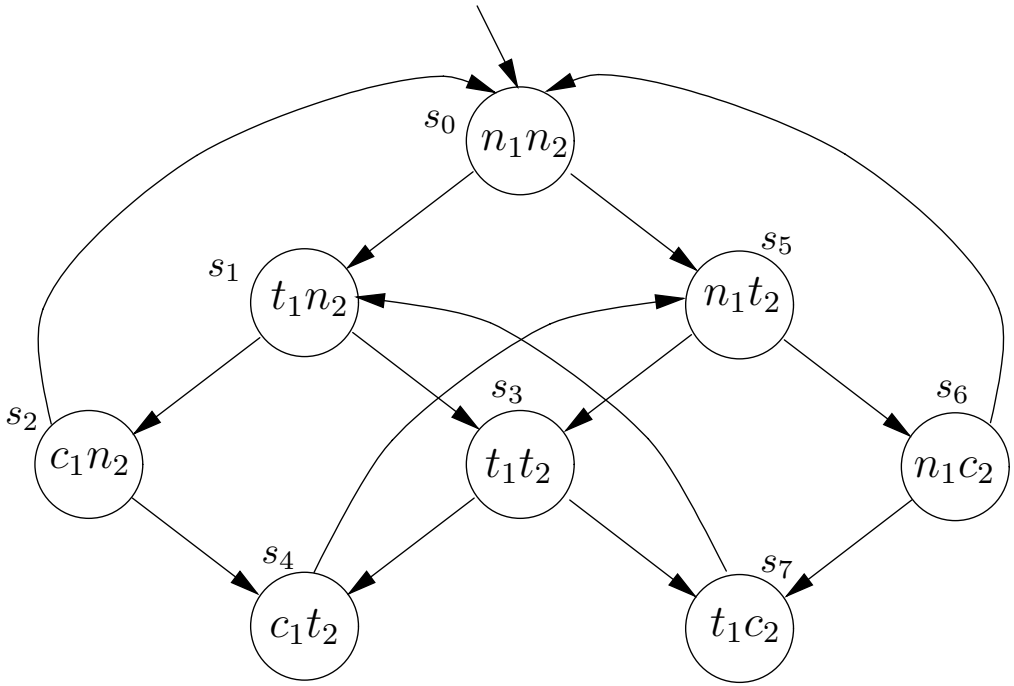

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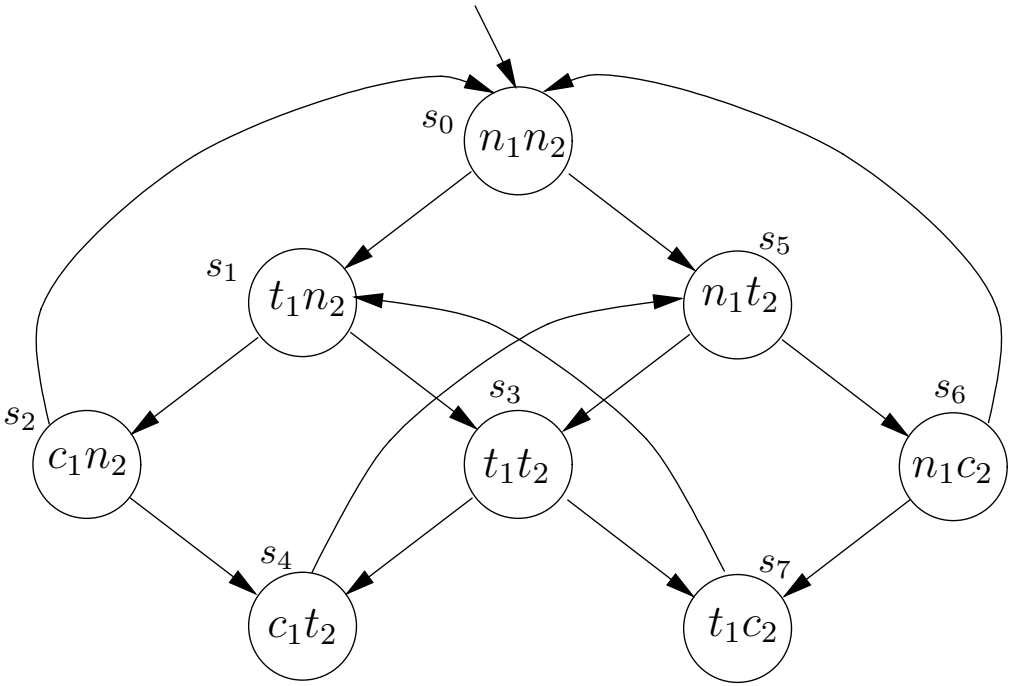

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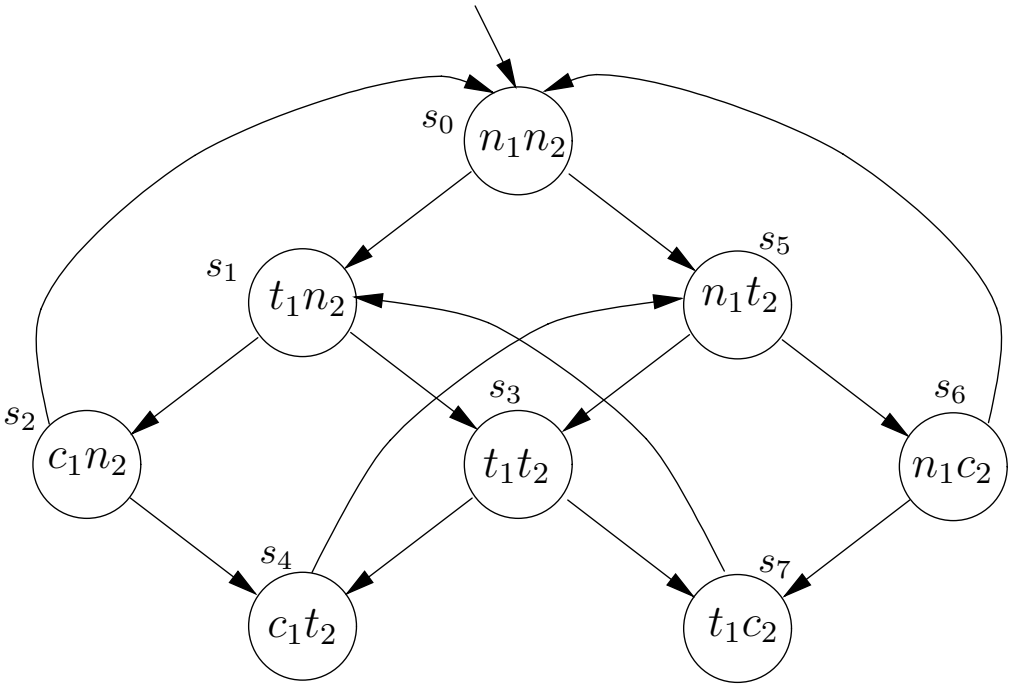

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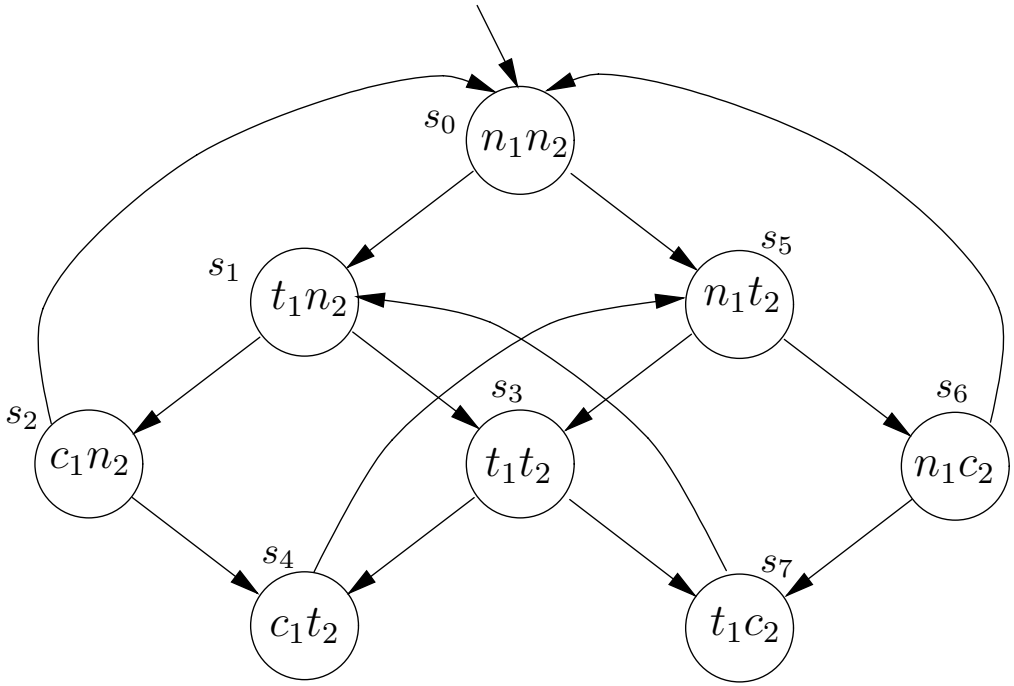

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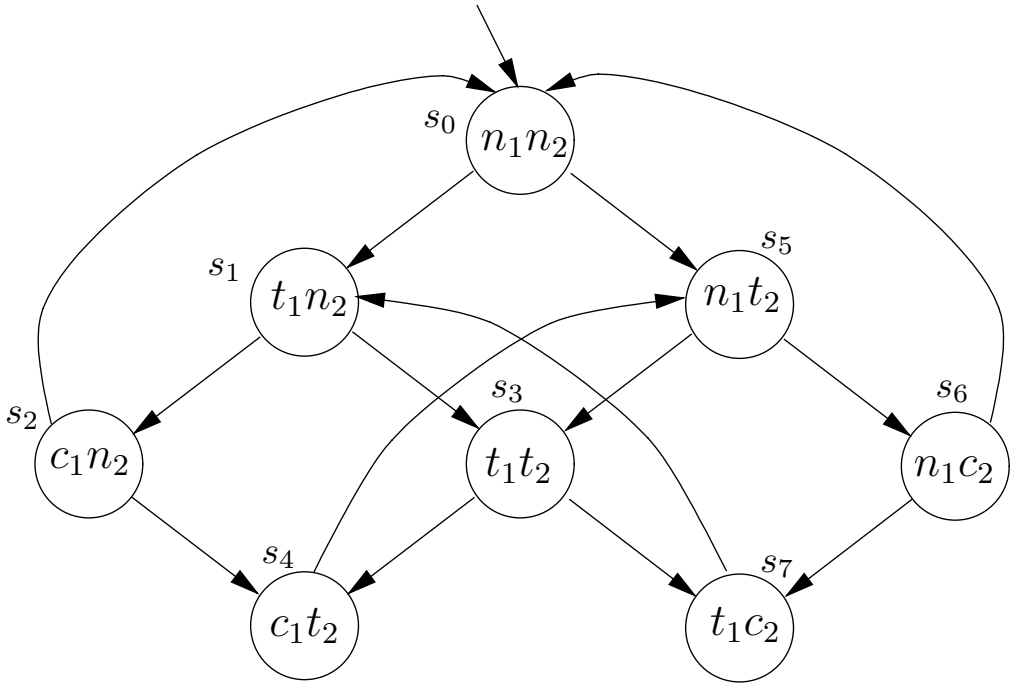

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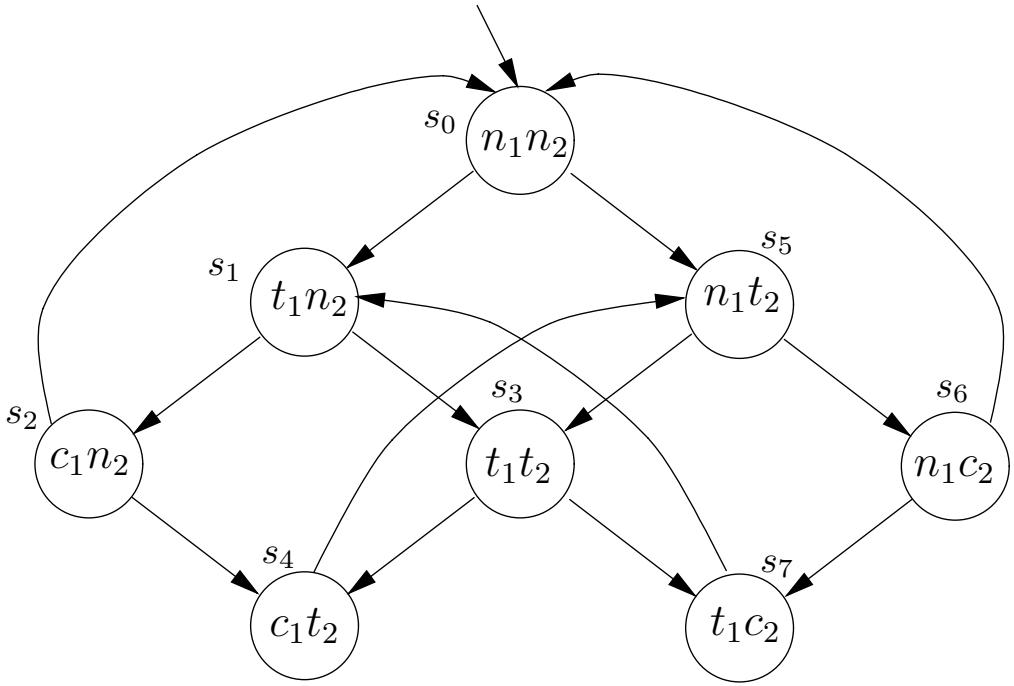

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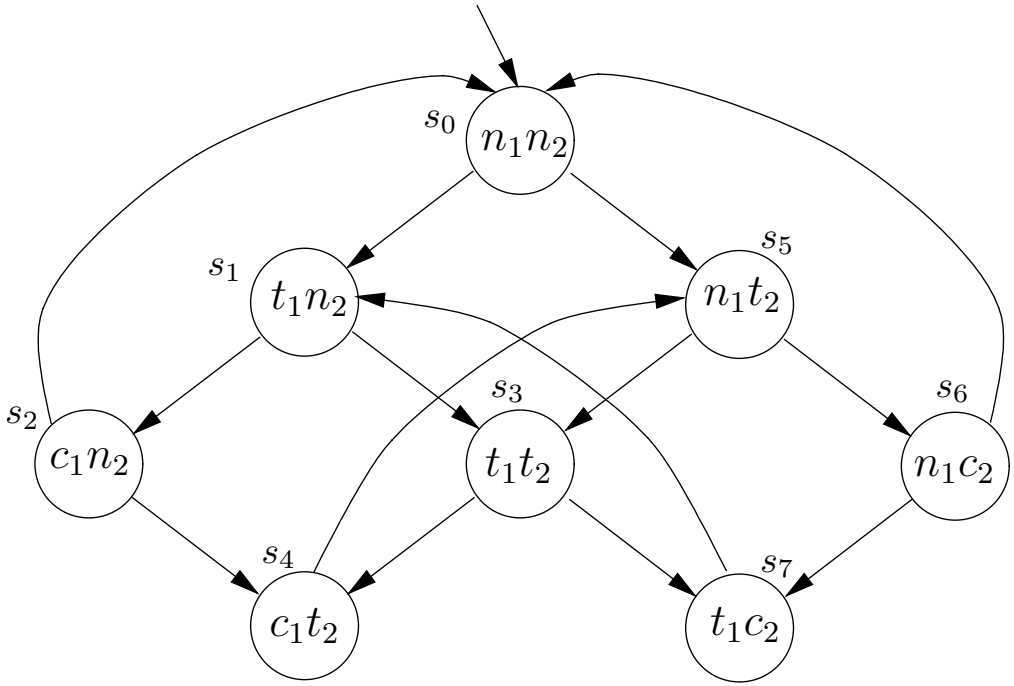

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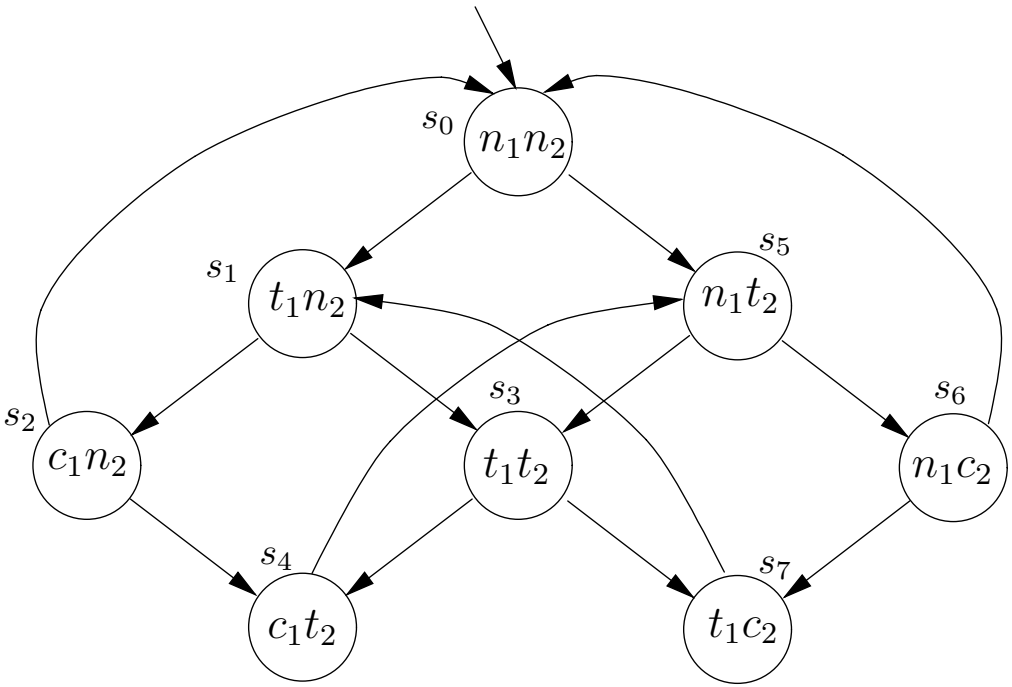

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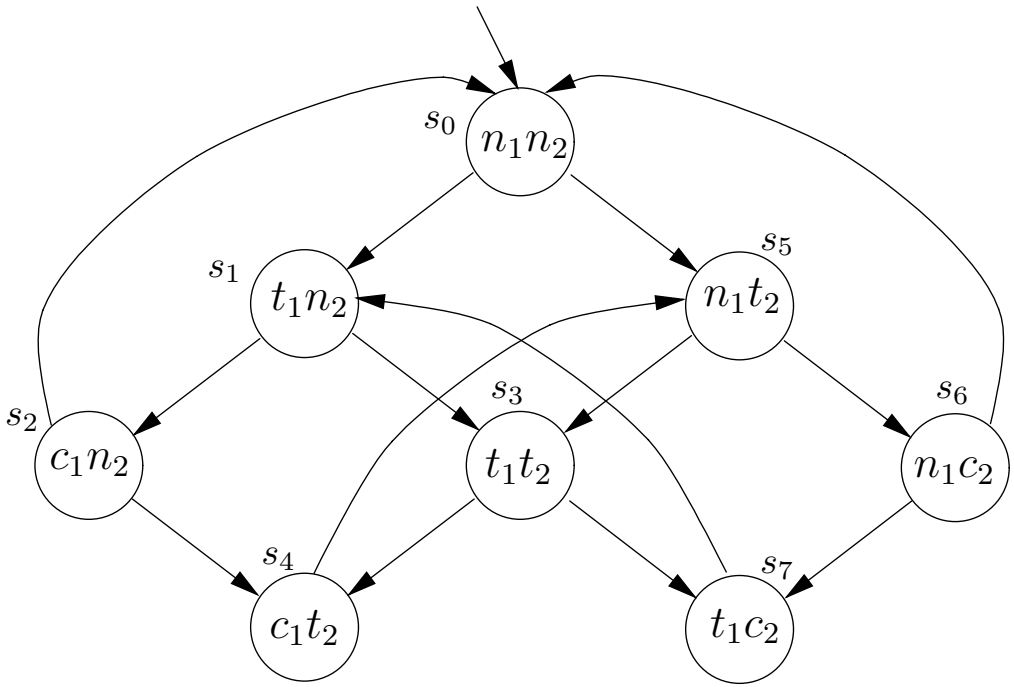

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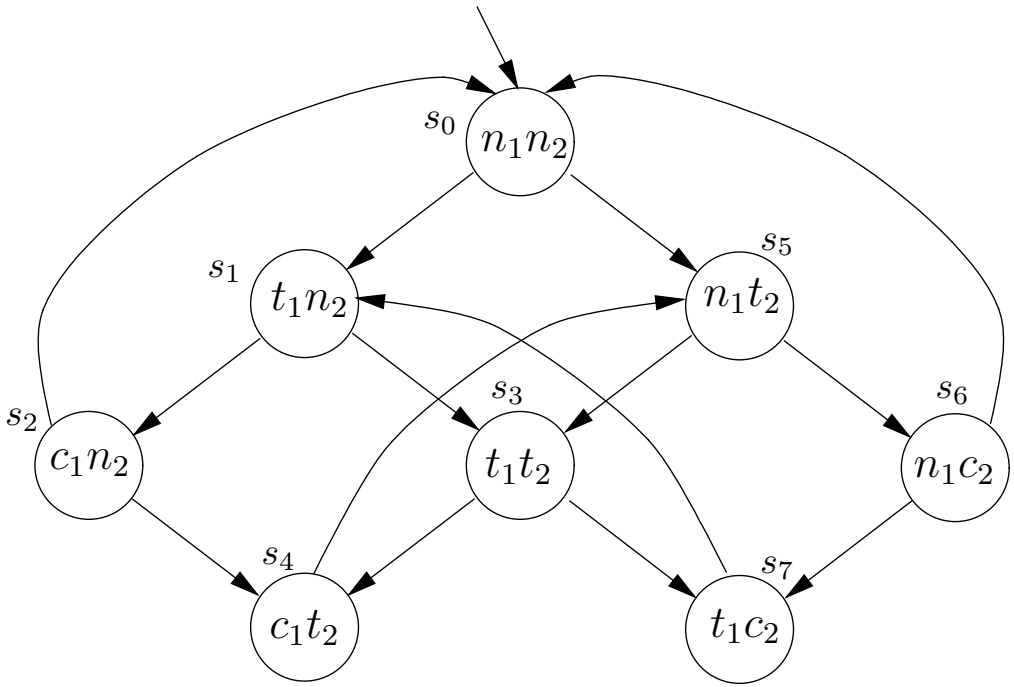

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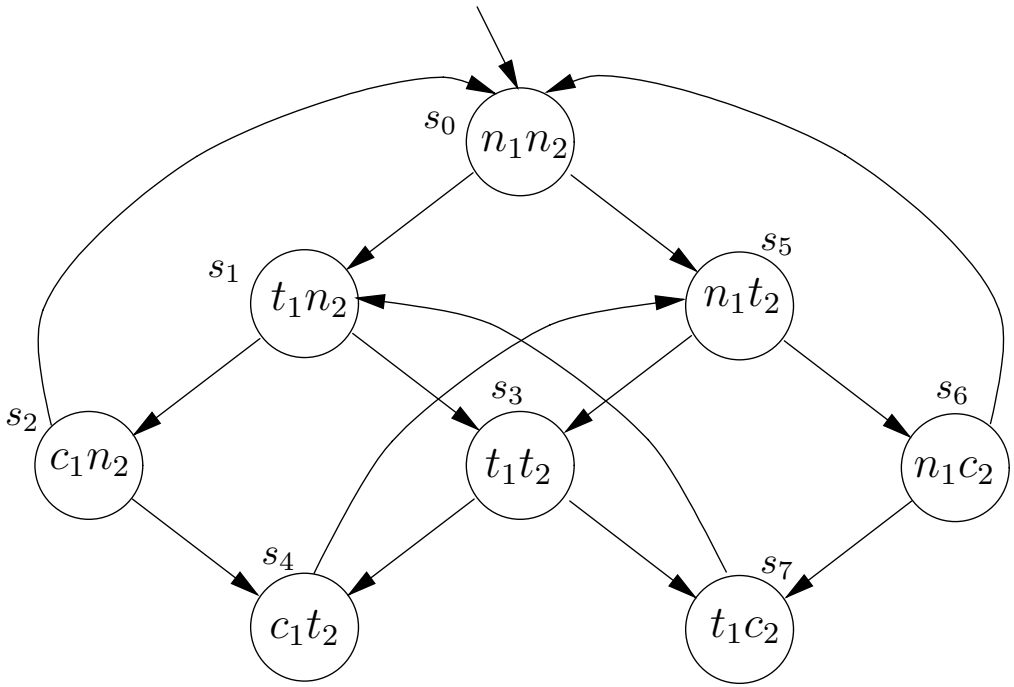

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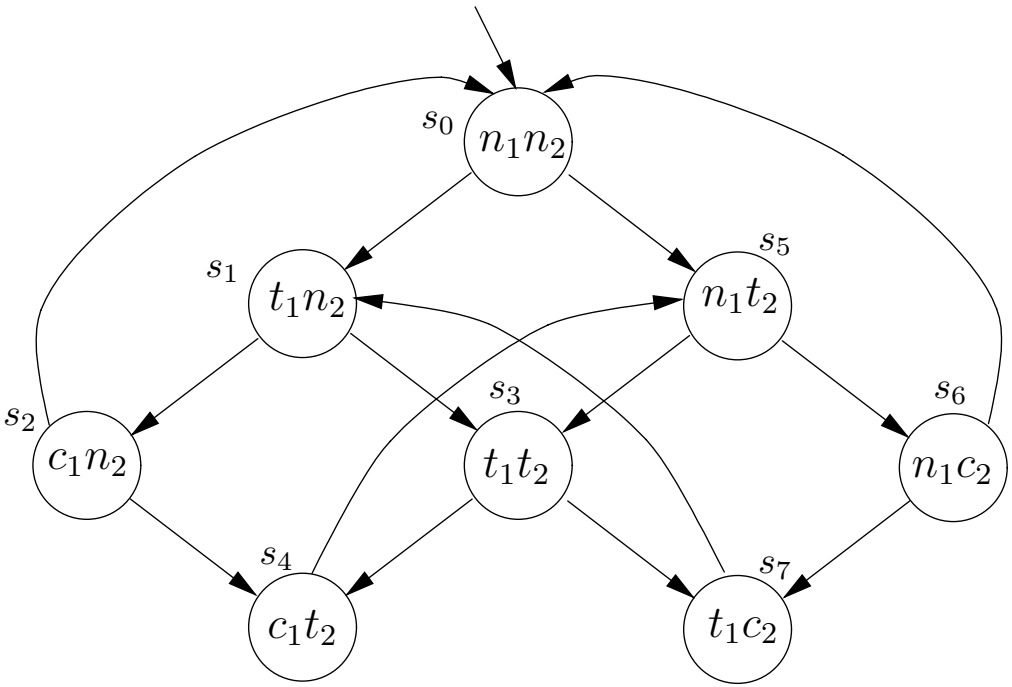

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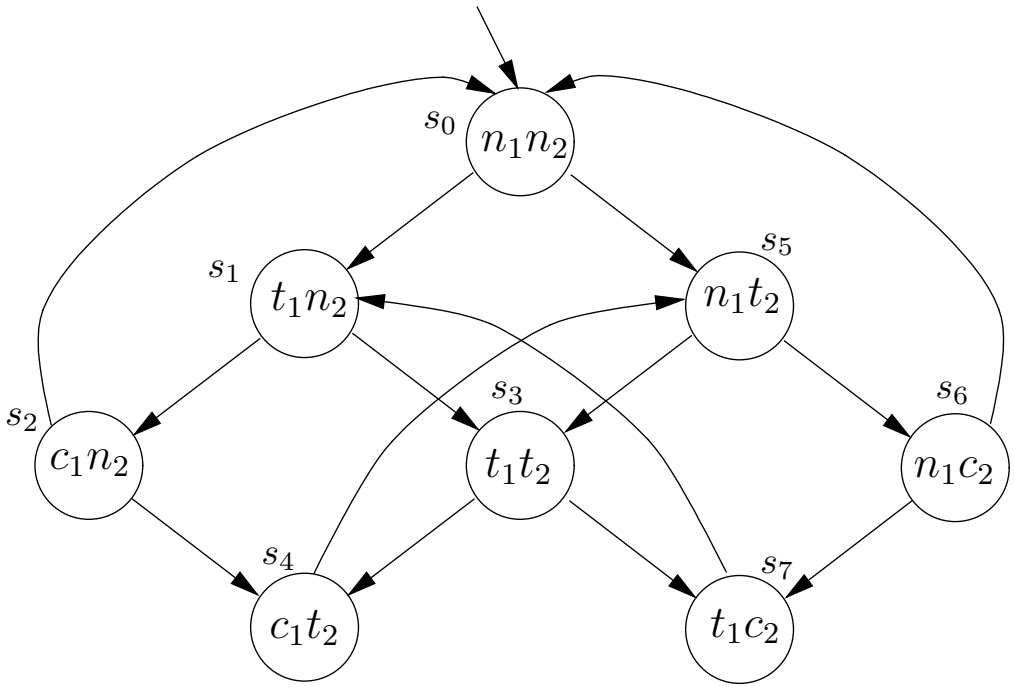

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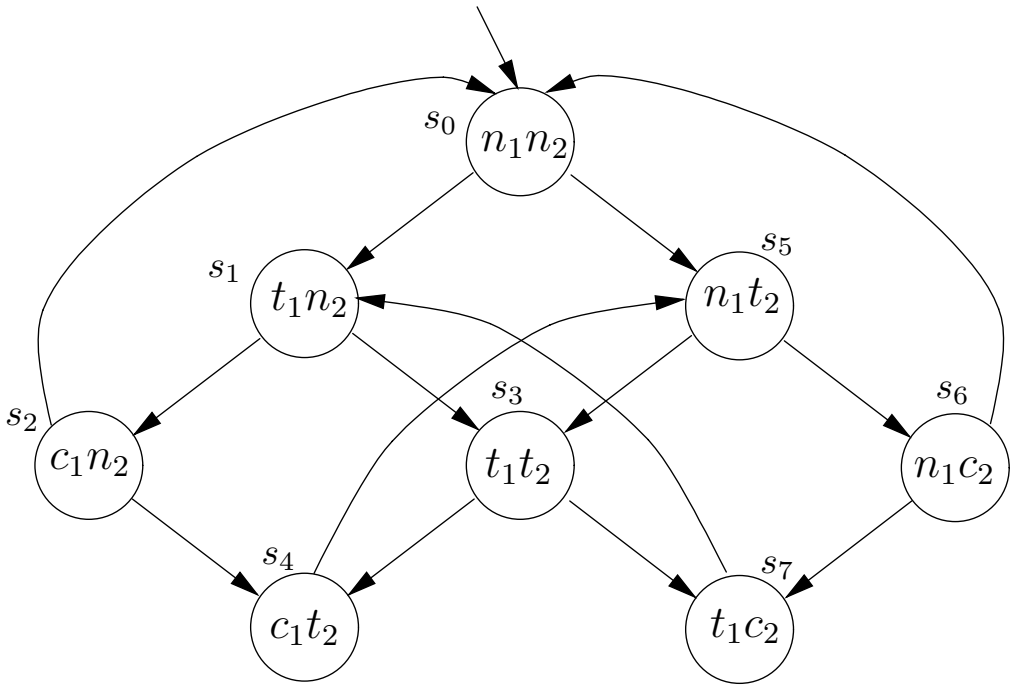

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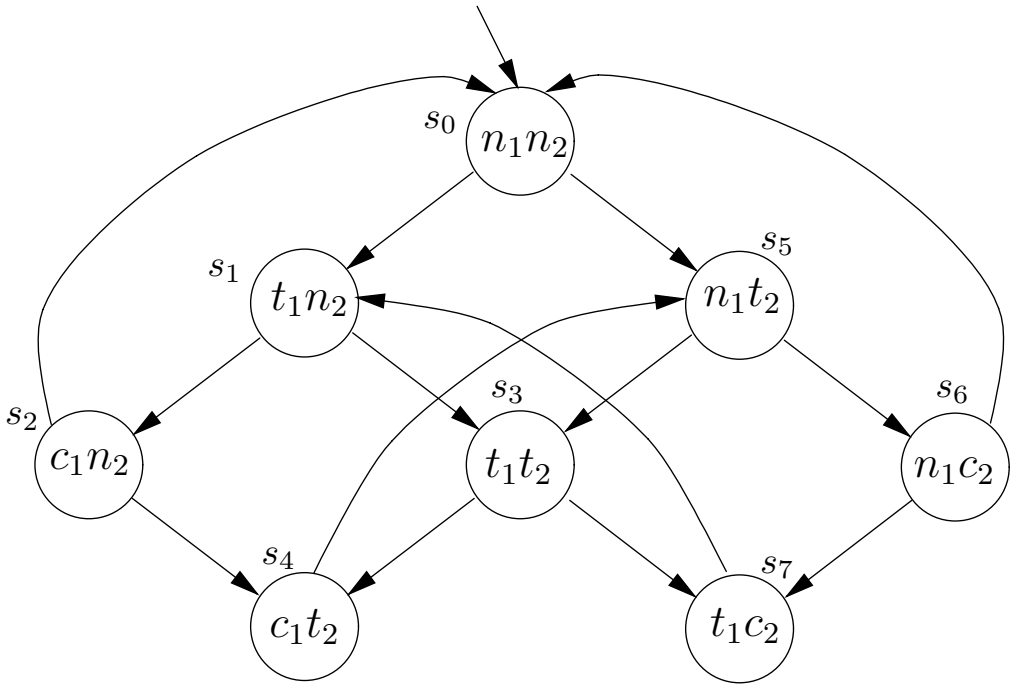

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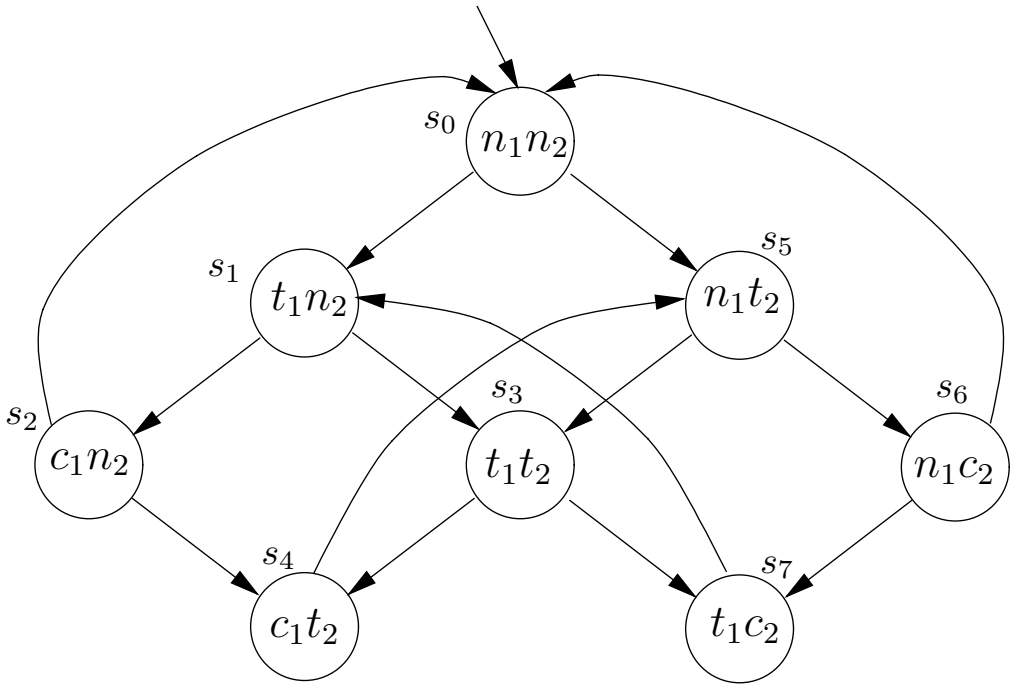

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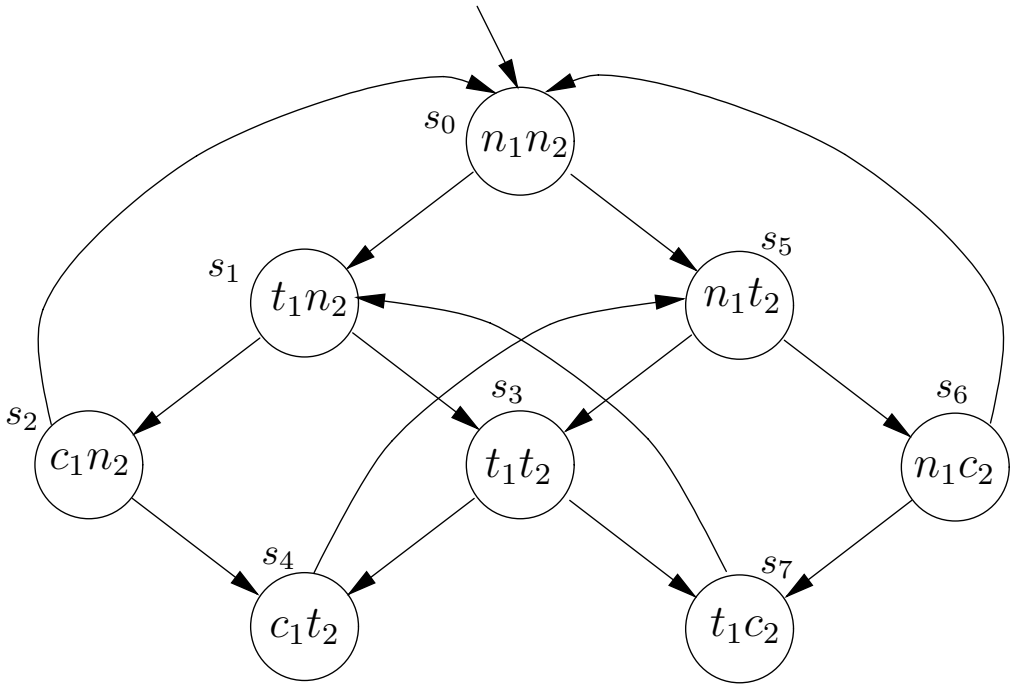

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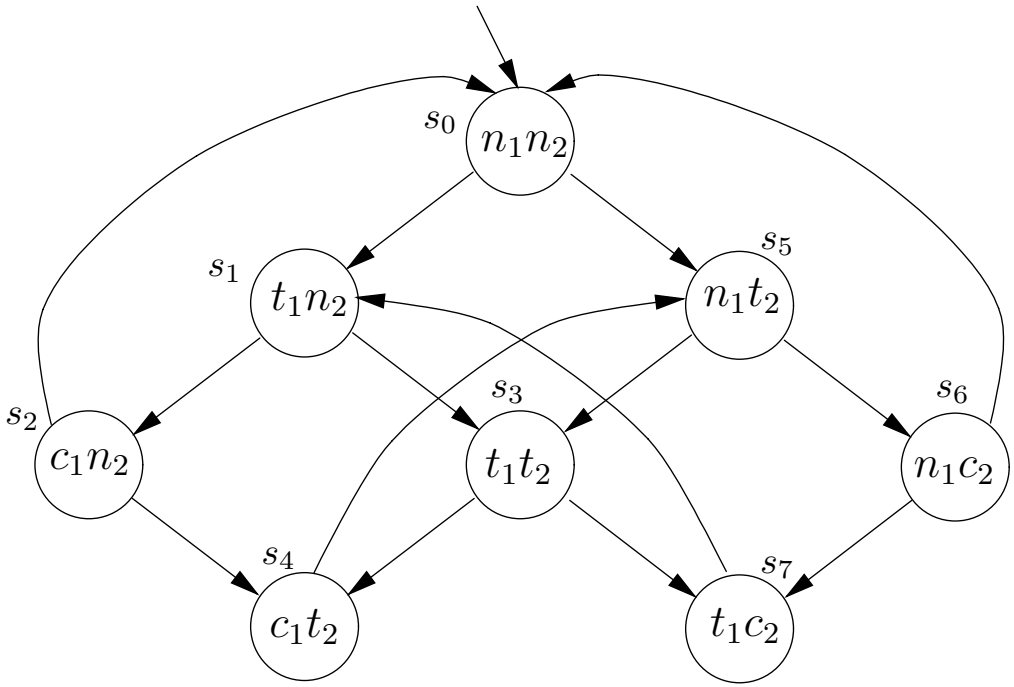

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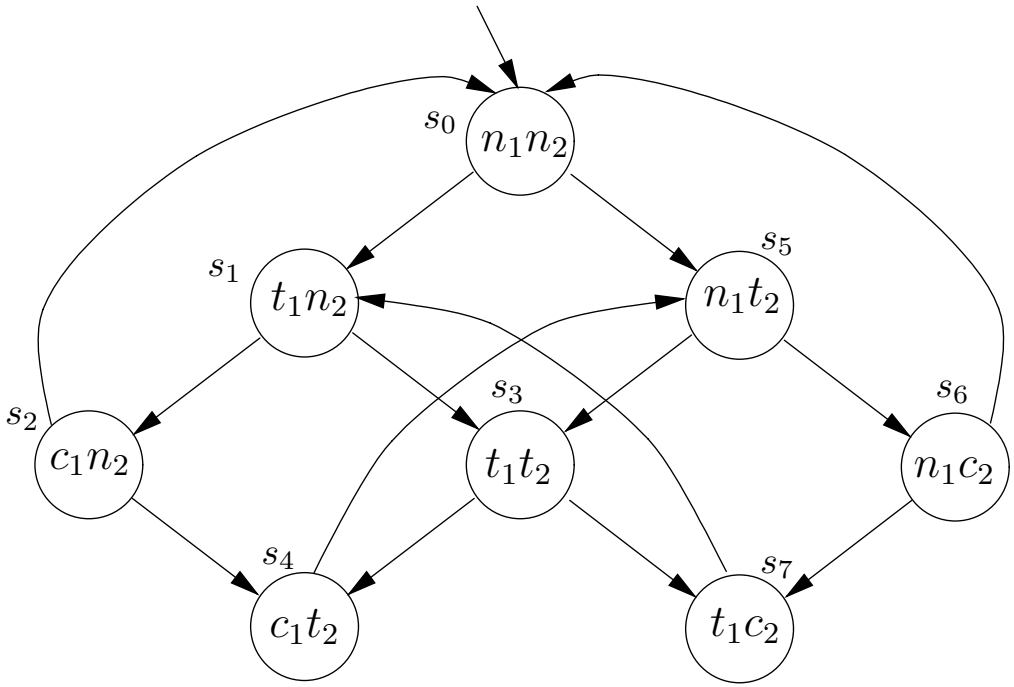

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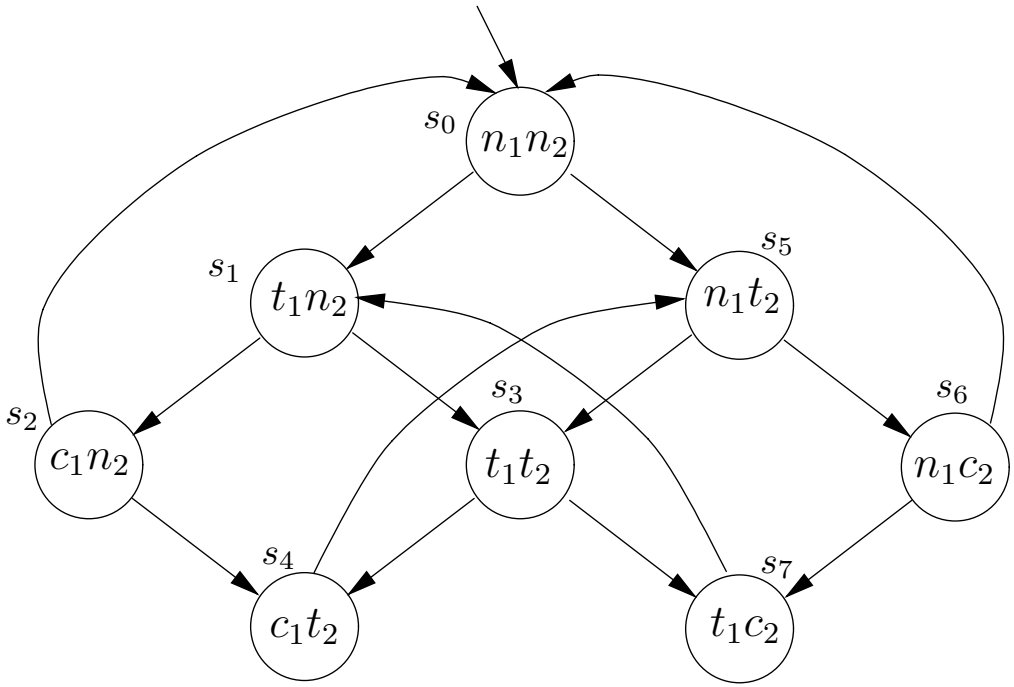

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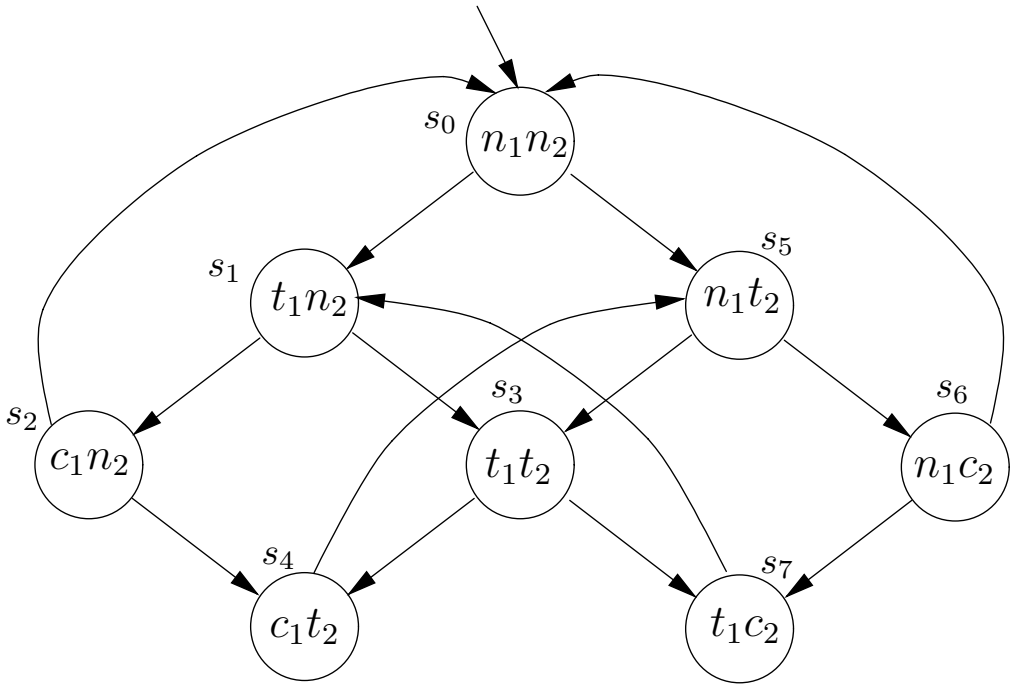

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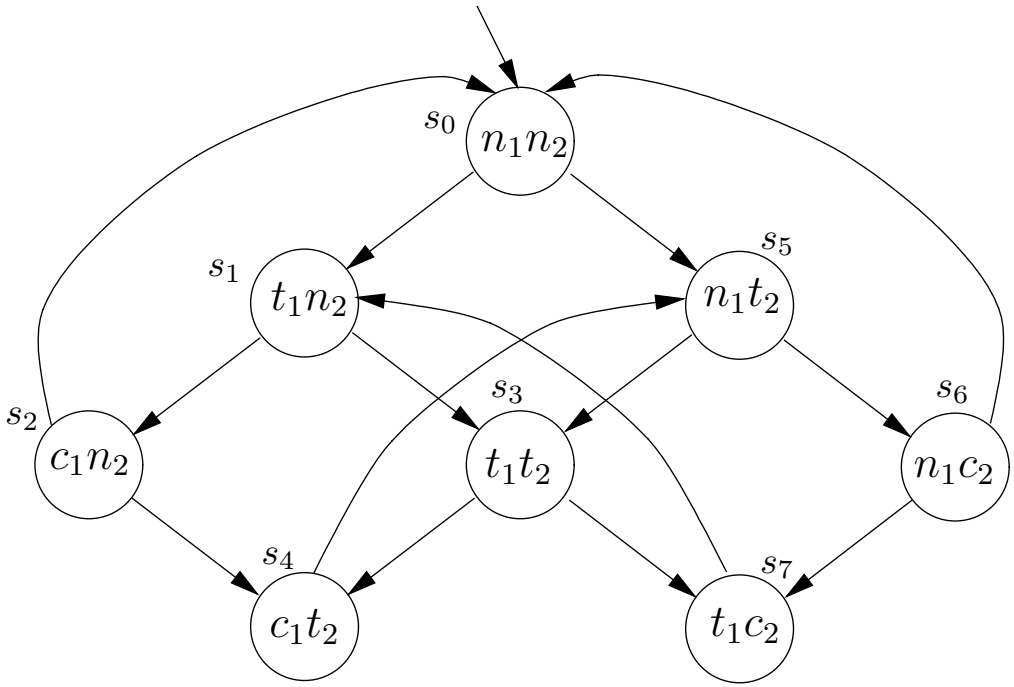

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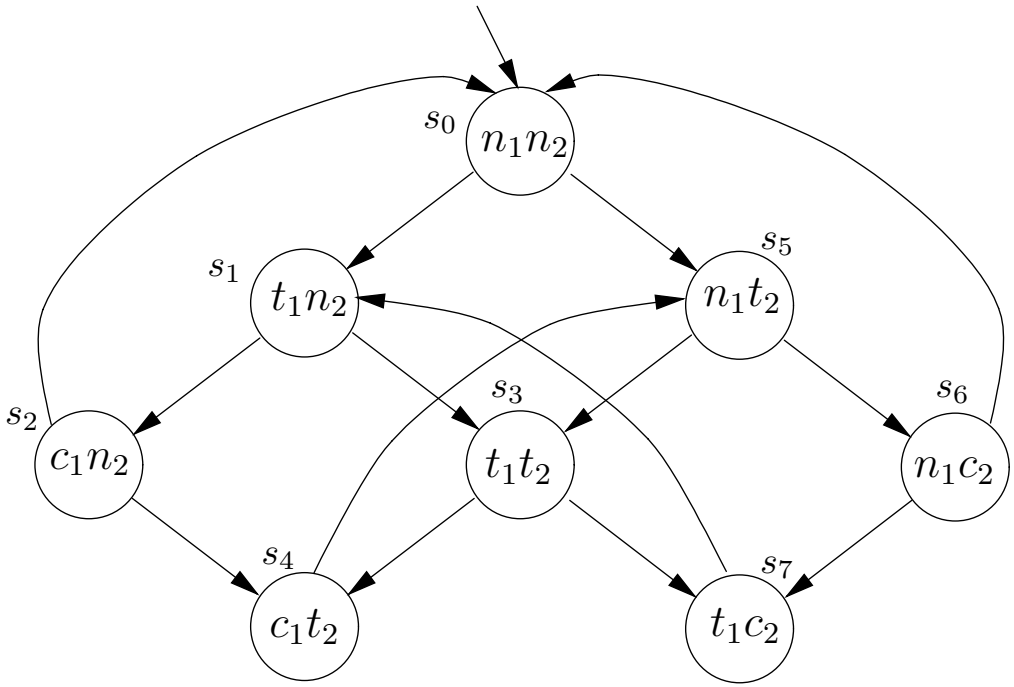

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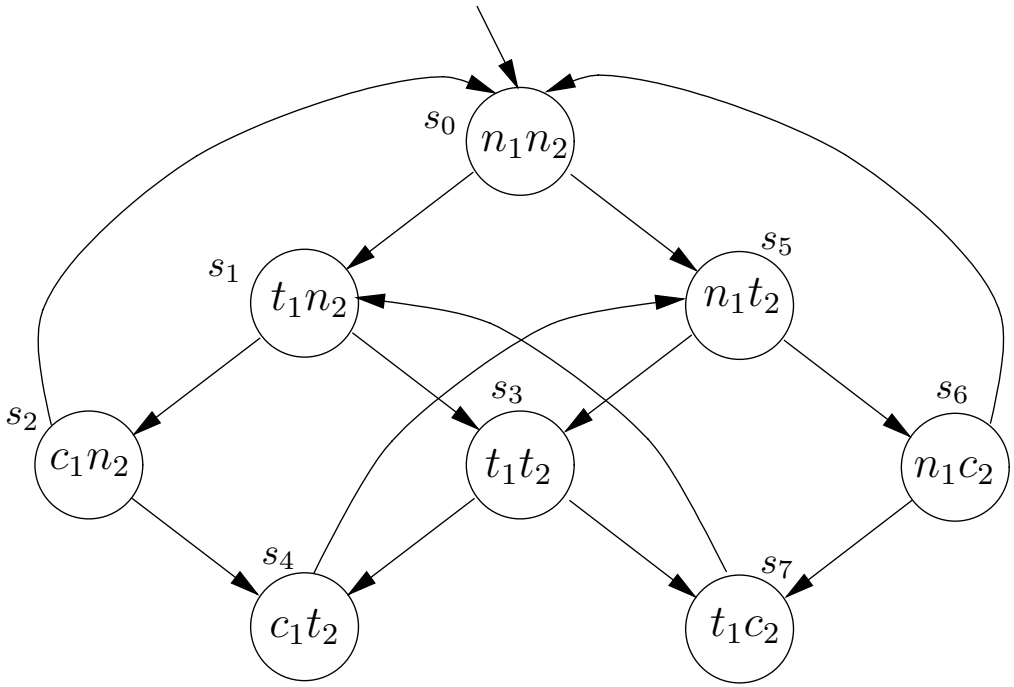

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Liveness: Whenever any process *requests* to enter its critical section, it will *eventually be permitted* to do so.

- LTL specification:

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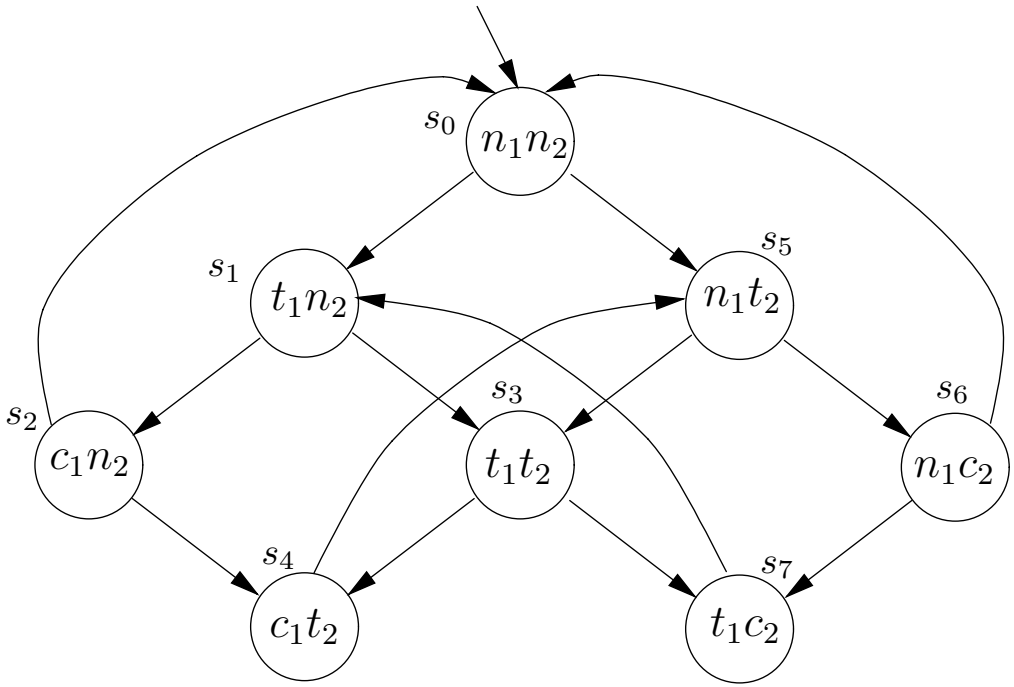

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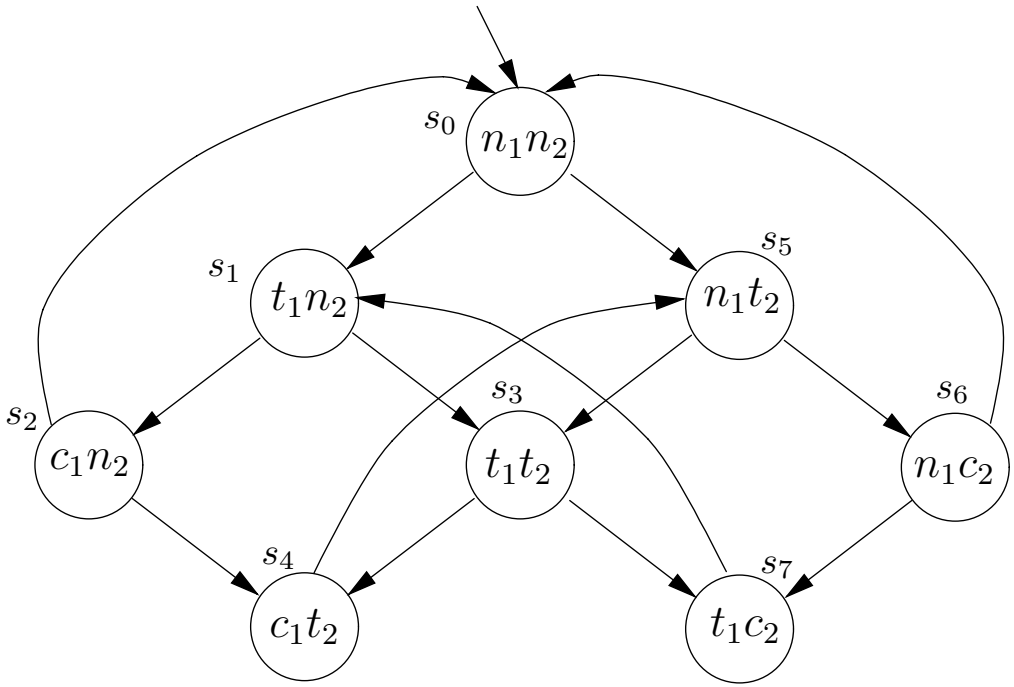

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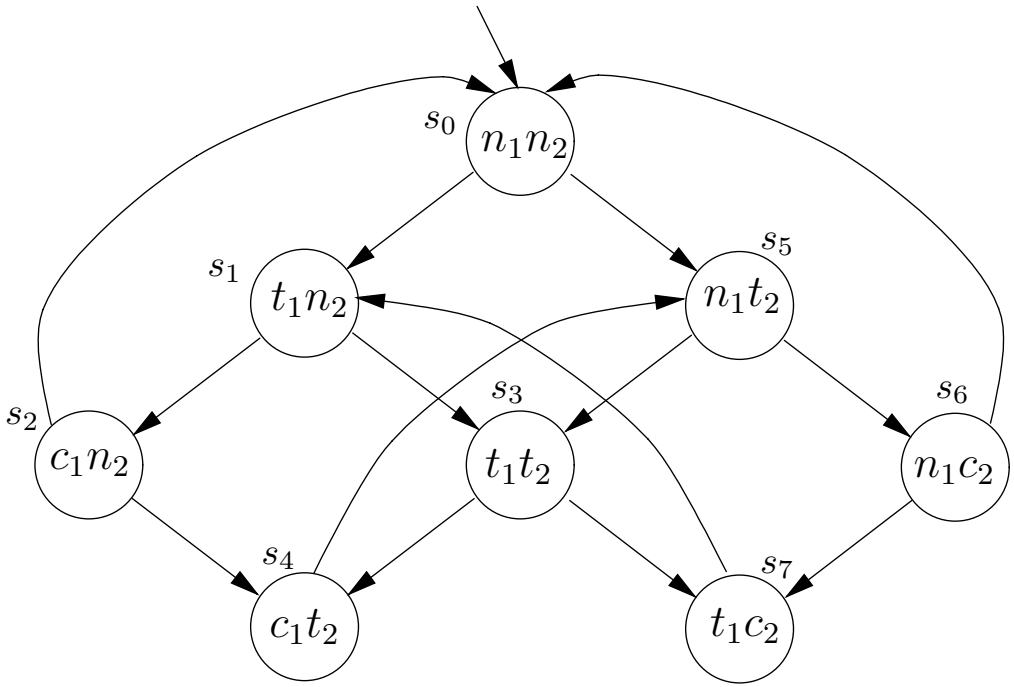

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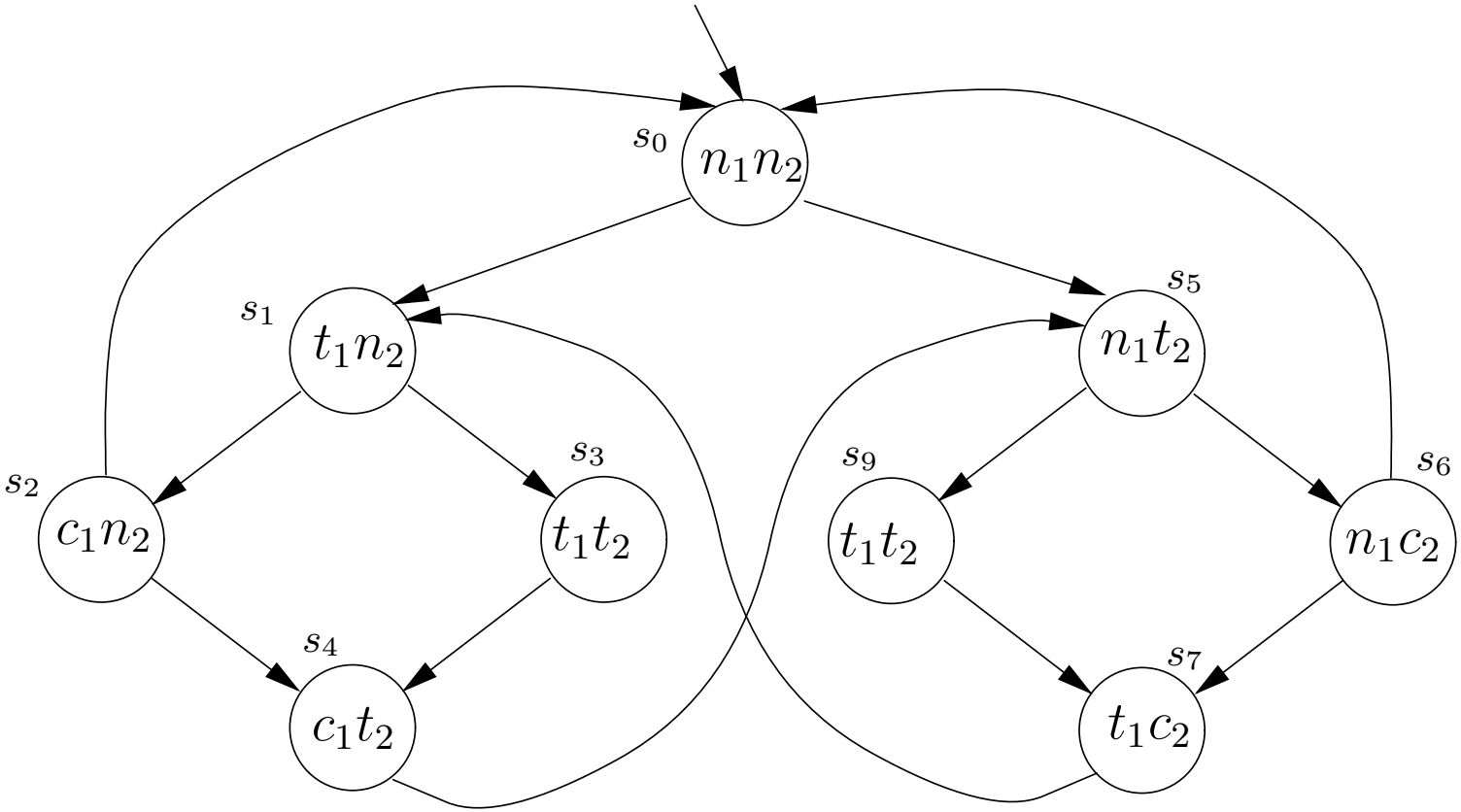

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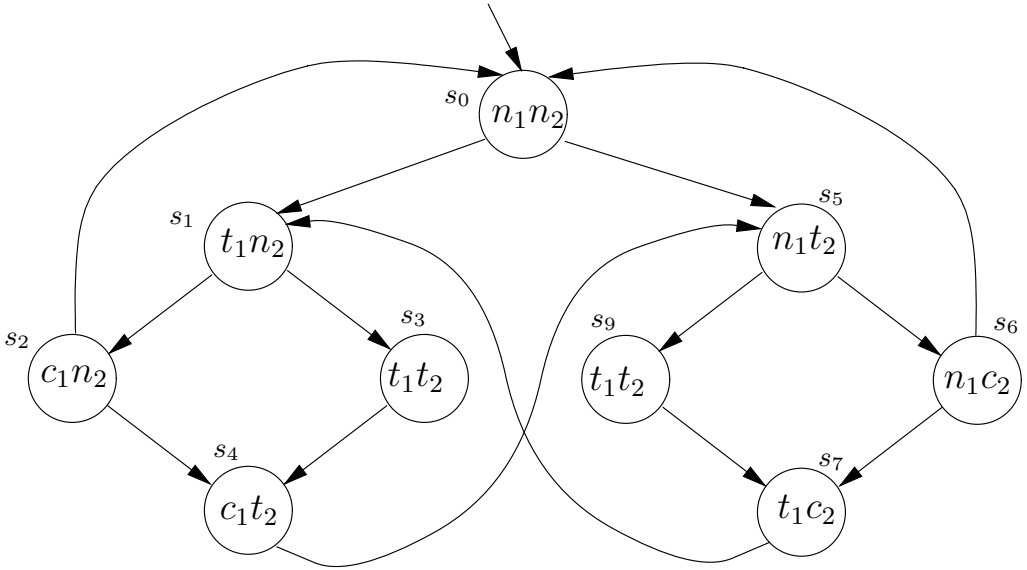

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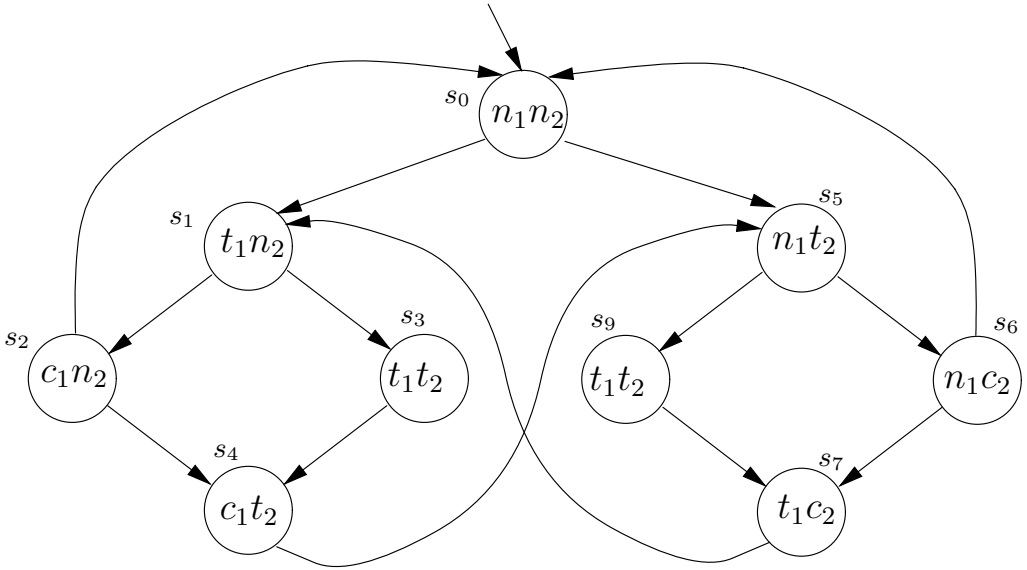

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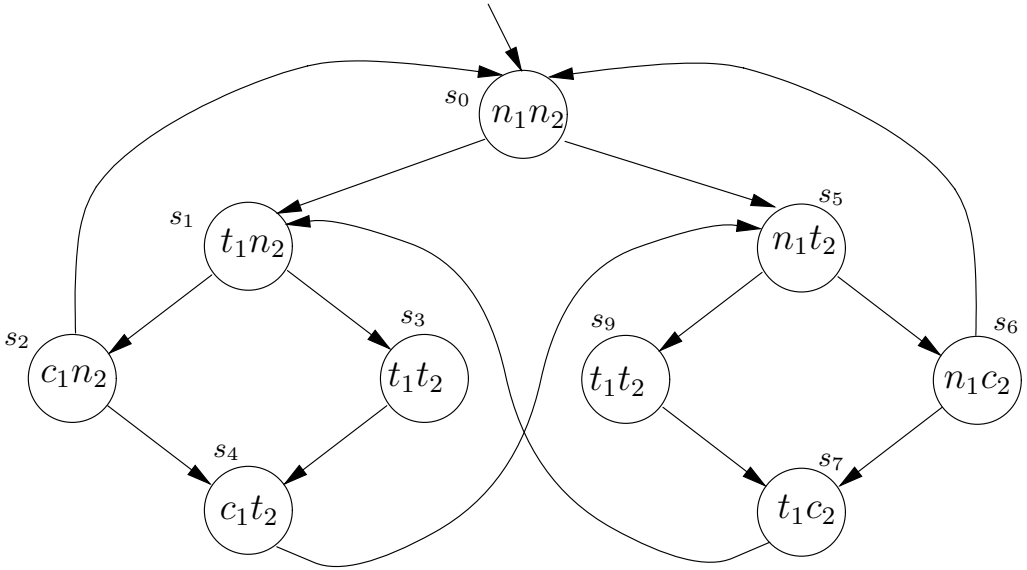

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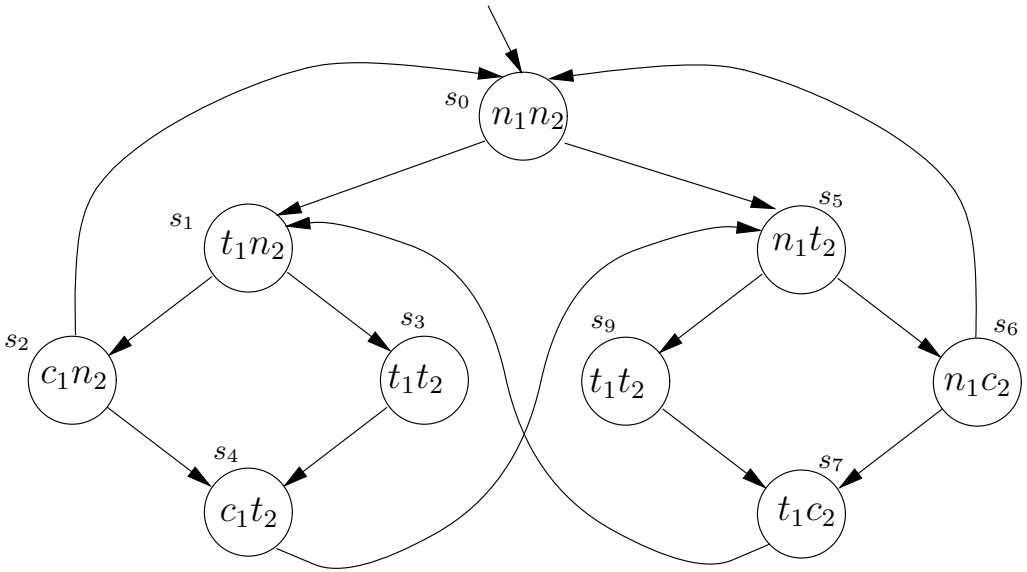

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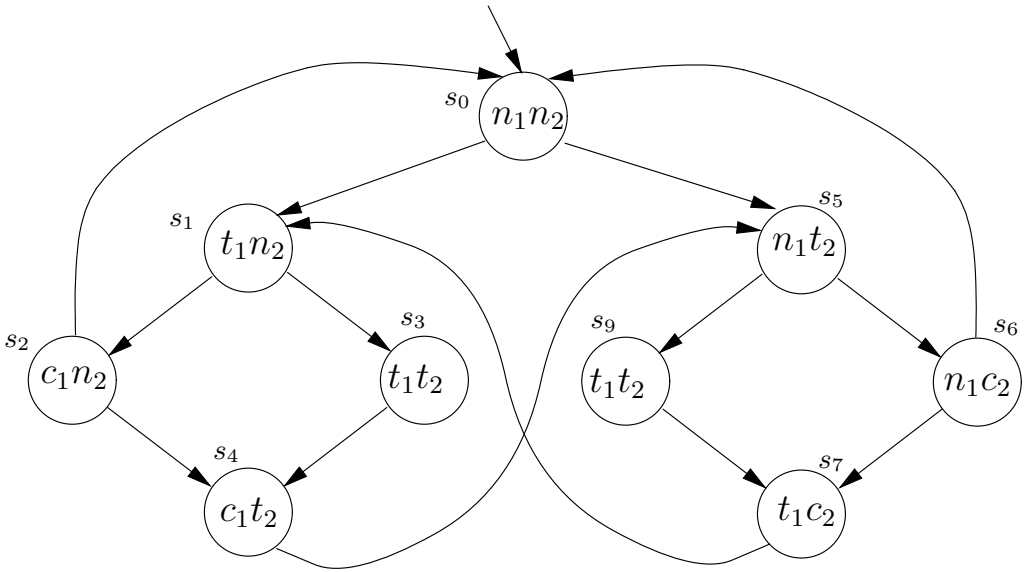

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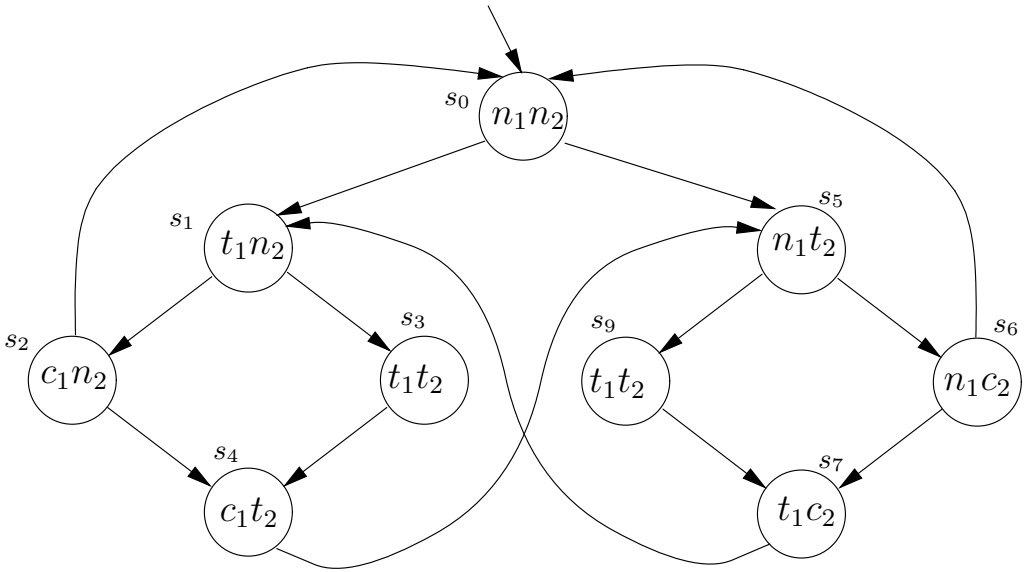

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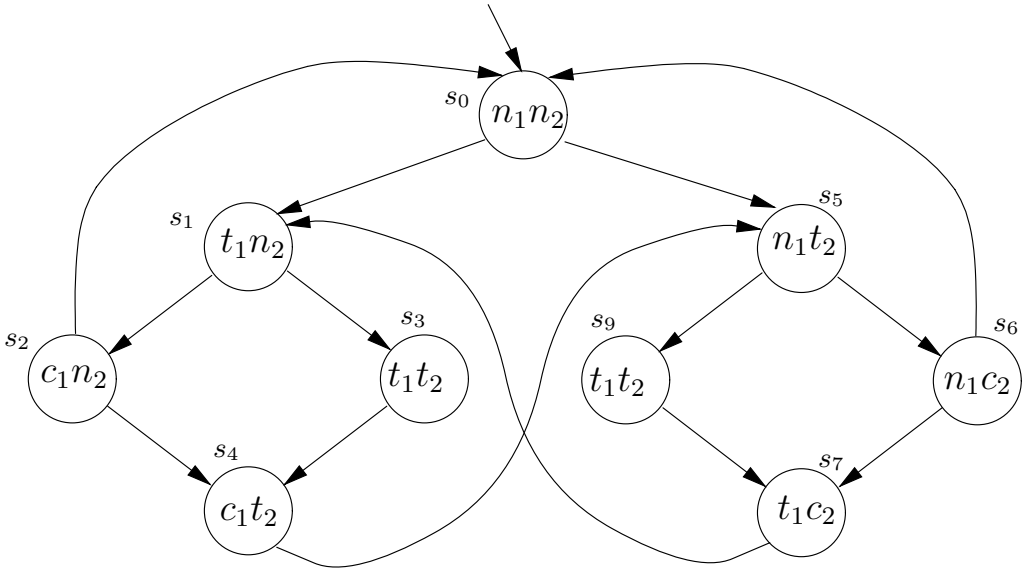

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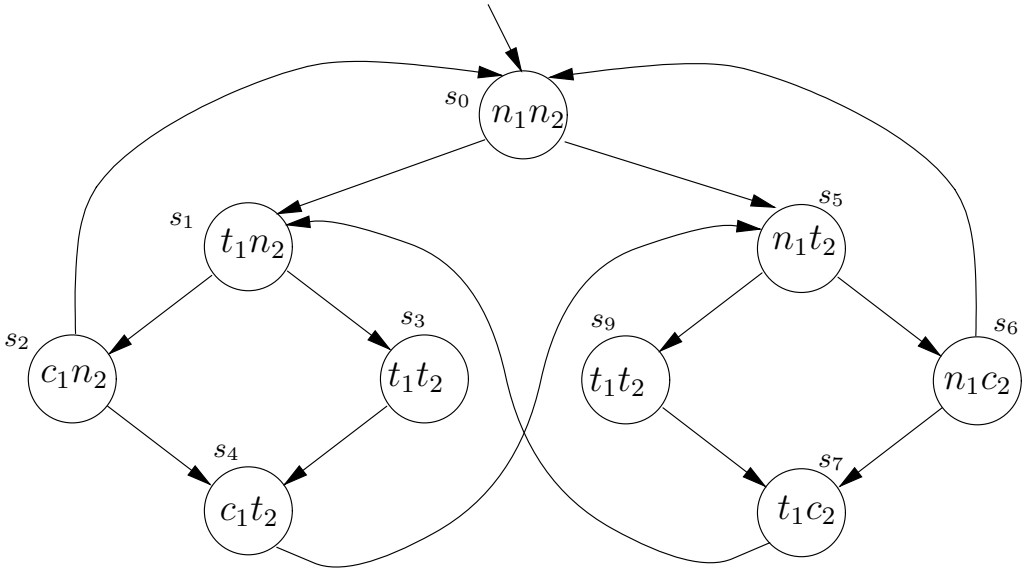

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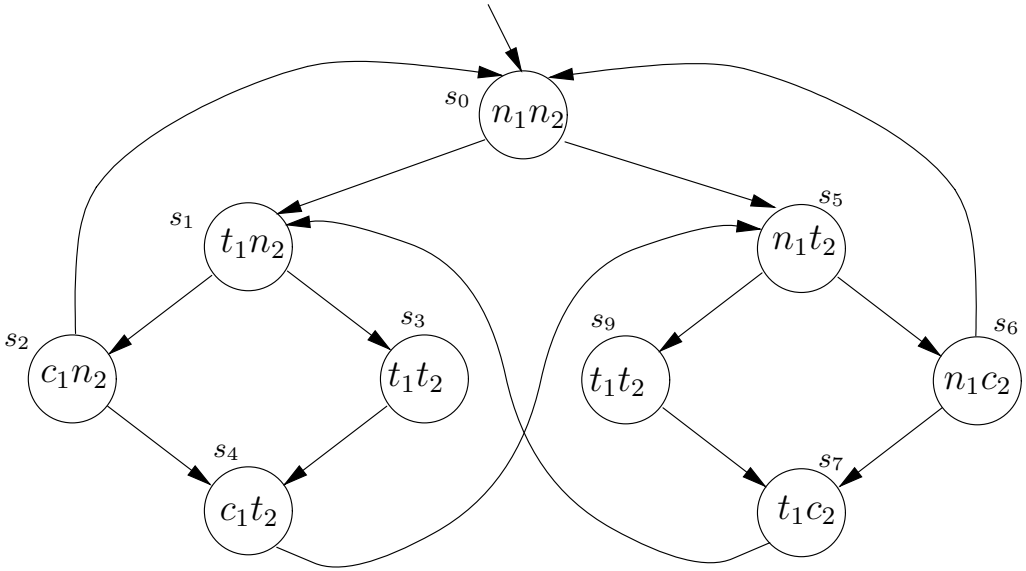

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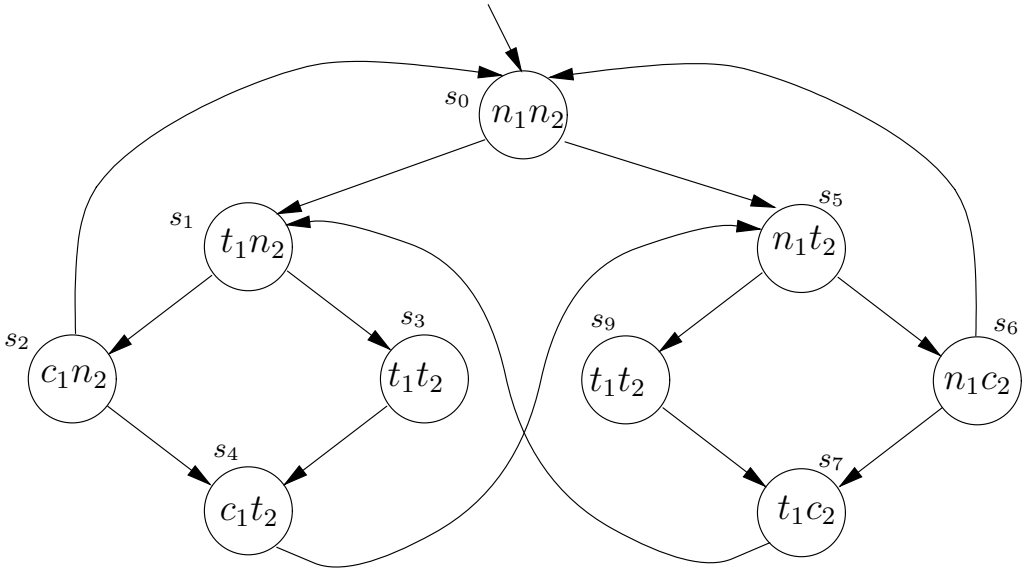

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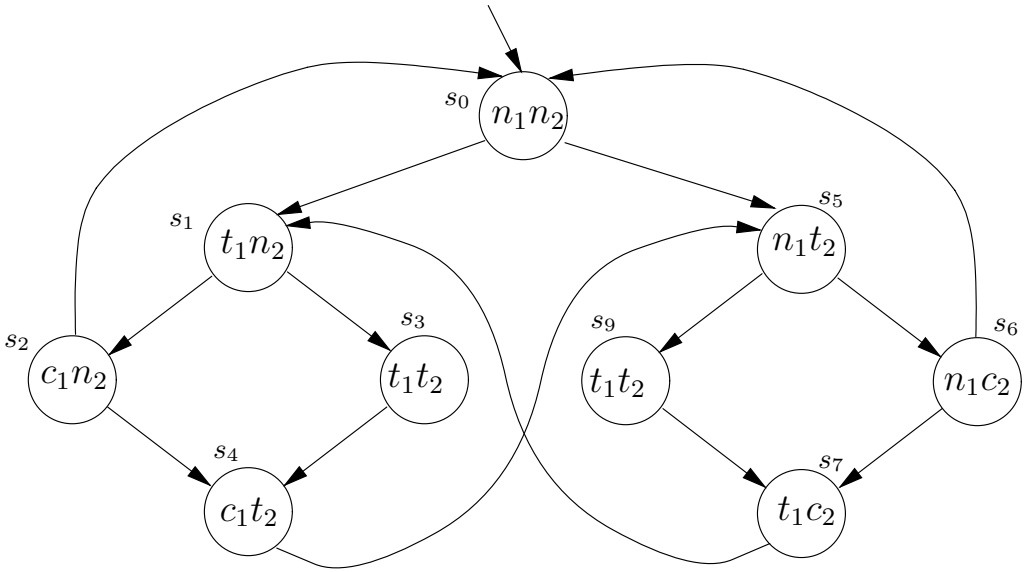

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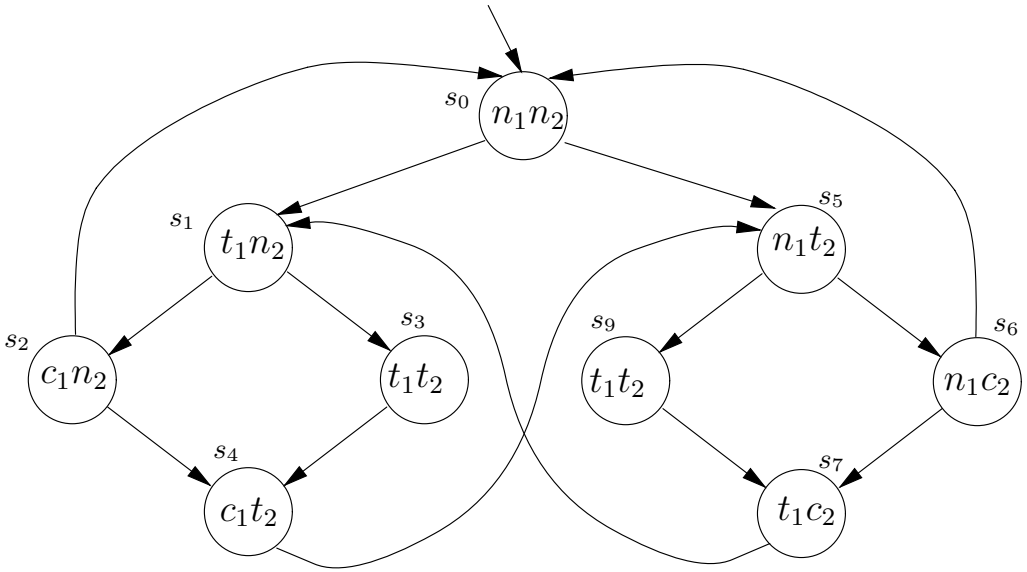

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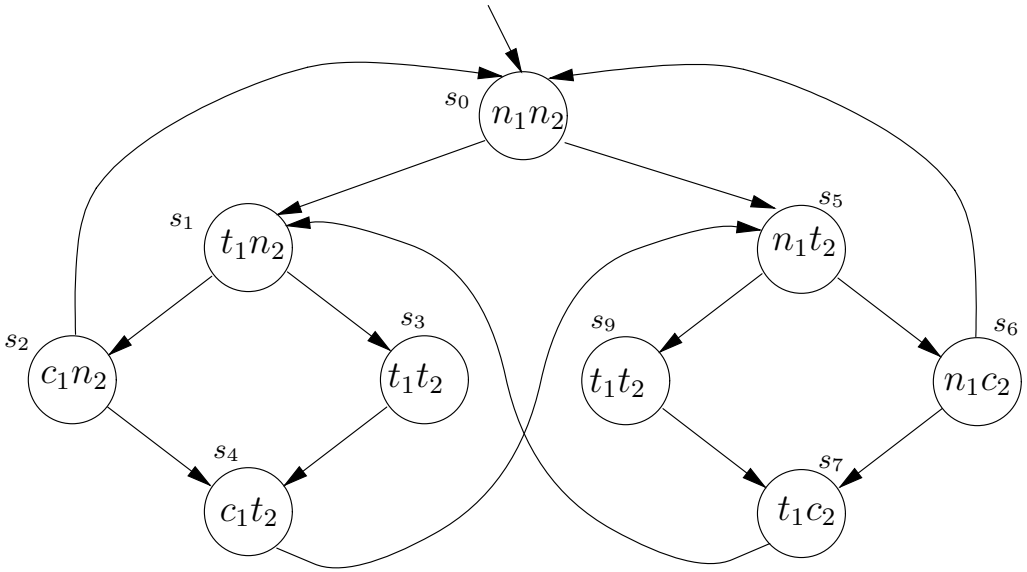

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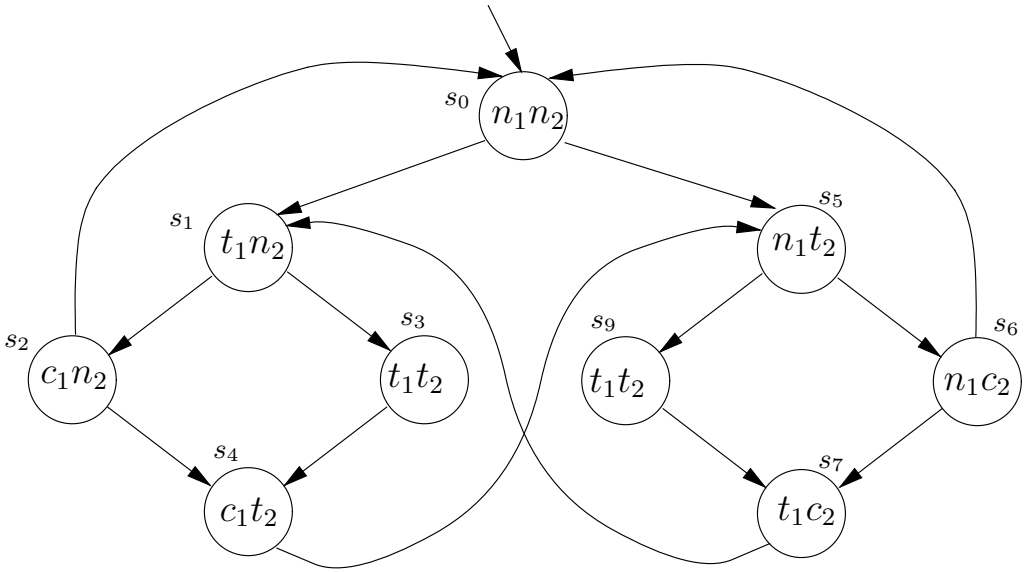

No strict sequencing: Processes need not enter their critical section in strict sequence

- there is a path with two distinct states satisfying c_1 such that no state in between them has that property
- LTL spec? Also no
- A complement LTL? OK...

$$\mathrm{G}\ (c_1 \rightarrow c_1\ \mathrm{W}\ (\neg c_1 \wedge \neg c_1\ \mathrm{W}\ c_2))$$

The complement LTL is false:

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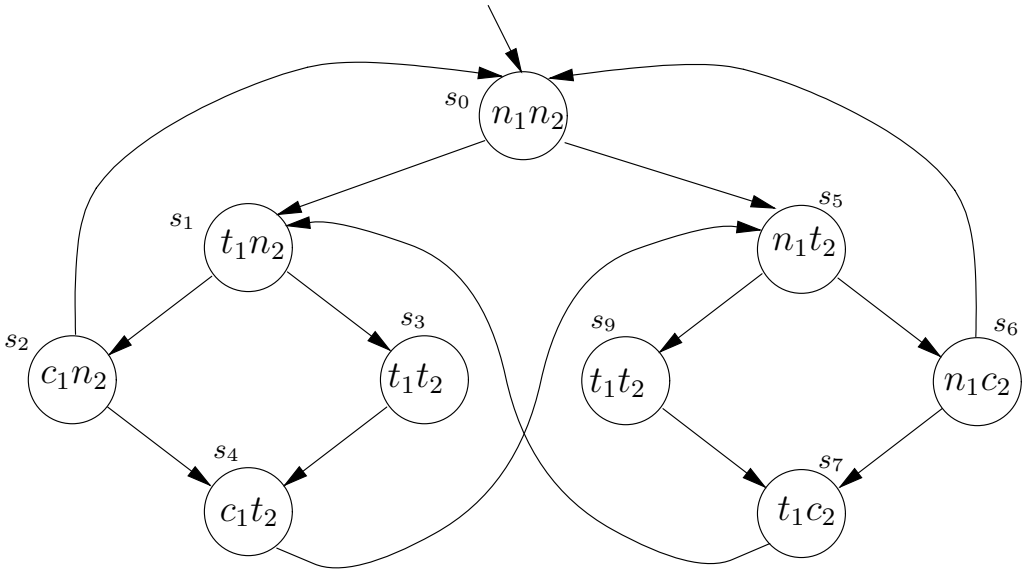

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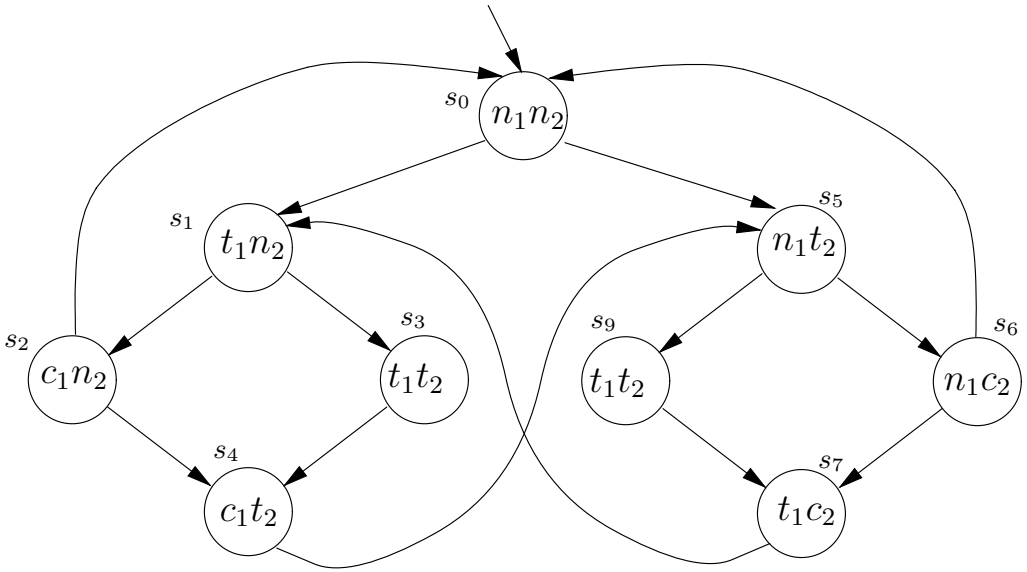

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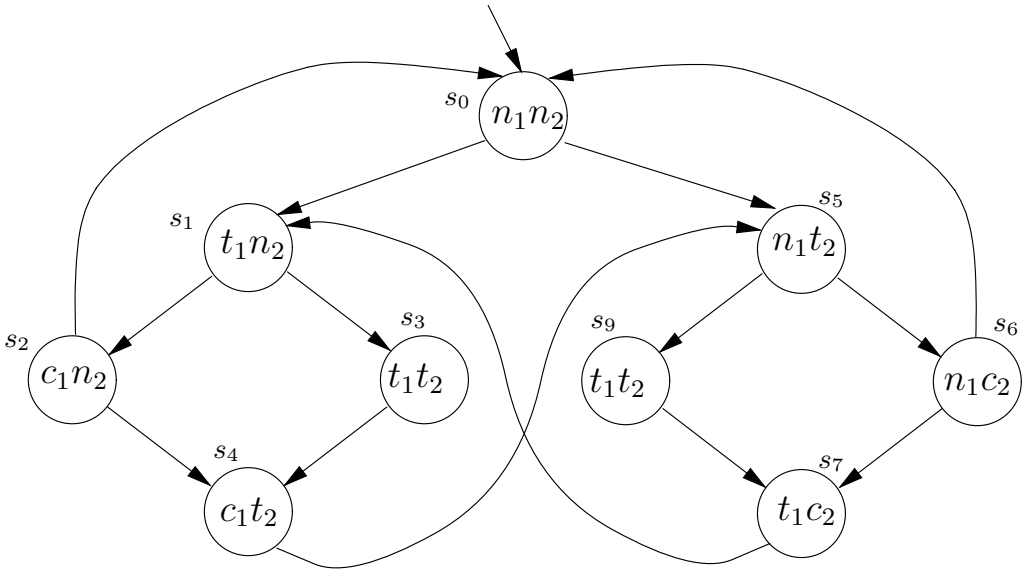

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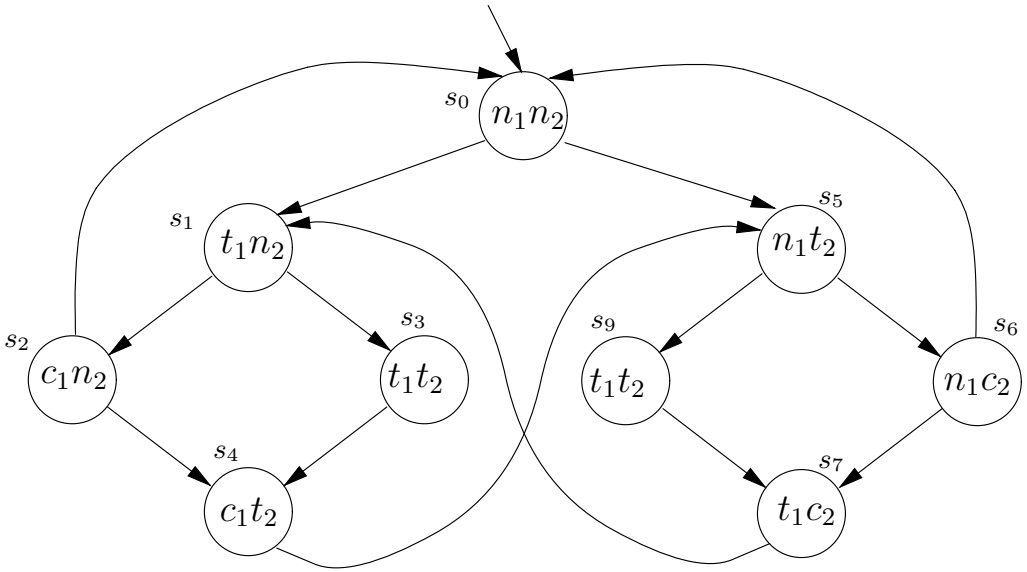

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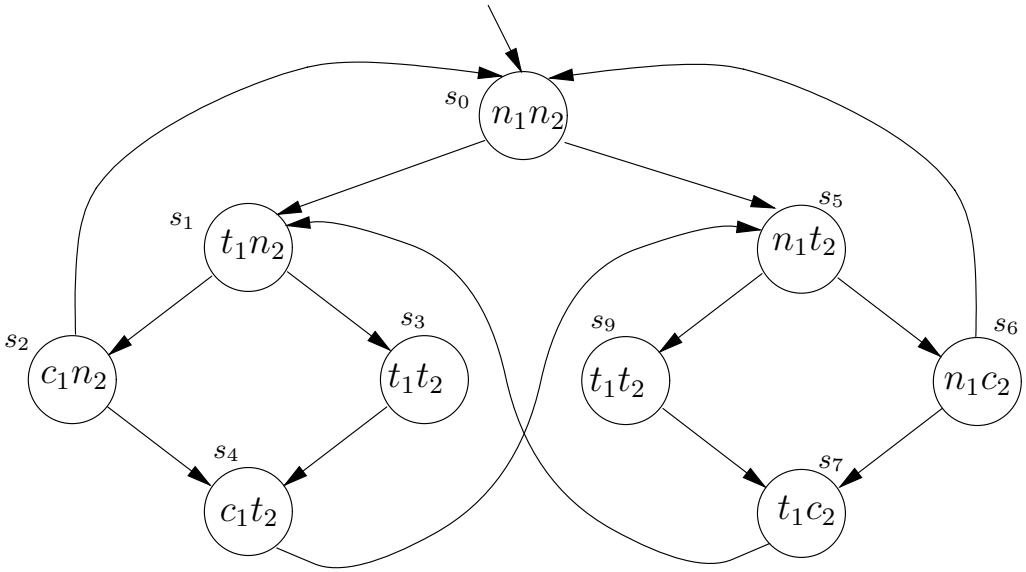

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新问题 1: What if a process can stay in its critical state for several ticks?, i.e,

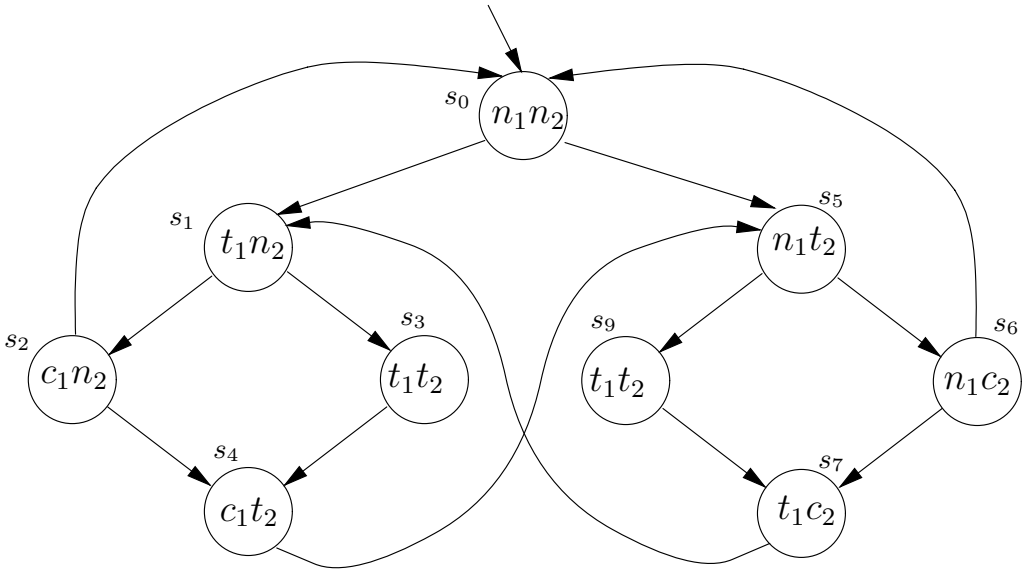
- we include an arrow from s_4, or s_7, to itself

Liveness:

$$\mathrm{G}\,(t_1 \to \mathrm{F}\; c_1)$$

Not Satisfied *again*

方法: Consider "fairness constraints", 见后



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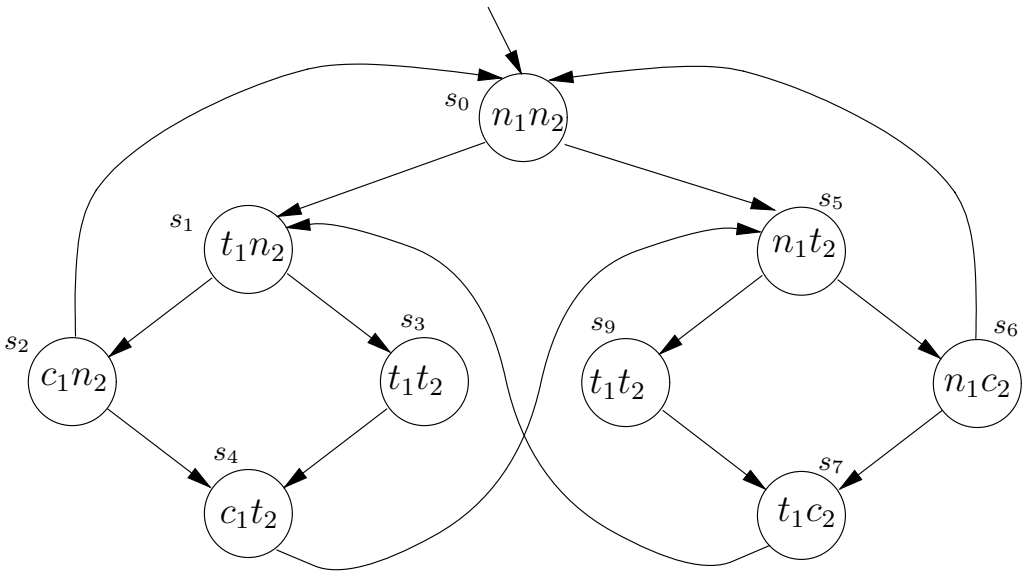

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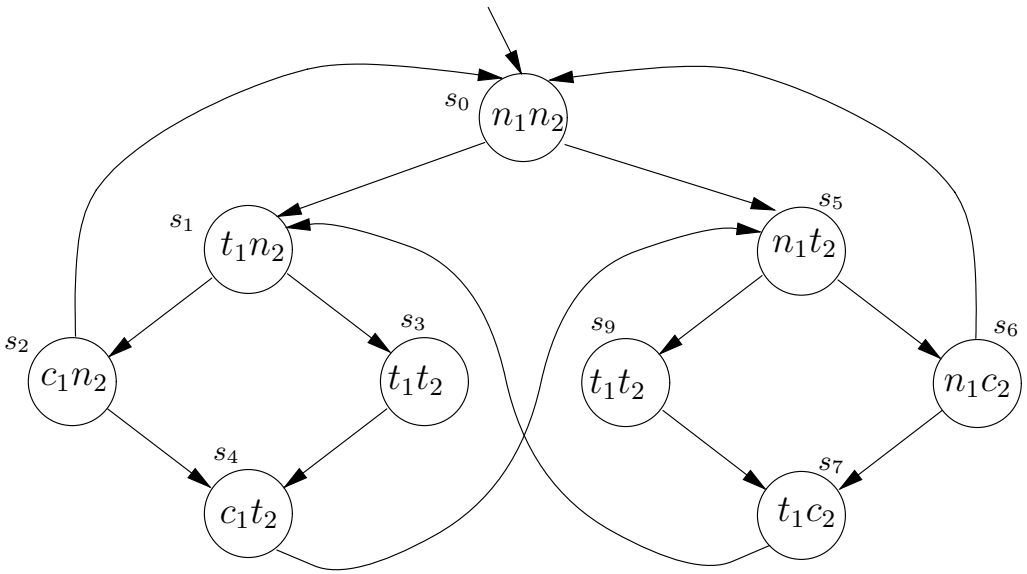

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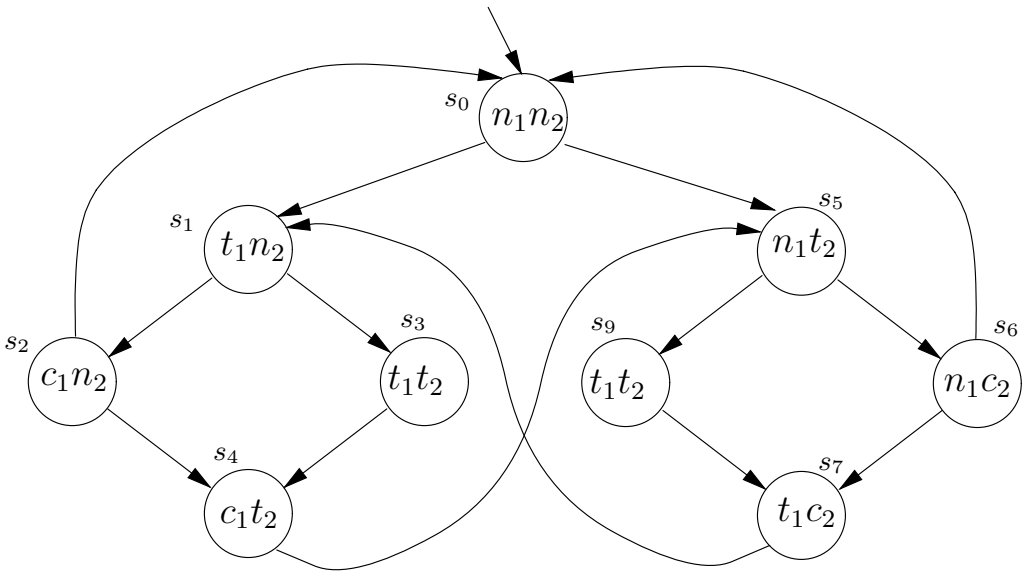

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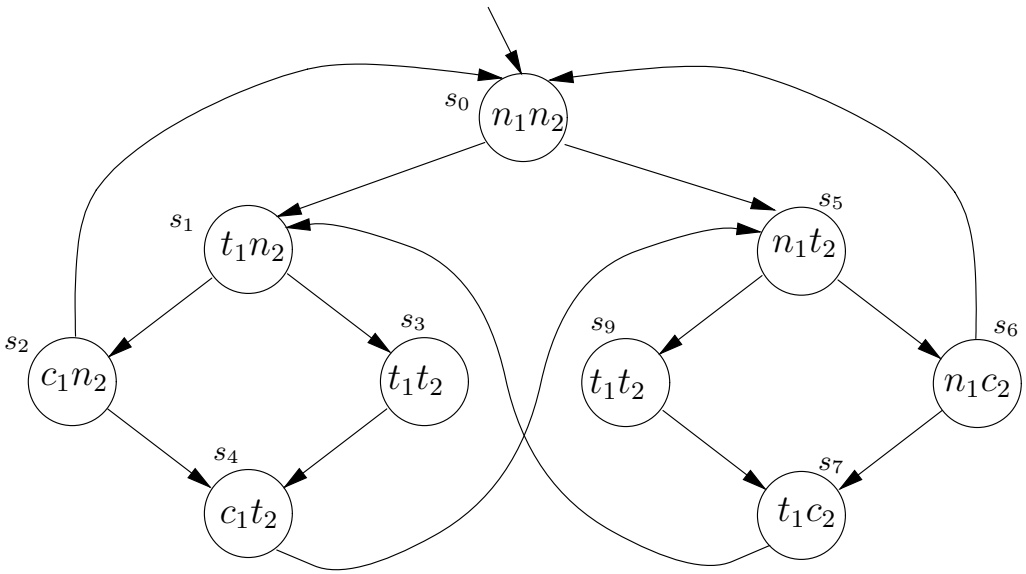

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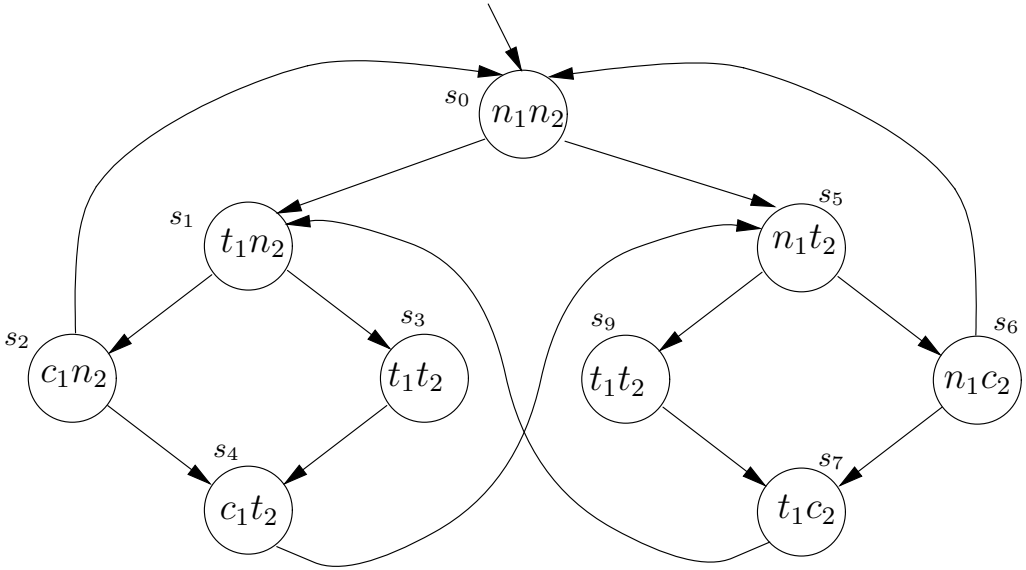
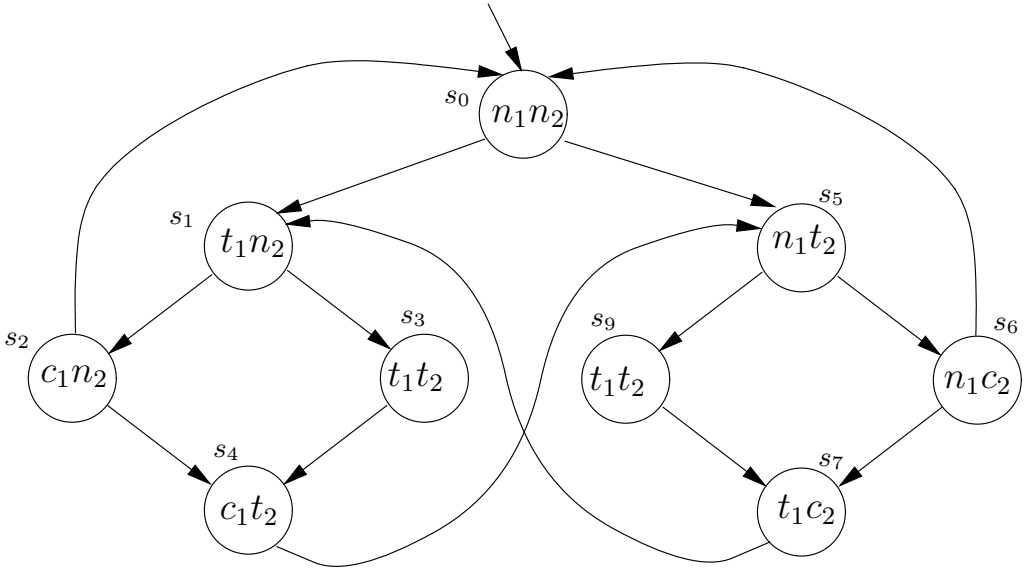


新问题 2: How to distinguish between states s_3 and s_9 in NuSMV?

方法: introduce a new variable, named turn, 见后



新问题 2: How to distinguish between states s_3 and s_9 in NuSMV?

方法: introduce a new variable, named turn, **见后**

3rd attempt

```
MODULE main
  VAR
    pr1: process prc(pr2.st, turn, FALSE);
    pr2: process prc(pr1.st, turn, TRUE);
    turn: boolean;
  ASSIGN
    init(turn) := FALSE;
    ...
```

问题 2 的解决方法: introduce a new variable, named **turn**

```
MODULE prc(other-st, turn, myturn)
  VAR
st: {n, t, c};
  ASSIGN
    init(st) := n;
...
```

So, the variables are: st of prc1, st of prc2, turn

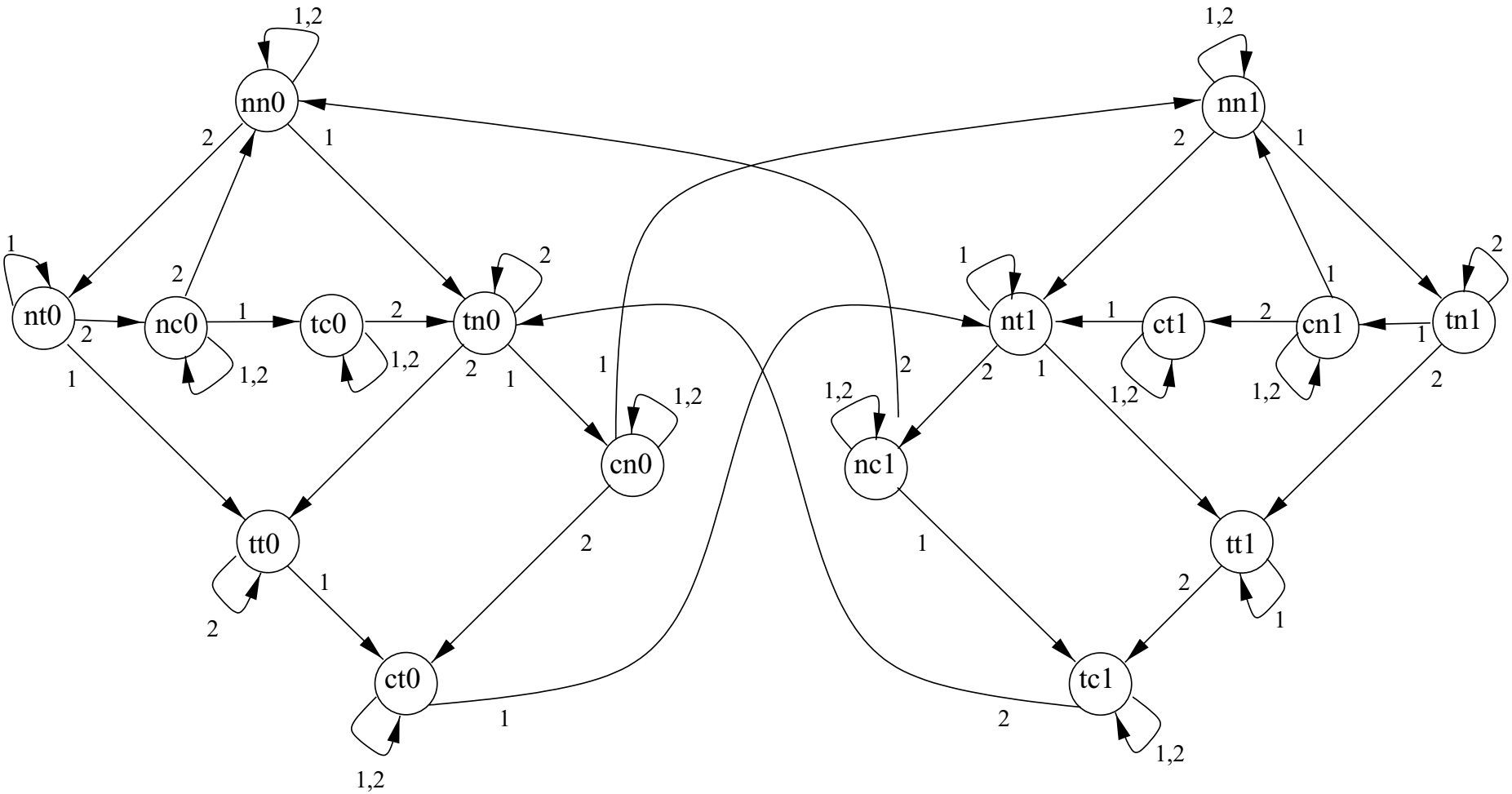
```
MODULE prc(other-st, turn, myturn)
...
next(st) :=
  case
    (st = n)      : {t,n};
    (st = t) & (other-st = n)   : c;
    (st = t) & (other-st = t) & (turn = myturn): c;
    (st = c)      : {c,n};
    TRUE    : st;
  esac;
...
```

```
MODULE prc(other-st, turn, myturn)
...
next(turn) :=
  case
    turn = myturn & st = c : !turn;
    TRUE                   : turn;
  esac;
...
```

```
MODULE prc(other-st, turn, myturn)
...
FAIRNESS running
FAIRNESS  ! (st = c)
...
```

问题 1 的解决方法: Consider "fairness constraints":

- We can restrict its search tree to execution paths along which an arbitrary *boolean formula* about the state ϕ is *true infinitely often*.


nn0
nt0
nc0
tc0
tn0
cn0
tt0
ct0
nn1
nt1
ct1
cn1
tn1
nc1
tt1
tc1
1,2
1
2

```
// safety
LTLSPEC  G!((pr1.st = c) & (pr2.st = c))
// liveness
LTLSPEC  G((pr1.st = t) -> F (pr1.st = c))
LTLSPEC  G((pr2.st = t) -> F (pr2.st = c))
// 'negation' of strict sequencing (desired to be false
LTLSPEC G(pr1.st=c -> ( G pr1.st=c | (pr1.st=c U
  ( pr1.st!=c & G pr1.st!=c | (( pr1.st!=c) U pr2.st=c)))
```

运行结果: $ ./NuSMV c-sample2-mutex.smv

```
-- specification  G !(pr1.st = c & pr2.st = c)  is true
-- specification  G (pr1.st = t ->  F pr1.st = c)  is true
-- specification  G (pr2.st = t ->  F pr2.st = c)  is true
-- specification  G (pr1.st = c -> ( G pr1.st = c | (pr1.st = c
U ((pr1.st !== c & &  G p ppr1.s.sssst ! !!====!=!=t !=.st !=r1.
st != G pr1.st !=c &  G p1r1.st !=!=t != c &  G 1spr1s.st !=1. c
st c!c=c c &  p1G p1r1.
-- as demonstrated by the following execution sequence
Trace Description: LTL Counterexample
Trace Type: Counterexample
  -> State: 1.1 <-
    pr1.st = n
    pr2.st = n
    turn = FALSE
```

运行结果: $ ./NuSMV c-sample2-mutex.smv

```
-> State: 1.1 <-
  pr1.st = n
  pr2.st = n
  turn = FALSE
-> Input: 1.2 <-
  _process_selector_ = pr1
  running = FALSE
  pr2.running = FALSE
  pr1.running = TRUE
-> State: 1.2 <-
-> Input: 1.3 <-
  _process_selector_ = pr2
  pr2.running = TRUE
  pr1.running = FALSE
-> State: 1.3 <-
  pr2.st = t
-> Input: 1.4 <-
-> State: 1.4 <-
  pr2.st = c
-> Input: 1.5 <-
  _process_selector_ = pr1
  pr2.running = FALSE
  pr1.running = TRUE
-> State: 1.5 <-
  pr1.st = t
-> Input: 1.6 <-
  _process_selector_ = pr2
  pr2.running = TRUE
  pr1.running = FALSE
-> State: 1.6 <-
  pr2.st = n
-> Input: 1.7 <-
  _process_selector_ = pr1
  pr2.running = FALSE
  pr1.running = TRUE
-> State: 1.7 <-
  pr1.st = c
-> Input: 1.8 <-
-> State: 1.8 <-
  pr1.st = n
  turn = TRUE
-> Input: 1.9 <-
-> State: 1.9 <-
  pr1.st = t
-> Input: 1.10 <-
-> State: 1.10 <-
  pr1.st = c
-> Input: 1.11 <-
-- Loop starts here
-> State: 1.11 <-
  pr1.st = n
-> Input: 1.12 <-
  _process_selector_ = main
  running = TRUE
  pr1.running = FALSE
-- Loop starts here
-> State: 1.12 <-
-> Input: 1.13 <-
  _process_selector_ = pr1
  running = FALSE
  pr1.running = TRUE
-- Loop starts here
-> State: 1.13 <-
-> Input: 1.14 <-
  _process_selector_ = pr2
  pr2.running = TRUE
  pr1.running = FALSE
-- Loop starts here
-> State: 1.14 <-
-> Input: 1.15 <-
  _process_selector_ = main
  running = TRUE
  pr2.running = FALSE
-> State: 1.15 <-
```

例: Foxes and Rabbits

如何用 NuSMV 进行*SAT* 求解?

- *Three* foxes and *three* rabbits have to cross a river
- There is only one boat that can carry *at most two* animals
- When the boat is *on the river*, at *each* of the *sides* the number of *foxes* should be $\leq$ the number of *rabbits*, otherwise the rabbits will be eaten

Is there a solution? which?

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要点: *Automated Reasoning*: *Do not* think about how to solve it, *only* specify the rules, and let the tool to solve it

Several ways to encode

We prefer not to define the moves in both directions separately

Variables:

- b: a boolean expressing where the boat is
- f: the number of foxes at the side where the boat is
- fb: the number of foxes that goes into the boat
- r: the number of rabbits at the side where the boat is
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```
MODULE main
  VAR
    r : 0..3;
    rb : 0..2;
    f : 0..3;
    fb : 0..2;
    b : boolean;
```

- b: a boolean expressing where the boat is
- f: the number of foxes at the side where the boat is
- fb: the number of foxes that goes into the boat
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```
INIT
b & f = 3 & r = 3
```

- b: a boolean expressing where the boat is
- f: the number of foxes at the side where the boat is
- fb: the number of foxes that goes into the boat
- r: the number of rabbits at the side where the boat is
- rb: the number of rabbits that goes into the boat

```
TRANS
next(b) = !b &
fb + rb <= 2 &
fb + rb >= 1 &
f - fb <= r - rb &
next(f) = 3 - f + fb &
next(r) = 3 - r + rb
CTLSPEC !EF(!b & f = 3 & r = 3)
```

运行结果: $ ./NuSMV c-sample3-fox.smv

```
-- specification !(EF ((!b & f = 3) & r = 3))  is false
-- as demonstrated by the following execution sequence
Trace Description: CTL Counterexample
Trace Type: Counterexample
```

```
-> State: 1.1 <-
  r = 3
  rb = 1
  f = 3
  fb = 1
  b = TRUE
-> State: 1.2 <-
  r = 1
  rb = 0
  f = 1
  b = FALSE
-> State: 1.3 <-
  r = 2
  f = 3
  fb = 2
  b = TRUE
```

```
-> State: 1.4 <-
  r = 1
  f = 2
  fb = 1
  b = FALSE
-> State: 1.5 <-
  r = 2
  rb = 1
  b = TRUE
-> State: 1.6 <-
  rb = 0
  b = FALSE
-> State: 1.7 <-
  r = 1
  fb = 2
  b = TRUE
```

```
-> State: 1.8 <-
  r = 2
  f = 3
  fb = 1
  b = FALSE
-> State: 1.9 <-
  r = 1
  rb = 1
  f = 1
  b = TRUE
-> State: 1.10 <-
  r = 3
  f = 3
  b = FALSE
```

b=FALSE, f=3, r=3

indeed showing that the final state where all animals reached the other side

运行结果: $ ./NuSMV c-sample3-fox.smv

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  r = 2
  f = 3
  fb = 2
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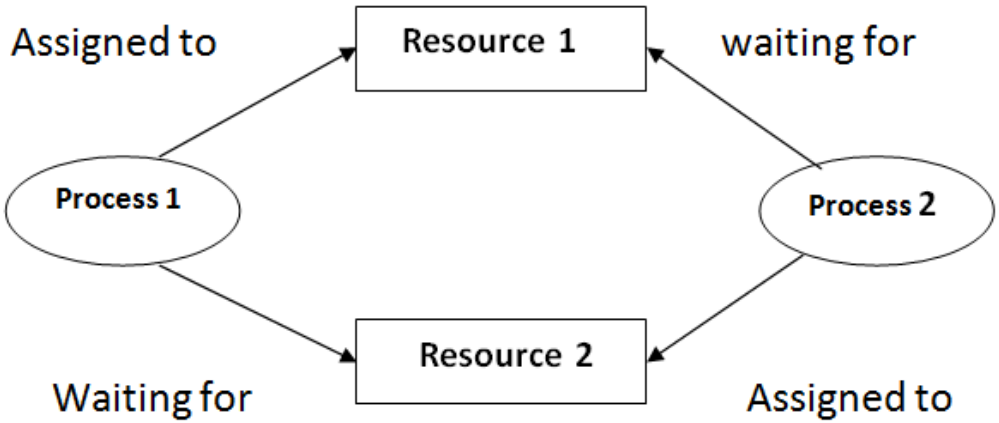
```

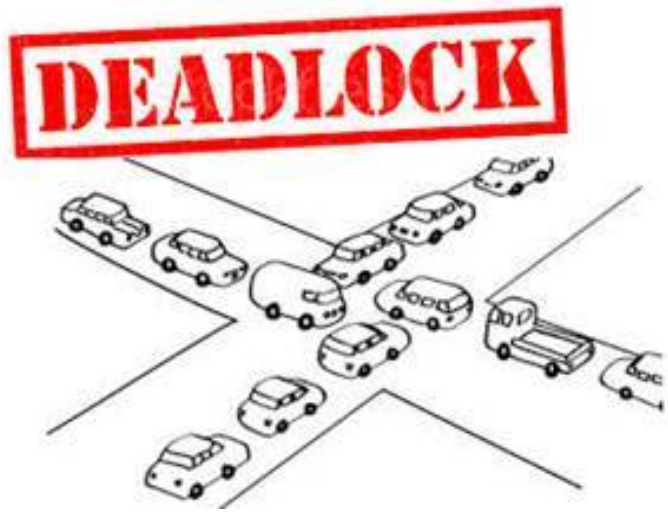
```
-> State: 1.4 <-
  r = 1
  f = 2
  fb = 1
  b = FALSE
-> State: 1.5 <-
  r = 2
  rb = 1
  b = TRUE
-> State: 1.6 <-
  rb = 0
  b = FALSE
-> State: 1.7 <-
  r = 1
  fb = 2
  b = TRUE
```

```
-> State: 1.8 <-
  r = 2
  f = 3
  fb = 1
  b = FALSE
-> State: 1.9 <-
  r = 1
  rb = 1
  f = 1
  b = TRUE
-> State: 1.10 <-
  r = 3
  f = 3
  b = FALSE
```

b=FALSE, f=3, r=3

indeed showing that the final state where all animals reached the other side





问题: What is a *deadlock* here?

- a *state* that cannot be changed by applying the rules

Occurs very often in hardware, network protocols,...

定义: Deadlock

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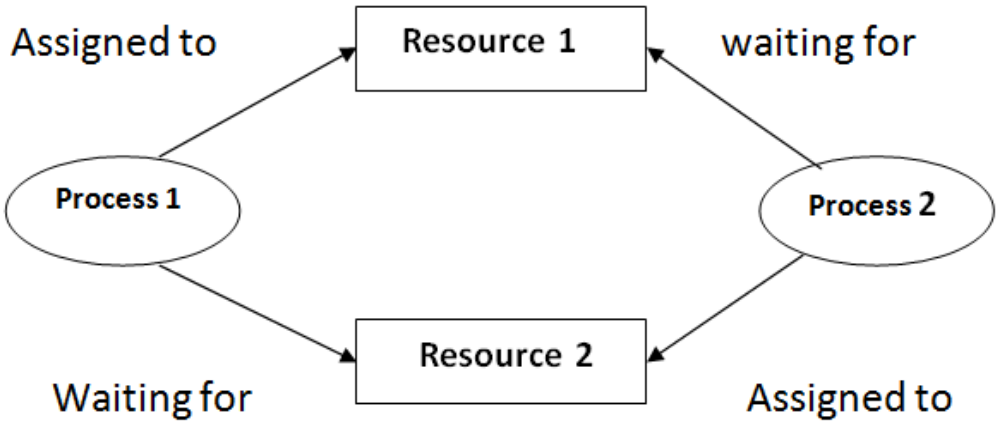

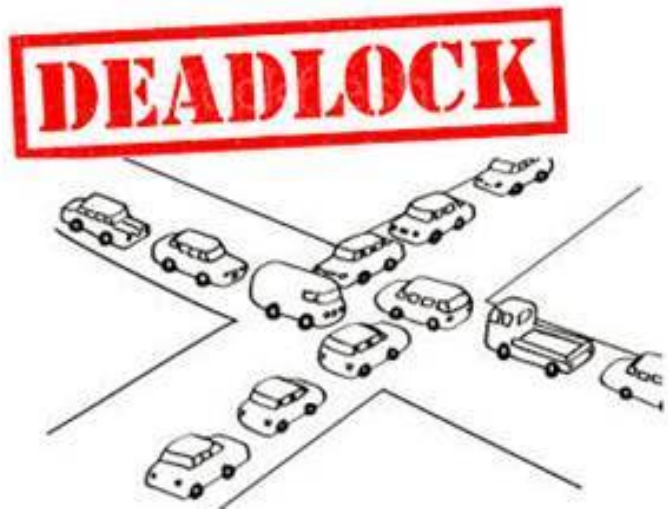

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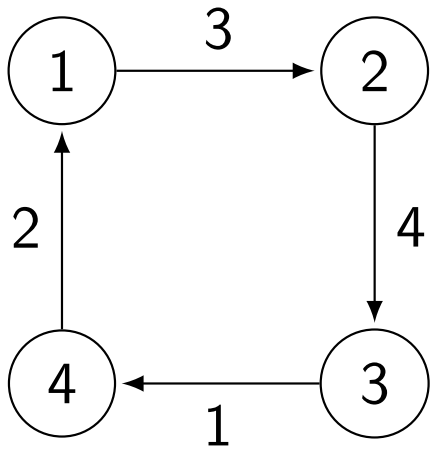
建模思路: Build a **Network** as a **Graph**

Messages in the Network:

- sent
- processed
- received

Edges are *channels*:

- either *empty*
- or filled by a *message* and a *destination*
  - So no two messages can be in the same channel



注: 这个 graph 与模型检测中的 transition system 模型的用途不同

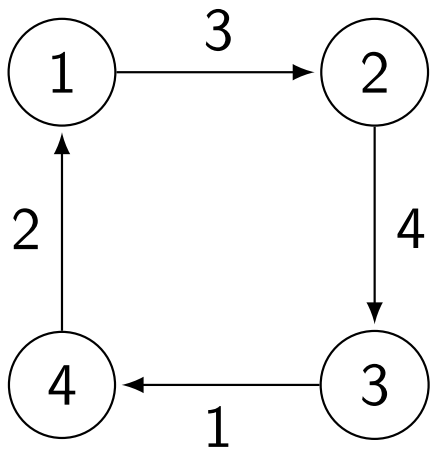
建模思路: Initialization

As the set of *initial states*, we choose the single state where every channel is empty

建模思路: Running

Our computation / processing is *asynchronous*

- That is, it is not controlled by a central clock, but *at any moment* a *send* step, a *processing* step or a *receiving* step *can be done*



验证思路: Specification

We wonder *whether* in a *particular network*, a deadlock state is *reachable*

实现: (1) Define the state space

- *message*: For investigating deadlocks, the *contents of the message* does not play a role: it will be *ignored*
- *node ID*: Number the nodes from 1 to n
- *channel*: So the *contents of a channel* is identified by
  - the *destination node* of the corresponding message, or
  - 0, if it is *empty*
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思路: **Determined** outgoing channel

For every node n and destination m, it should be *determined which outgoing channel c* from n is *allowed* to be chosen for passing a message to m

实现: (2) Define OK(n, m, c)

Write OK(n, m, c), if this is *allowed*

讨论: *Typically*, OK(n, m, c) yields true, if and only if *c is the first edge* of *a shortest path* from n to m

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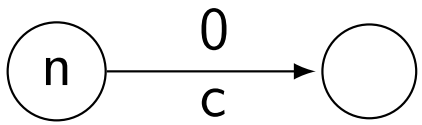
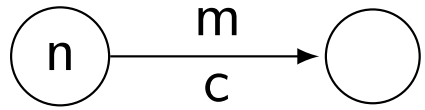
replace 

by 

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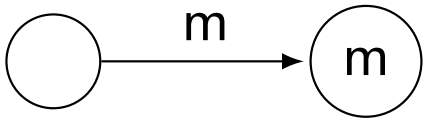
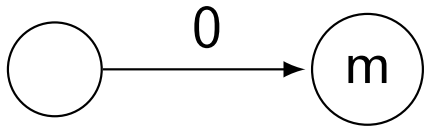
replace 

by 

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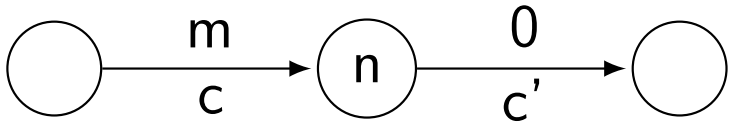
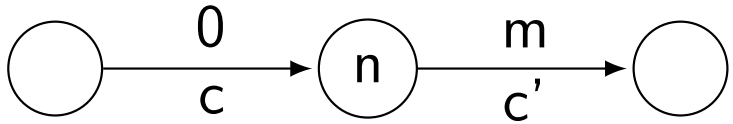
replace 

by 

c=m
c'=0

next(c)=0
next(c')=m

实现: (3) Define the transitions of states - **Disjunction**

The transition relation is a big *disjunction* of all possible *send*, *receive* and *processing* steps

```
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回顾: write *OK(n, m, c)*, if it is allowed to pass the message to the outgoing channel c from n, when a message has to be sent from n to m

- *send* steps: *if OK(n, m, c)*, then

- *receive* steps:

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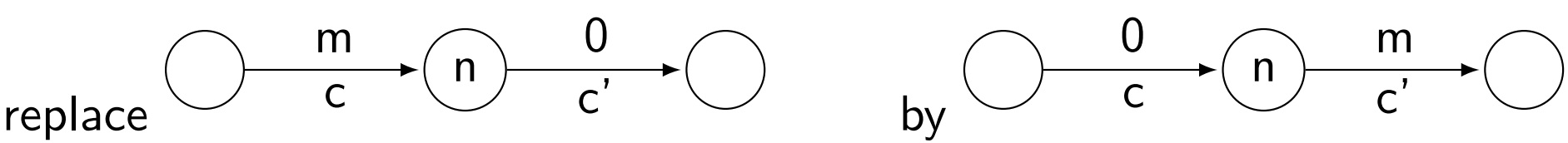

Let *M* be the set of *main* nodes: nodes that are allowed to send messages, and to which messages can be sent

Choose $M = \{1, 2, 3\}$ in

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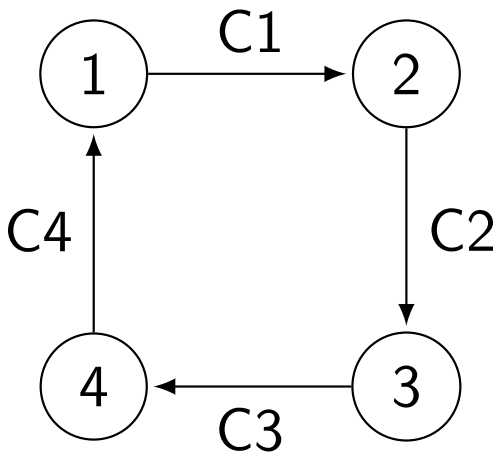

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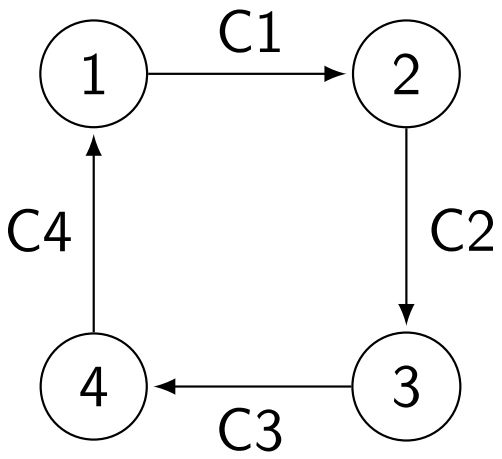

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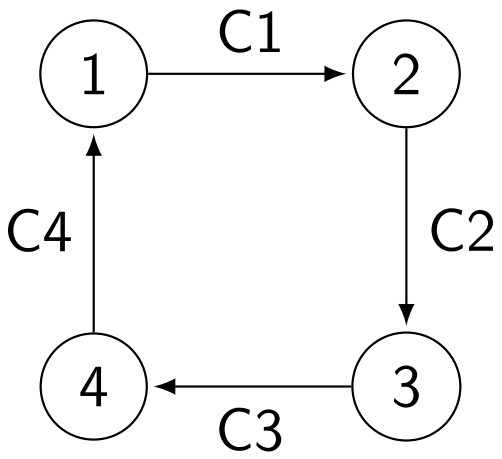

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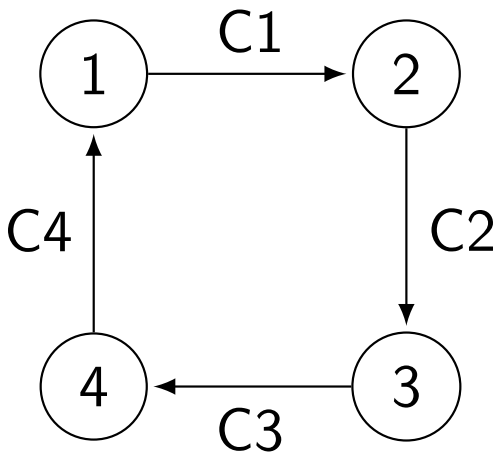

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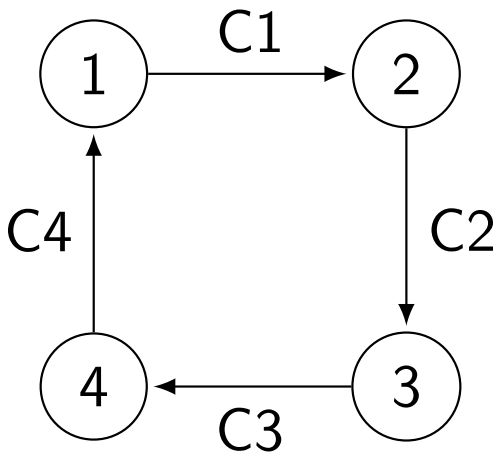

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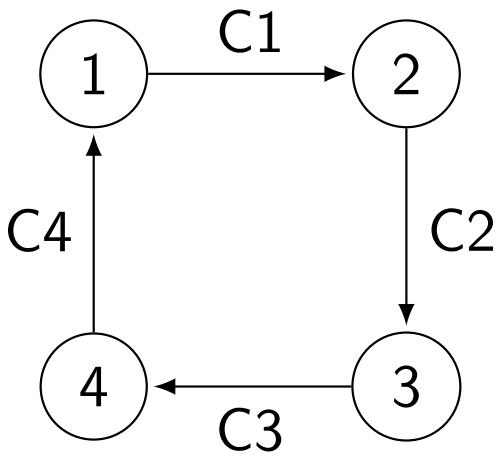

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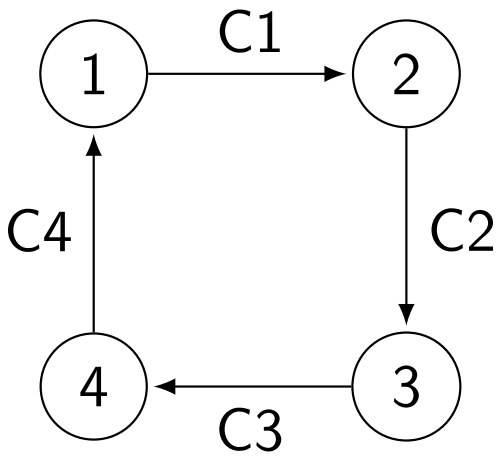

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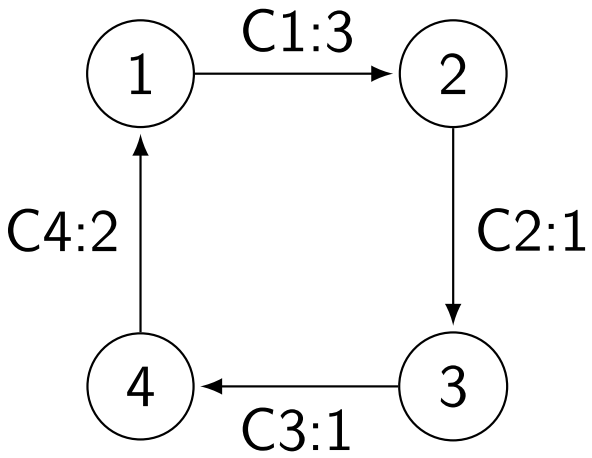

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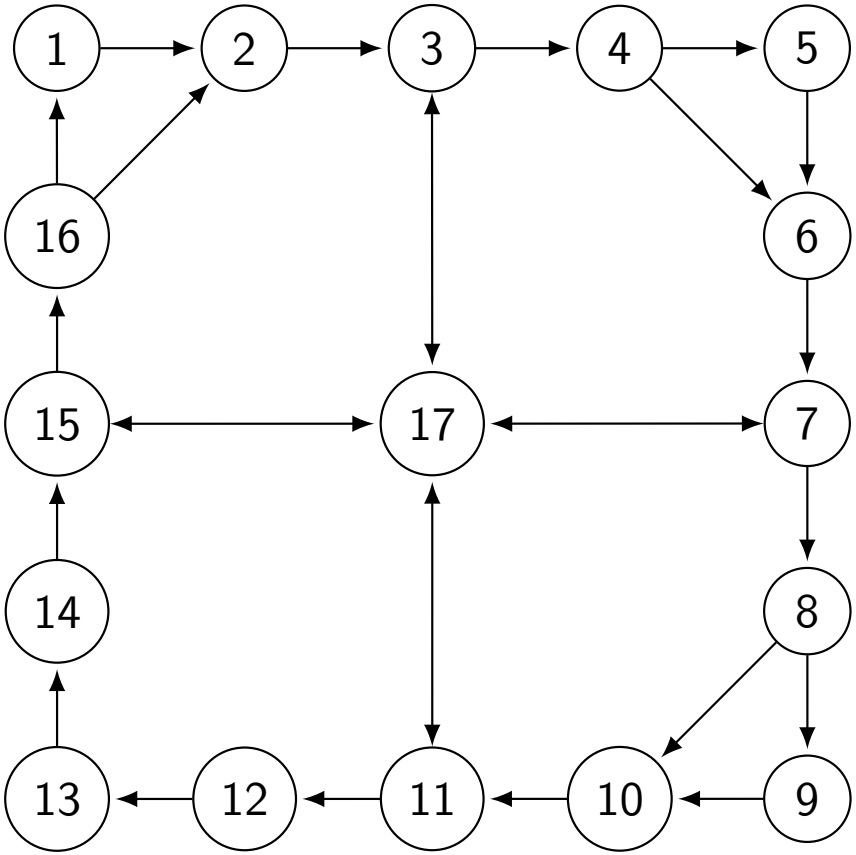

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But when taking $M = \{2, 4, 6\}$, a deadlock is reachable

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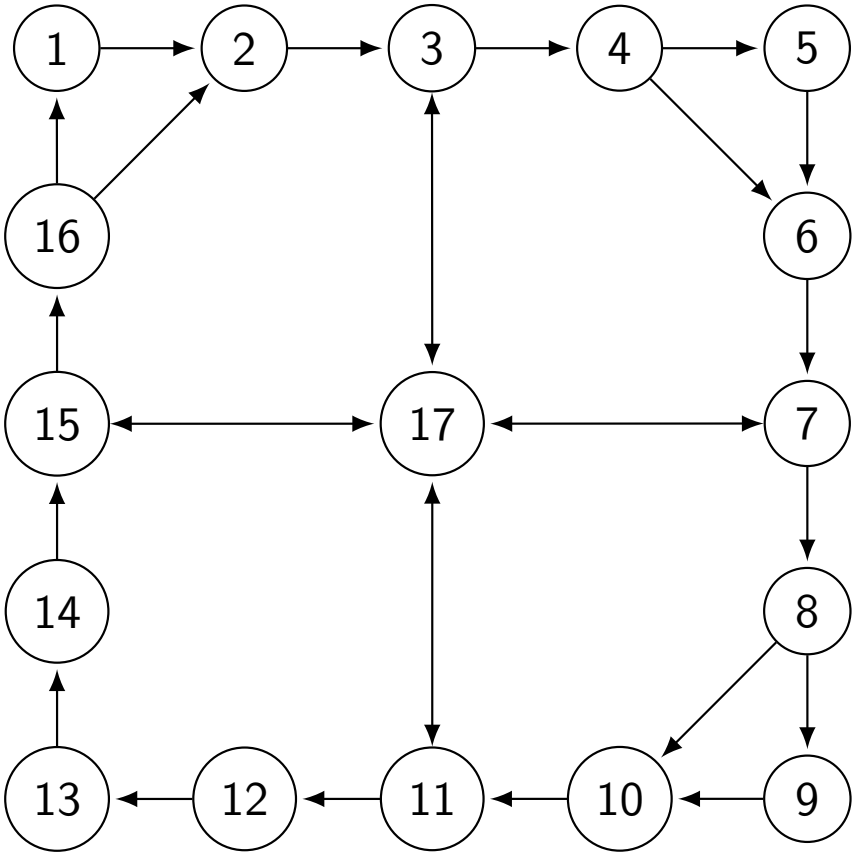

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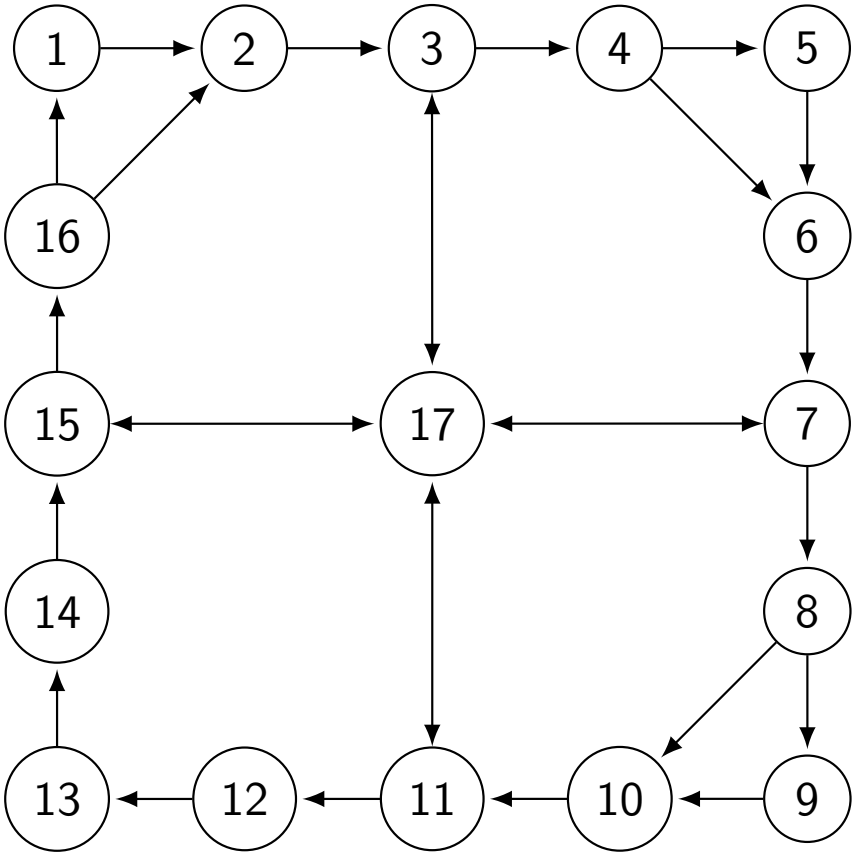

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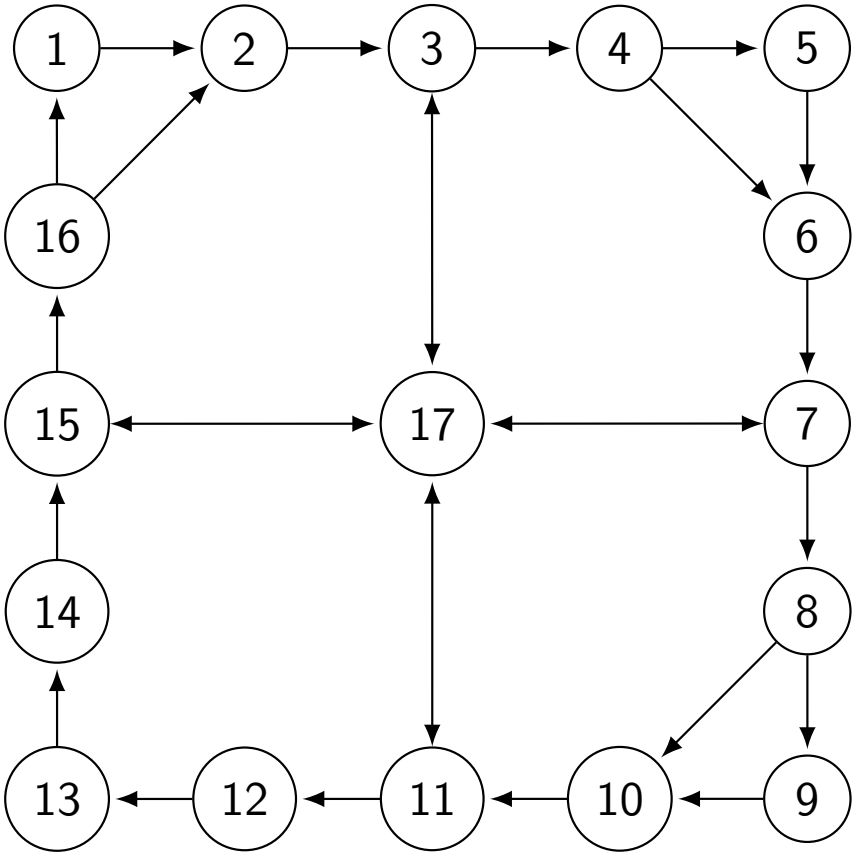

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Typical desired *property* to be verified: *No deadlock state is reachable*
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- Deadlock D is obtained as !Q in which Q is the disjunction of all non-TRUE branches in all these case statements

An interesting *variant* of deadlock: *local deadlock*:

- a particular variable *will never change* in the future
- for checking whether a channel c having value x causes such a local deadlock, we need a nested CTL formula
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总结: NuSMV for model checking, which can be used to

- model and verify a model
- solve an SAT problem

与普通编程语言的区别:

- *Do not* think about functions, think about *states* and transitions of states
- *Do not* think about how to solve it, *only* specify the rules, and let the tool to solve it

作业

实验小作业: 使用 NuSMV 实现 PPT 中 first-attempt model, 要求

- 用 CTL 设计 Non-blocking, No strict sequencing, 并验证所有四个性质
- 给出源码、实验报告

实验大作业（可选）: 选择一篇 CCF A 类论文，自己用 NuSMV 设计论文中的模型，并验证，附完整文档。
(也可选择 NuSMV 中 example 中的 A 类论文, 对已给出的模型进行阅读，并附完整的阅读、试验报告、以及心得体会)

实验大作业（可选）: 实现 PPT 中的 deadlock 验证，并针对 complicated example 中所给的结论进行验证。要求

- 附上源码和实验报告