On the complexity of monitoring Orchids signatures

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Orchids

- An intrusion detection system,
  initially based on model-checking ideas [GL, Roger, CSFW'01]
  semantics and optimizations made precise in [GL, Olivain, RV'08]

- Should really be seen as a **trace-based monitor**.

- Detection can be expensive (at least in theory).

- Detection cost depends on signatures (=rules, =specifications):
  Which signatures are expensive?
  Can we decide which, **algorithmically**?

Complexity of monitors

- **Goal:** Estimate upper bound $f_S(n)$ on
  number of threads (=monitor instances)
  — after reading n events
  — while monitoring signature S
  We shall give a simple **definition** of $f_S(n)$.

- **Decision problem**:
  INPUT: a signature S
  QUESTION: is $f_S(n)$ asymptotically polynomial?
  [Bonus question: if so, for which k is it $O(n^k)$?]
  We give a **linear-time algorithm**.

Related work

- Complexity of monitor algorithms:
  - **RV-Monitor** [Luo et al., RV'14], data-driven:
    $f_S(n)$ polynomial, degree k = #parameters
  - **MonPoly-*** [Basin et al., JACM'15]:
    $f_S(n)$ polynomial, degree k: see paper
- We will reduce our problem to asymptotics of **recurrence equations**: see **Analytic Combinatorics** [Flajolet, Sedgwick '09], but:
  — Our solution is more elementary
  — Our problem is slightly outside the scope of AC (max operator)

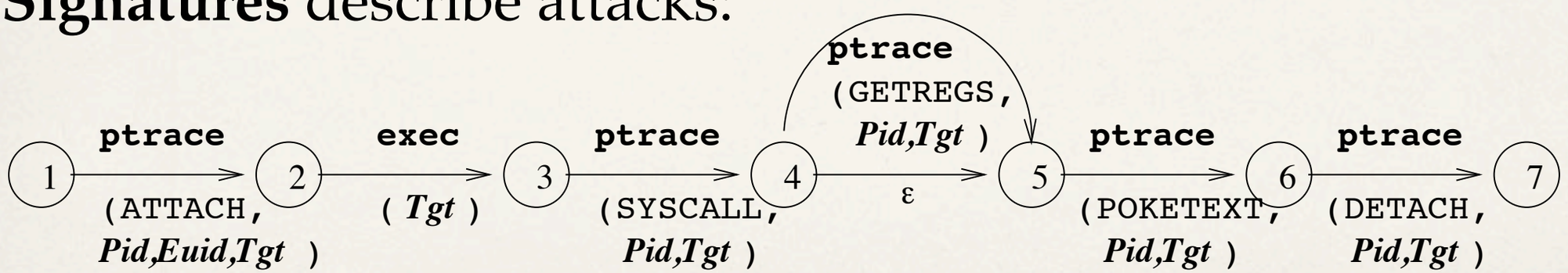
Intrusion detection through model-checking [JGL&Roger, CSF01]

- The monitored machines collect **events**:

Time

```
open ("/etc/passwd", "r", pid=58, euid=500)
ptrace (ATTACH, pid=57, euid=500, 58)
ptrace (ATTACH, pid=100, euid=500, 101)
exec (prog="modprobe", pid=101)
ptrace (ATTACH, pid=100, euid=500, 101)
exit (pid=58)
ptrace (SYSCALL, pid=100, 101)
ptrace (GETREGS, pid=100, 101)
ptrace (POKETEXT, pid=100, 101)
ptrace (POKETEXT, pid=100, 101)
ptrace (POKETEXT, pid=100, 101)
ptrace (DETACH, pid=100, 101)
```

- **Signatures** describe attacks:



Orchids signatures, really

```
rule pidtrack synchronized($pid)
{
  state init
  {
    expect (.auditd.syscall==SYS_clone)
      goto newpid;
  }

  state newpid! {
    $pid = .auditd.exit;
    $uid = .auditd.euid;
    $gid = .auditd.egid;
    goto wait;
  }

  state wait!
  {
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_execve &&
            (.auditd.uid != .auditd.euid || .auditd.gid != .auditd.egid) &&
            .auditd.success == "yes")
      goto update_uid_gid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresuid ||
             .auditd.syscall == SYS_setreuid ||
             .auditd.syscall == SYS_setuid) &&
            .auditd.success == "yes")
      goto update_setuid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresgid ||
             .auditd.syscall == SYS_setregid ||
             .auditd.syscall == SYS_setgid) &&
            .auditd.success == "yes")
      goto update_setgid;
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_exit)
      goto end;
    expect (.auditd.pid == $pid &&
            (.auditd.euid != $uid || .auditd.egid != $gid))
      goto alert;
  }

  state update_uid_gid!
  {
    $uid = .auditd.euid;
    $gid = .auditd.egid;
    goto wait;
  }

  state update_setuid!
  {
    case (.auditd.egid != $gid) goto alert;
    else goto update_uid_gid;
  }

  state update_setgid!
  {
    case (.auditd.euid != $uid) goto alert;
    else goto update_uid_gid;
  }

  state alert!
  {
    $newuid = .auditd.euid;
    $newgid = .auditd.egid;
    report();
  }

  state end!
  {
    /* all went well */
  }
}
```

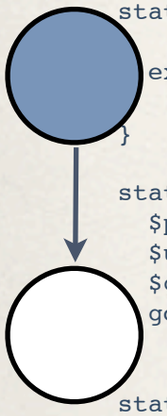
Orchids signatures: checking

Create new thread (=monitor instance),
waiting for some event satisfying Boolean condition

```
rule pi
{
  state

    expect (.auditd.syscall==SYS_clone)
      goto newpid;
  }

  state newpid! {
    $pid = .auditd.exit;
    $uid = .auditd.euid;
    $gid = .auditd.egid;
    goto wait;
  }

  state wait!
  {
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_execve &&
            (.auditd.uid != .auditd.euid || .auditd.gid != .auditd.egid) &&
            .auditd.success == "yes")
      goto update_uid_gid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresuid ||
             .auditd.syscall == SYS_setreuid ||
             .auditd.syscall == SYS_setuid) &&
            .auditd.success == "yes")
      goto update_setuid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresgid ||
             .auditd.syscall == SYS_setregid ||
             .auditd.syscall == SYS_setgid) &&
            .auditd.success == "yes")
      goto update_setgid;
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_exit)
      goto end;
    expect (.auditd.pid == $pid &&
            (.auditd.euid != $uid || .auditd.egid != $gid))
      goto alert;
  }
```

```
  state update_uid_gid!
  {
    $uid = .auditd.euid;
    $gid = .auditd.egid;
    goto wait;
  }

  state update_setuid!
  {
    case (.auditd.egid != $gid) goto alert;
    else goto update_uid_gid;
  }

  state update_setgid!
  {
    case (.auditd.euid != $uid) goto alert;
    else goto update_uid_gid;
  }

  state alert!
  {
    $newuid = .auditd.euid;
    $newgid = .auditd.egid;
    report();
  }

  state end!
  {
    /* all went well */
  }
}
```

Orchids signatures: checking



If found, fork new thread going to next state

```
rule pidtrack synchronized($pid)
{
  state init
  {
    exp
      g
  }

  state
    $pid = .auditd.exit;
    $uid = .auditd.euid;
    $gid = .auditd.egid;
    goto wait;

  state wait!
  {
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_execve &&
            (.auditd.uid != .auditd.euid || .auditd.gid != .auditd.egid) &&
            .auditd.success == "yes")
      goto update_uid_gid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresuid ||
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             .auditd.syscall == SYS_setuid) &&
            .auditd.success == "yes")
      goto update_setuid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresgid ||
             .auditd.syscall == SYS_setregid ||
             .auditd.syscall == SYS_setgid) &&
            .auditd.success == "yes")
      goto update_setgid;
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_exit)
      goto end;
    expect (.auditd.pid == $pid &&
            (.auditd.euid != $uid || .auditd.egid != $gid))
      goto alert;
  }

  state update_setuid!
  {
    case (.auditd.egid != $gid) goto alert;
    else goto update_uid_gid;
  }

  state update_setgid!
  {
    case (.auditd.euid != $uid) goto alert;
    else goto update_uid_gid;
  }

  state alert!
  {
    $newuid = .auditd.euid;
    $newgid = .auditd.egid;
    report();
  }

  state end!
  {
    /* all went well */
  }
}
```
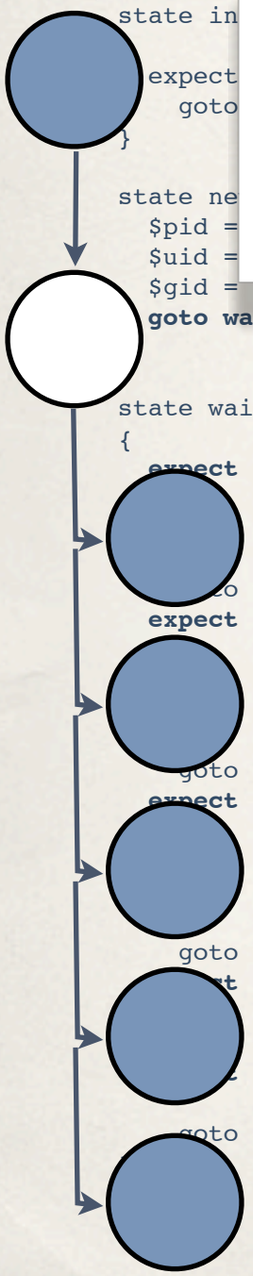

Orchids signatures: checking



```
rule pidtrack synchronized($pid)
{
  state in
    expect
      goto
  }

  state ne
    $pid =
    $uid =
    $gid = .auditd.egid;
    goto wait;

  state wait!
  {
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_execve &&
            (.auditd.uid != .auditd.euid || .auditd.gid != .auditd.egid) &&
            .auditd.success == "yes")
      goto update_uid_gid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresuid ||
             .auditd.syscall == SYS_setreuid ||
             .auditd.syscall == SYS_setuid) &&
            .auditd.success == "yes")
      goto update_setuid;
    expect (.auditd.pid == $pid &&
            (.auditd.syscall == SYS_setresgid ||
             .auditd.syscall == SYS_setregid ||
             .auditd.syscall == SYS_setgid) &&
            .auditd.success == "yes")
      goto update_setgid;
    expect (.auditd.pid == $pid &&
            .auditd.syscall == SYS_exit)
      end;
    expect (.auditd.pid == $pid &&
            (.auditd.euid != $uid || .auditd.egid != $gid))
      goto alert;
```

goto next state, waiting on 5 Boolean conditions:
create 5 threads, one for each

```
  state update_setuid!
  {
    case (.auditd.egid != $gid) goto alert;
    else goto update_uid_gid;
  }

  state update_setgid!
  {
    case (.auditd.euid != $uid) goto alert;
    else goto update_uid_gid;
  }

  state alert!
  {
    $newuid = .auditd.euid;
    $newgid = .auditd.egid;
    report();
  }

  state end!
  {
    /* all went well */
  }
}
```

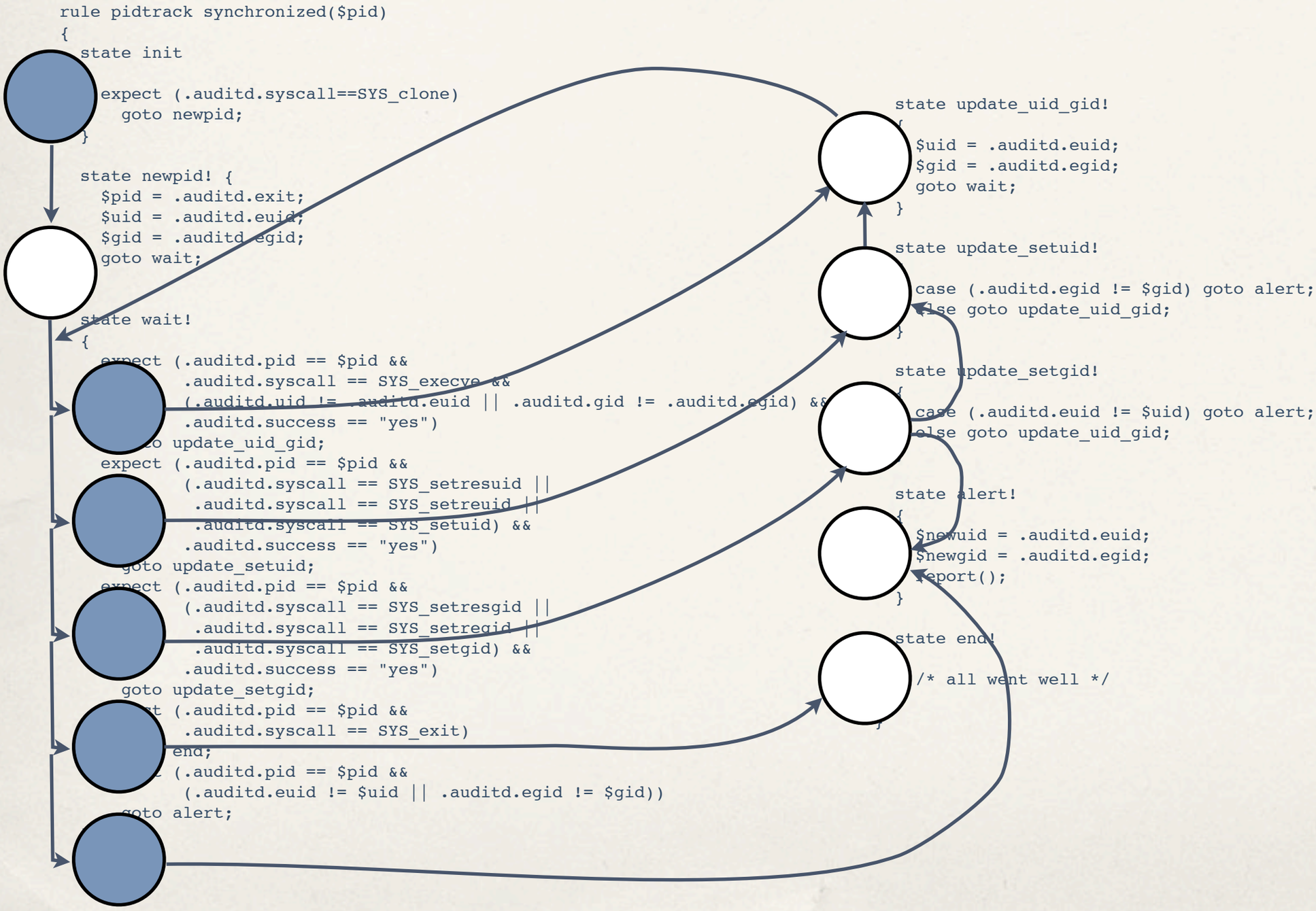
Orchids signatures: checking

```
rule pidtrack synchronized($pid)
{
  state init

    expect (.auditd.syscall==SYS_clone)
    }

  stat
    $p
    $u
    $gid = .auditd.egid;
    goto wait;

state wait!
{
  expect (.auditd.pid == $pid &&
          .auditd.syscall == SYS_execve &&
          (.auditd.uid != .auditd.euid || .auditd.gid != .auditd.egid) &&
          .auditd.success == "yes")
    goto update_uid_gid;
  expect (.auditd.pid == $pid &&
          (.auditd.syscall == SYS_setresuid ||
           .auditd.syscall == SYS_setreuid ||
           .auditd.syscall == SYS_setuid) &&
          .auditd.success == "yes")
    goto update_setuid;
  expect (.auditd.pid == $pid &&
          (.auditd.syscall == SYS_setresgid ||
           .auditd.syscall == SYS_setregid ||
           .auditd.syscall == SYS_setgid) &&
          .auditd.success == "yes")
    goto update_setgid;
    t (.auditd.pid == $pid &&
          .auditd.syscall == SYS_exit)
    end;
    (.auditd.pid == $pid &&
          (.auditd.euid != $uid || .auditd.egid != $gid))
    goto alert;
```

```
state update_uid_gid!

state update_setuid!

  case (.auditd.egid != $gid) goto alert;
  else goto update_uid_gid;
}

state update_setgid!
{
  case (.auditd.euid != $uid) goto alert;
  else goto update_uid_gid;

state alert!
{
  $newuid = .auditd.euid;
  $newgid = .auditd.egid;
  report();
}

state end!

  /* all went well */
}
```

If found, fork new thread going to next state

Orchids signatures, as automata



From signatures to recurrence equations

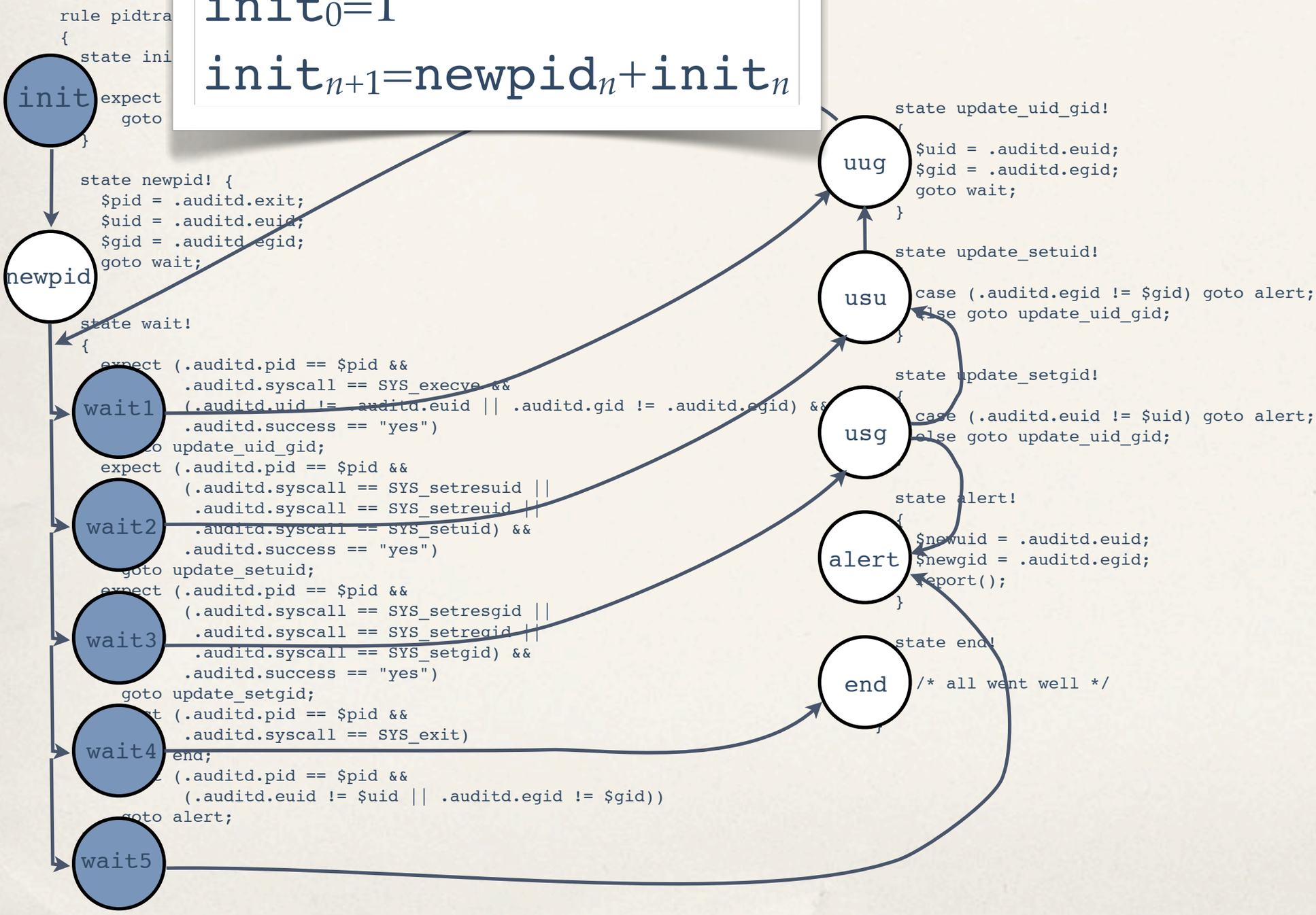
- For each program point q,
  define a sequence of natural numbers q_n, $n \in \mathbb{N}$, so that:
  — if we start one thread at q,
  — and proceed to read n events
  then, after the n events have been read,
  at most q_n threads are in existence.

- We do not **compute** q_n,
  rather we **generate the equations** they must satisfy,
  symbolically.

Recurrence equations

$$init_0 = 1$$

$$init_{n+1} = newpid_n + init_n$$

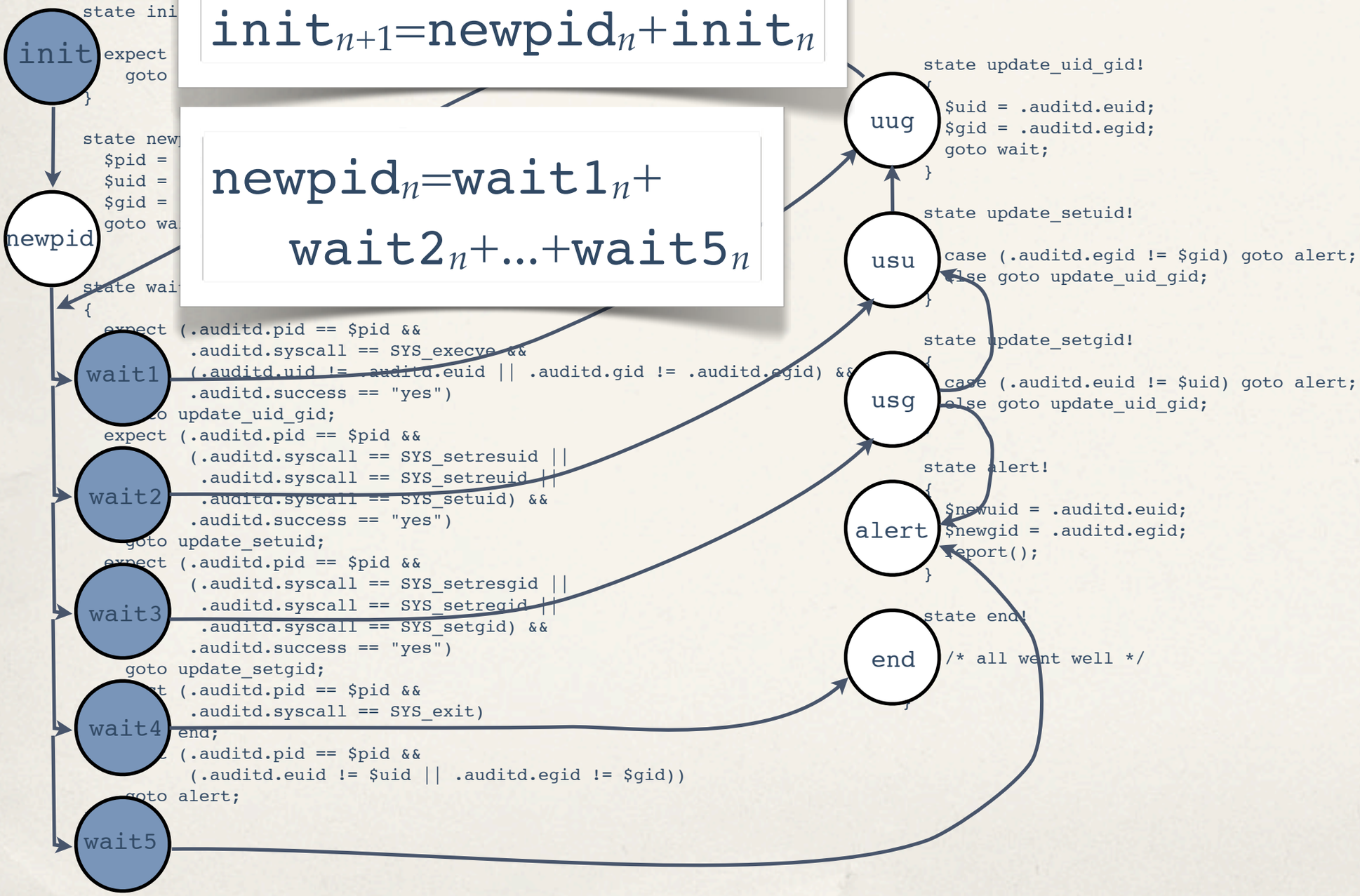


Recurrence equations

$$init_0 = 1$$

$$init_{n+1} = newpid_n + init_n$$

$$newpid_n = wait1_n + wait2_n + \ldots + wait5_n$$



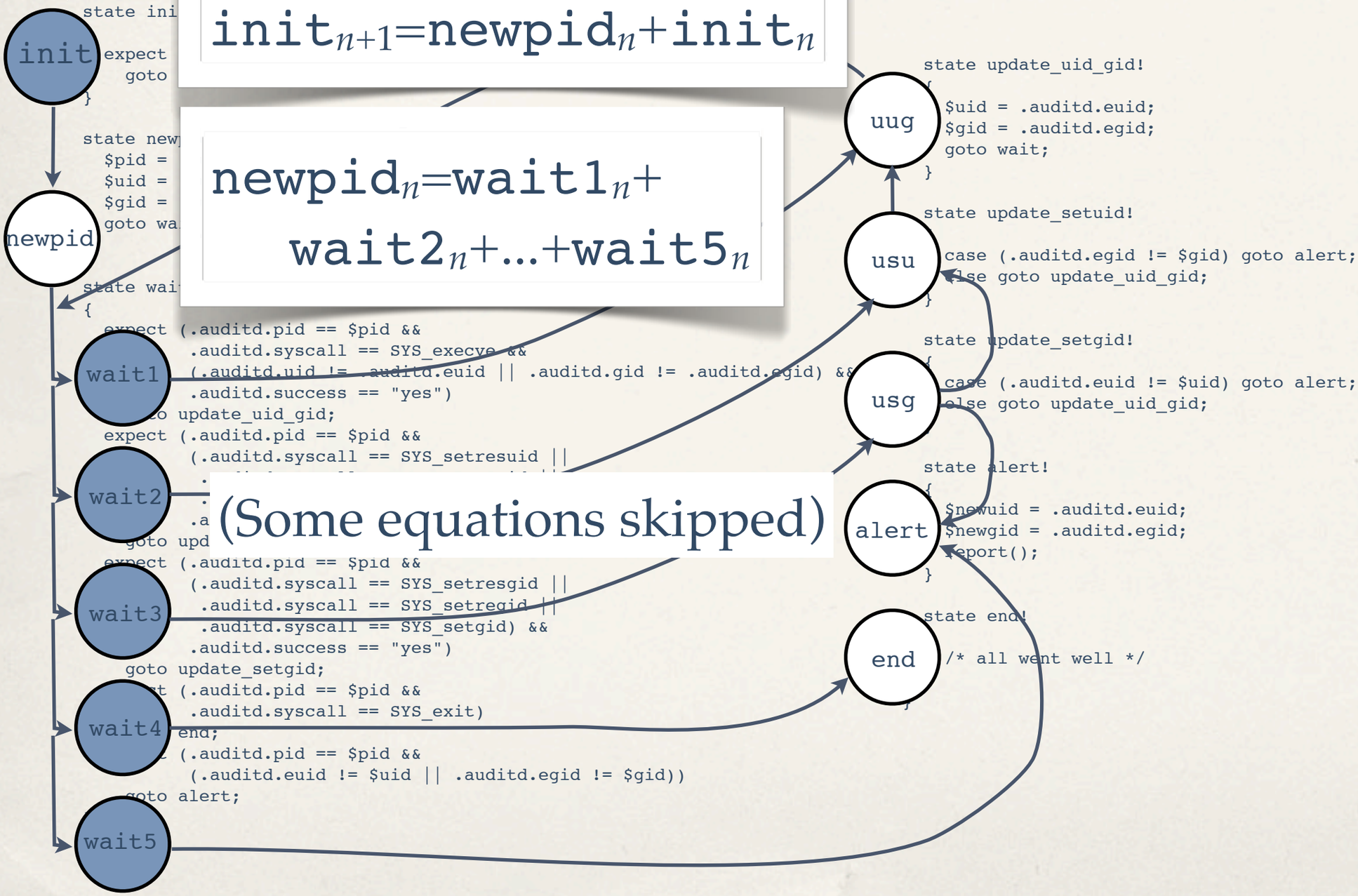
Recurrence equations

$$init_0 = 1$$

$$init_{n+1} = newpid_n + init_n$$

$$newpid_n = wait1_n + wait2_n + \ldots + wait5_n$$

(Some equations skipped)



Recurrence equations

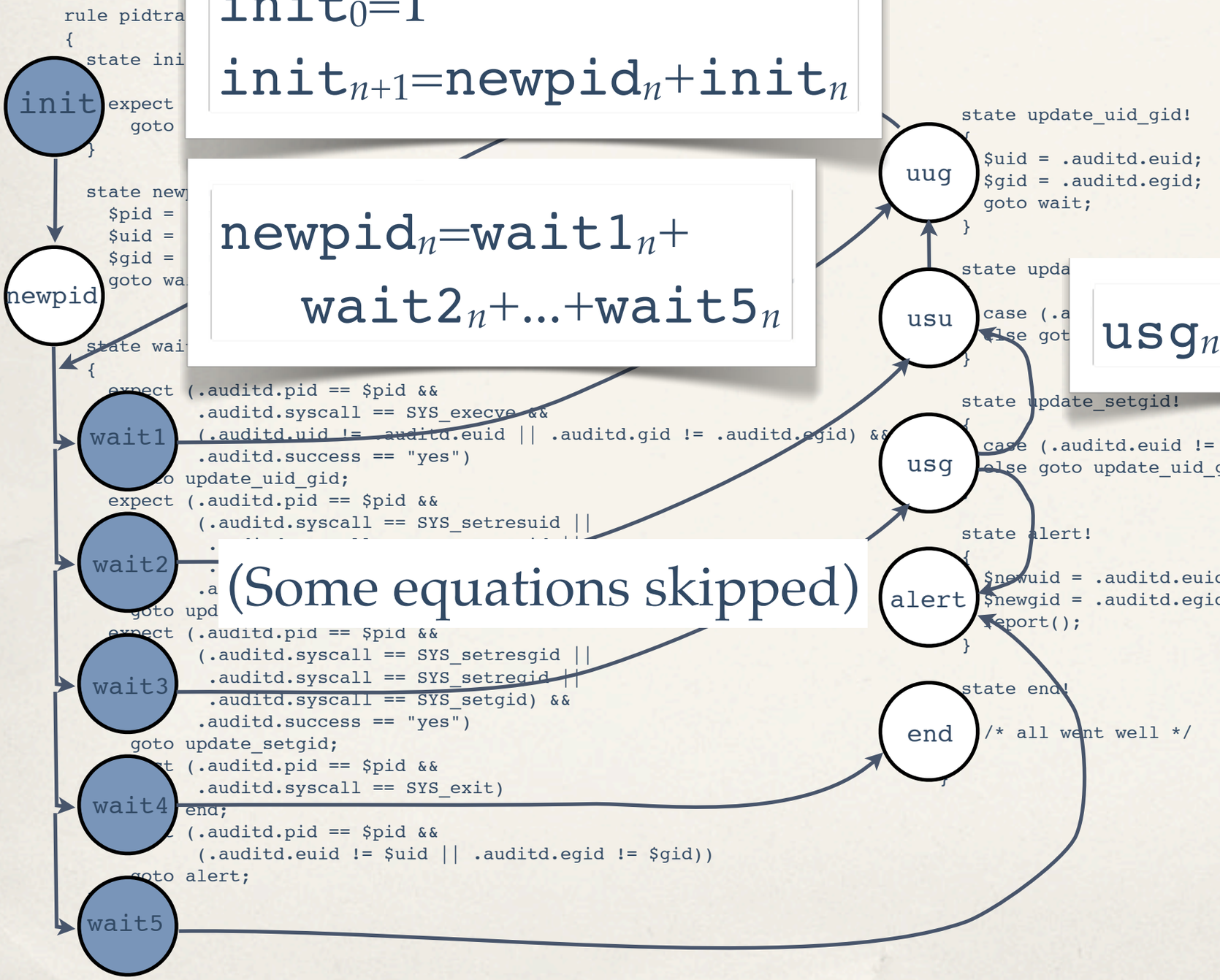
$$init_0 = 1$$

$$init_{n+1} = newpid_n + init_n$$

$$newpid_n = wait1_n + wait2_n + \ldots + wait5_n$$

$$usg_n = \max(usu_n, alert_n)$$

(Some equations skipped)



Recurrence equations: syntax

- INPUT: finite collection of equations of the form
  - (sums) $\boldsymbol{u_{n+k}=a_1\, v_n + a_2\, w_n + \ldots}$, where each $a_i>0$ integer, k natural
  - (max) $\boldsymbol{u_{n+k}=\max(v_n, w_n, \ldots)}$, k natural number
  - plus initial conditions u_0=constant ($\geq$=1, natural).
- Goal: find asymptotic formulae for every u_n, v_n, w_n, etc.

Converting to graphs

- Encode those equations as graphs, where:
  — each sequence (u_n) is a vertex u

  — there are + and max vertices 

  — $u_{n+k}=a_1\, v_n + a_2\, w_n + \ldots$ is encoded as

  — $u_{n+k}=\mathbf{max}(v_n, w_n, \ldots)$ is encoded as

- Close to initial automaton,
  but not quite the same

- Our algorithm works entirely on the graph.

Converting to graphs

- Encode those equations as graphs, where:
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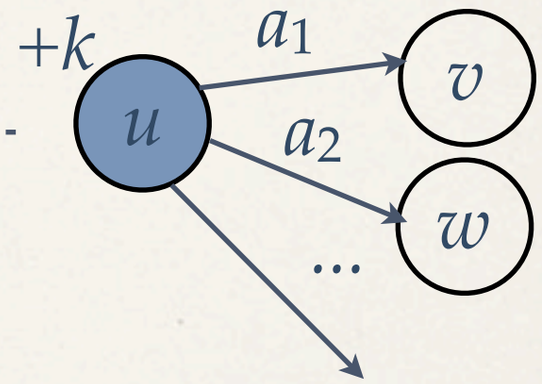
  — $u_{n+k}=a_1\, v_n + a_2\, w_n + \ldots$ is encoded as 

  — $u_{n+k}=\max(v_n, w_n, \ldots)$ is encoded as

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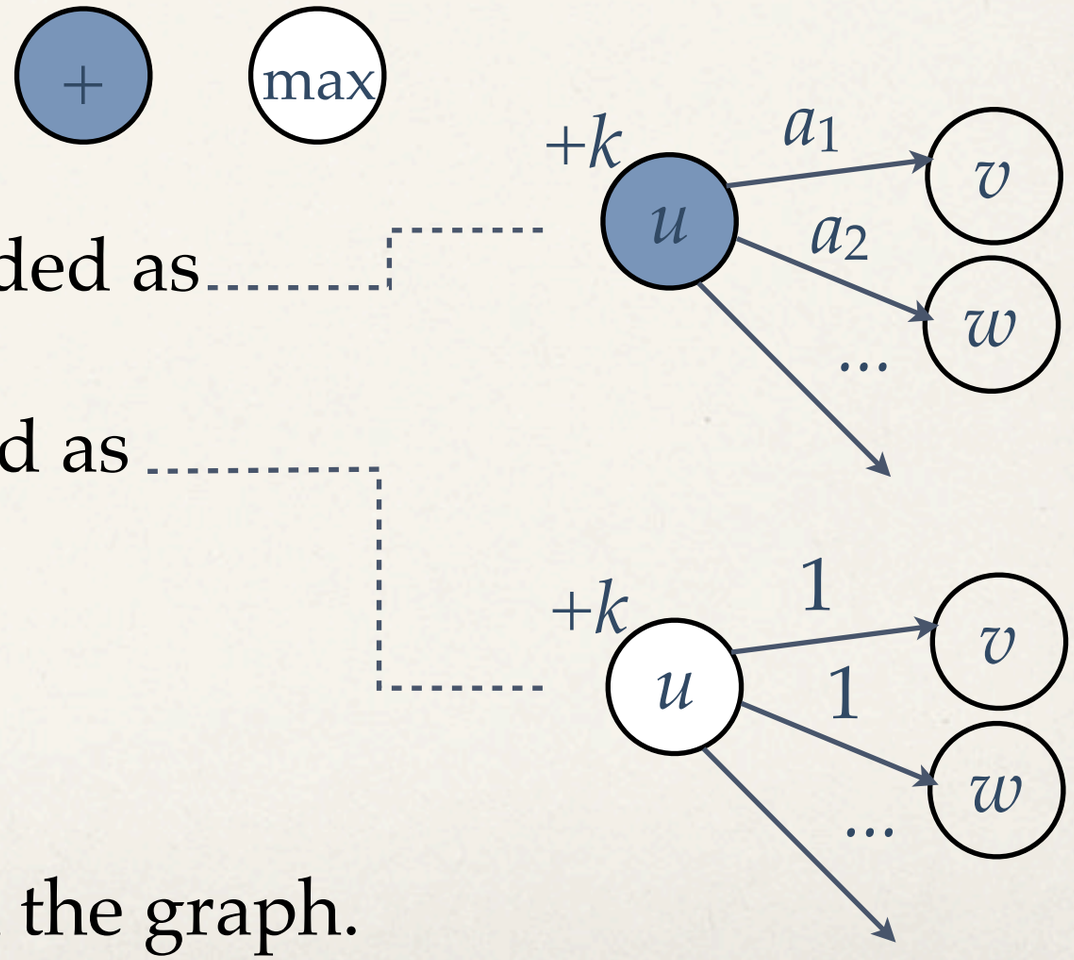
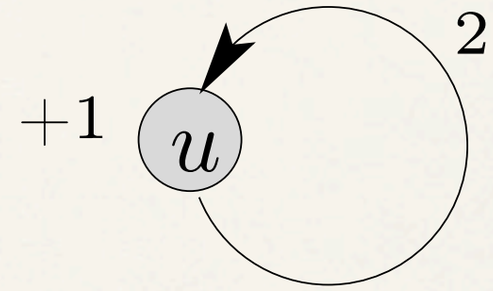


- Close to initial automaton,
  but not quite the same

- Our algorithm works entirely on the graph.

Exponential behaviors 1

- Here is the simplest example of a sequence that is asymptotically exponential



Equation: $u_{n+1}=2u_n$

- In general, we wish to find a simple criterion to detect which vertices have exponential behaviors
  (the **bad*** vertices)

- Will depend on the **strongly connected components** (SCCs) of the graph.

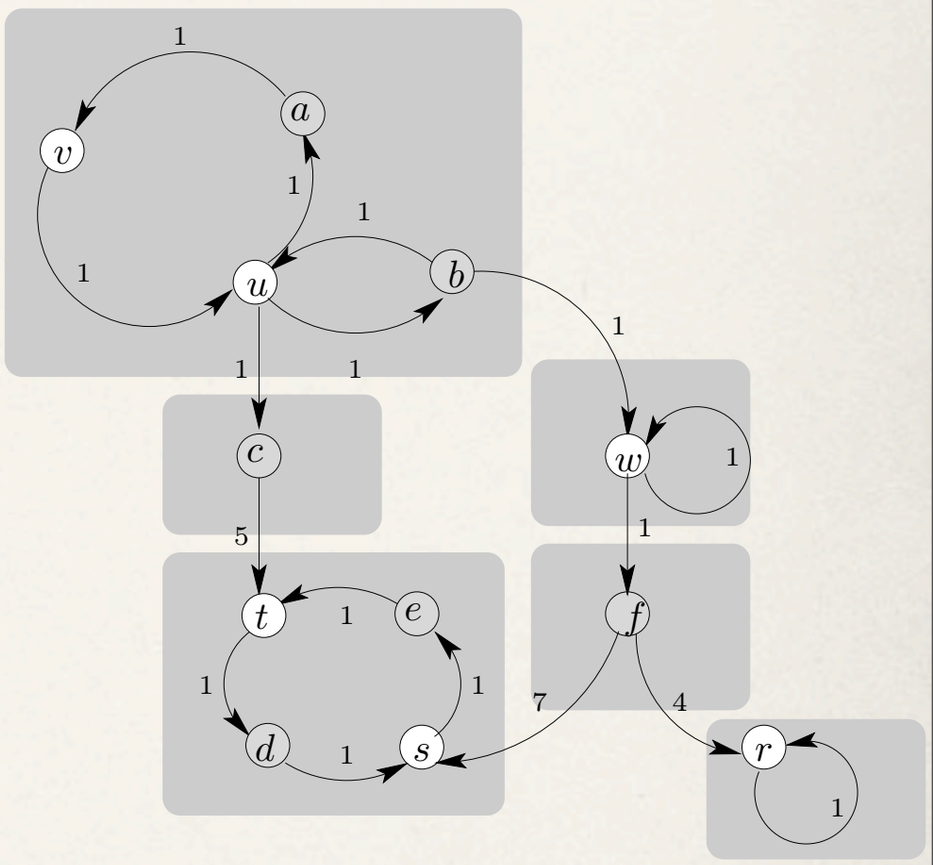
SCCs (a classic of graph theory)

- A set of vertices A is **strongly connected** iff every vertex of A is reachable from every other.

- An **SCC** is a maximal strongly connected set.

- SCCs can be computed in linear time by Tarjan's algorithm [J.Computing'72]

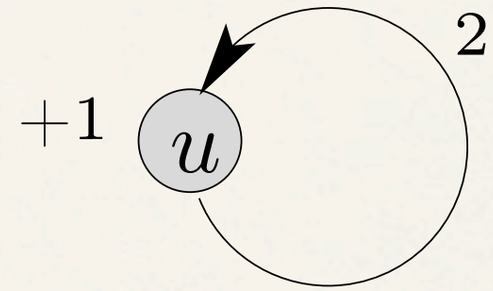
- The SCCs form the vertices of the so-called **condensation graph**, which is acyclic



[SCCs shown as gray boxes]

Exponential behaviors 2

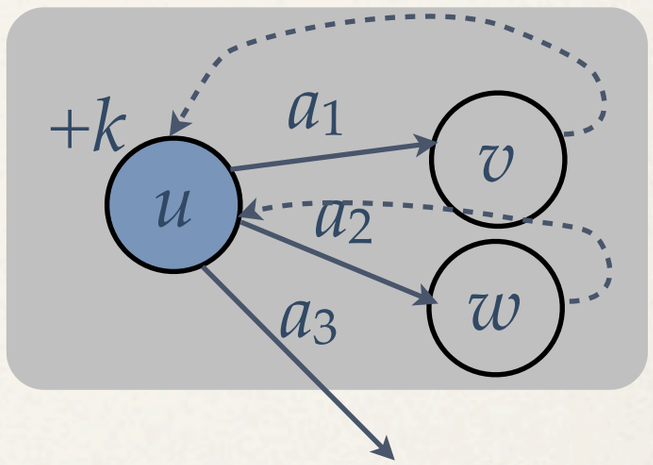
- In general, call a vertex u **bad** iff
  — u is a + vertex
  — the sum of the labels of edges out of u but remaining in the same SCC is ≥2



(Example)

- A vertex is **bad*** iff there is a path from that vertex to a bad vertex

- **Prop.** The bad* vertices are exactly those that have exponential behavior.



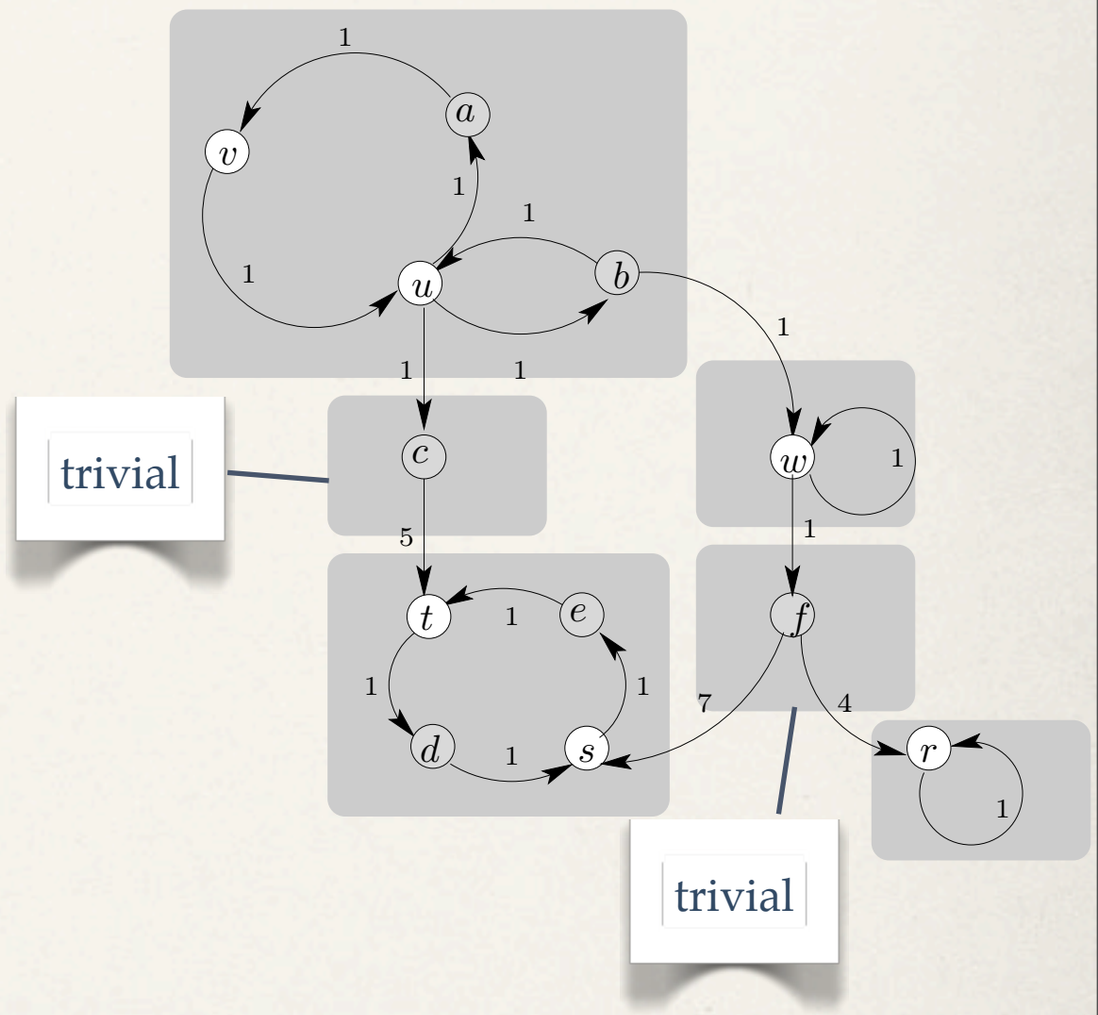
u is bad iff $a_1 + a_2 \geq 2$
(a_3 is *not* counted)

Polynomial behaviors 1: trivial SCCs

- Now assume there is no bad vertex. We shall map each SCC A to a number k so that u_n=O(n^k) for every vertex u in A.

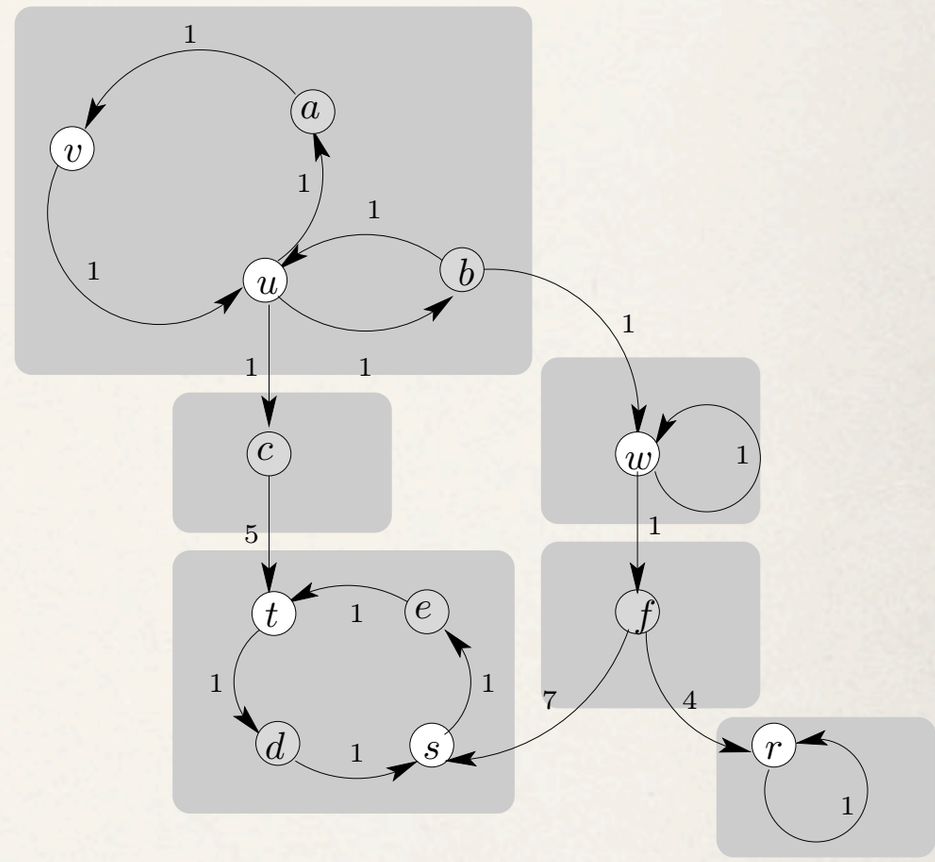
- Look at the **trivial SCCs**: those with no edge entirely inside the SCC

- c_{n+1}=5t_n: if t_n=O(n^k) then c_n=O(n^k) — **no increase** in degree.



Polynomial behaviors 2

- Now assume there is no bad vertex. In every SCC, every + vertex has at most one outgoing edge that remains in the SCC, and it has label 1.



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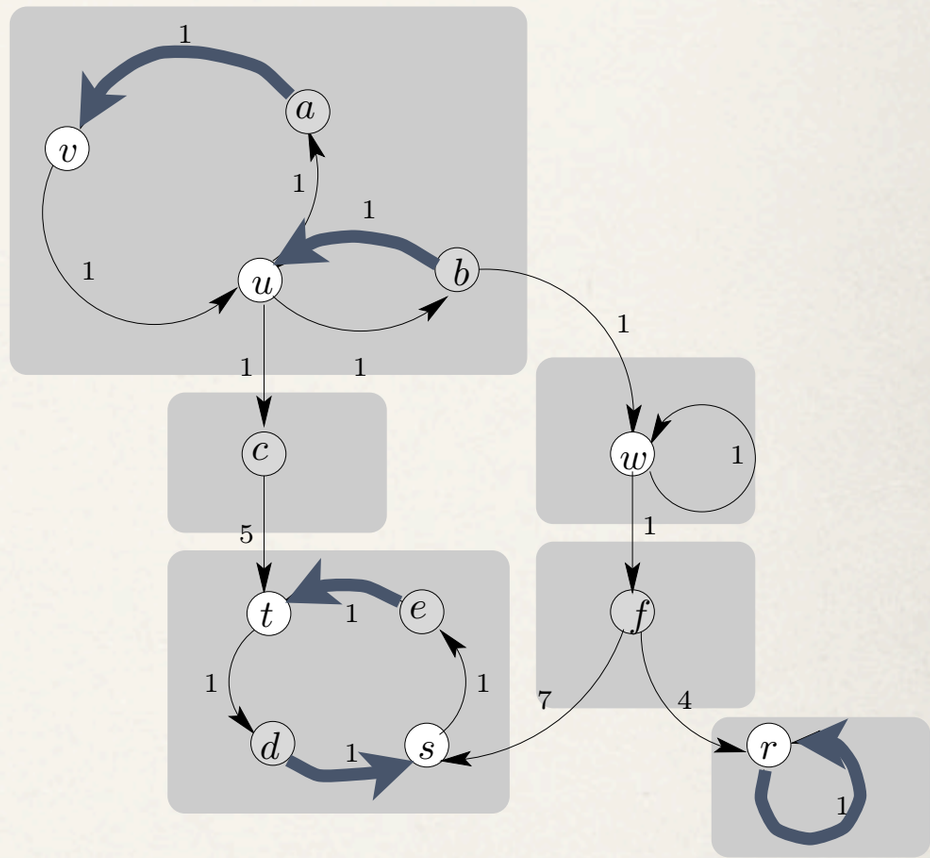

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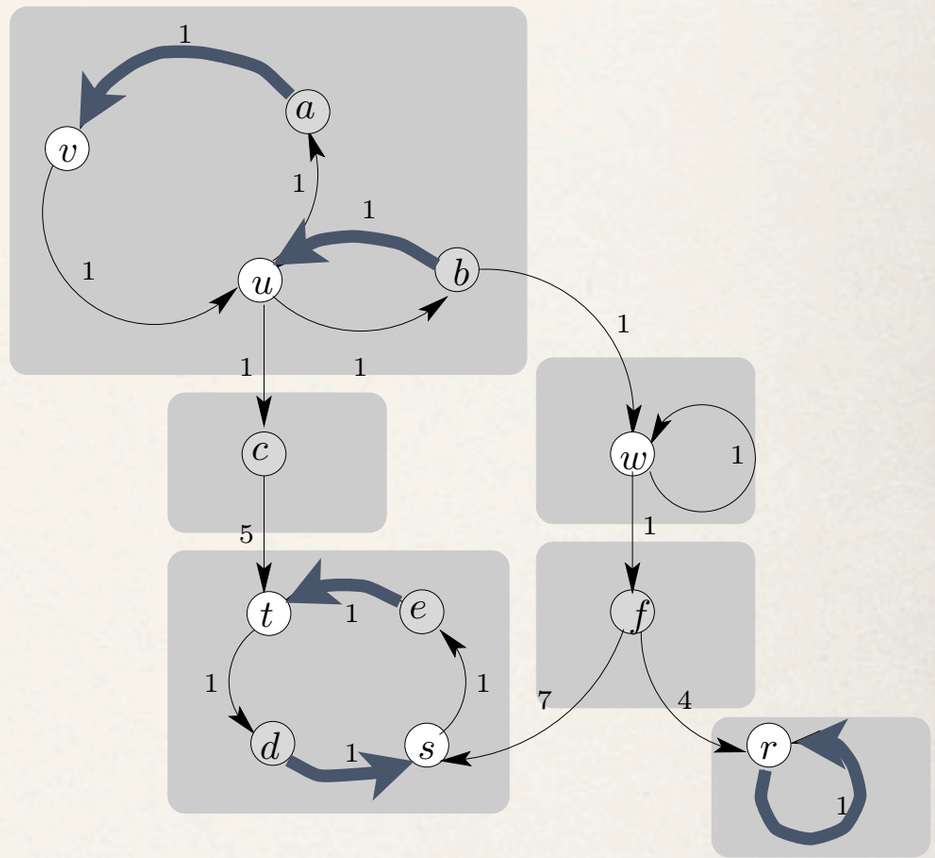

- For a non-trivial SCC A, an edge $u \to v$ going out of A is:
  — **expensive** iff u is a + vertex
  — **cheap** iff u is a max vertex

- (Call cheap any edge out of a trivial SCC, too.)

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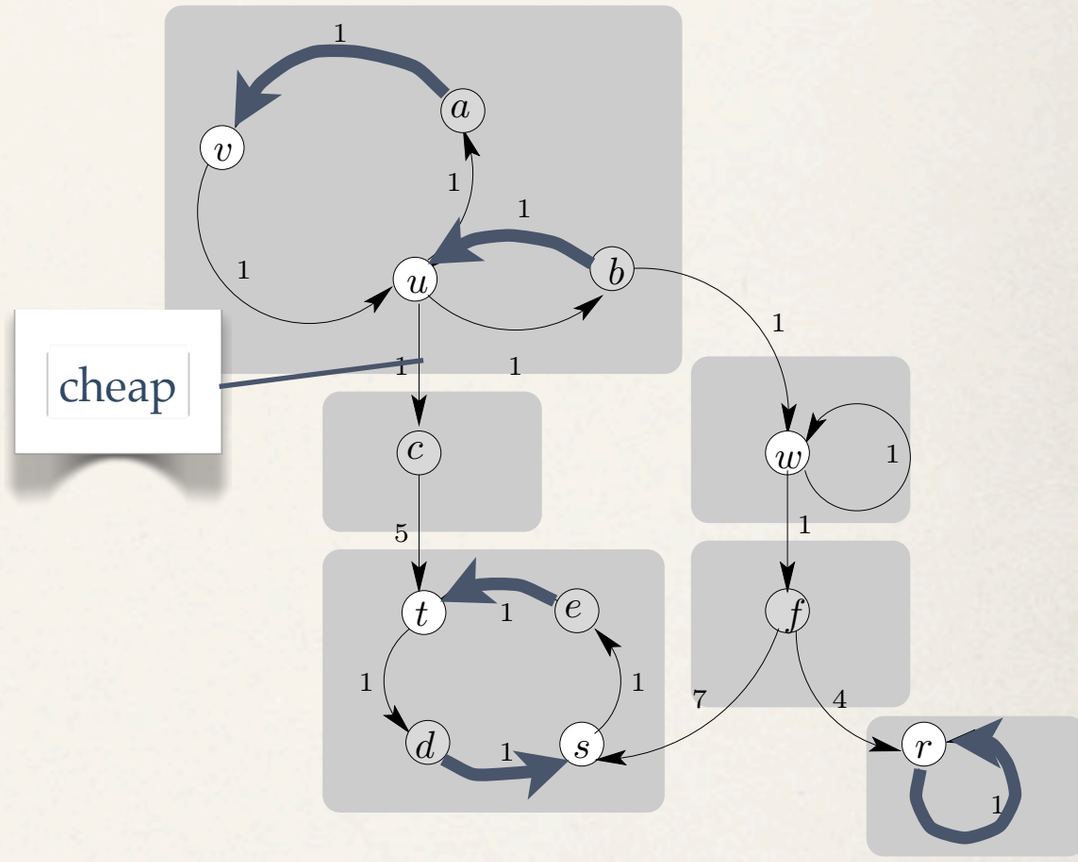

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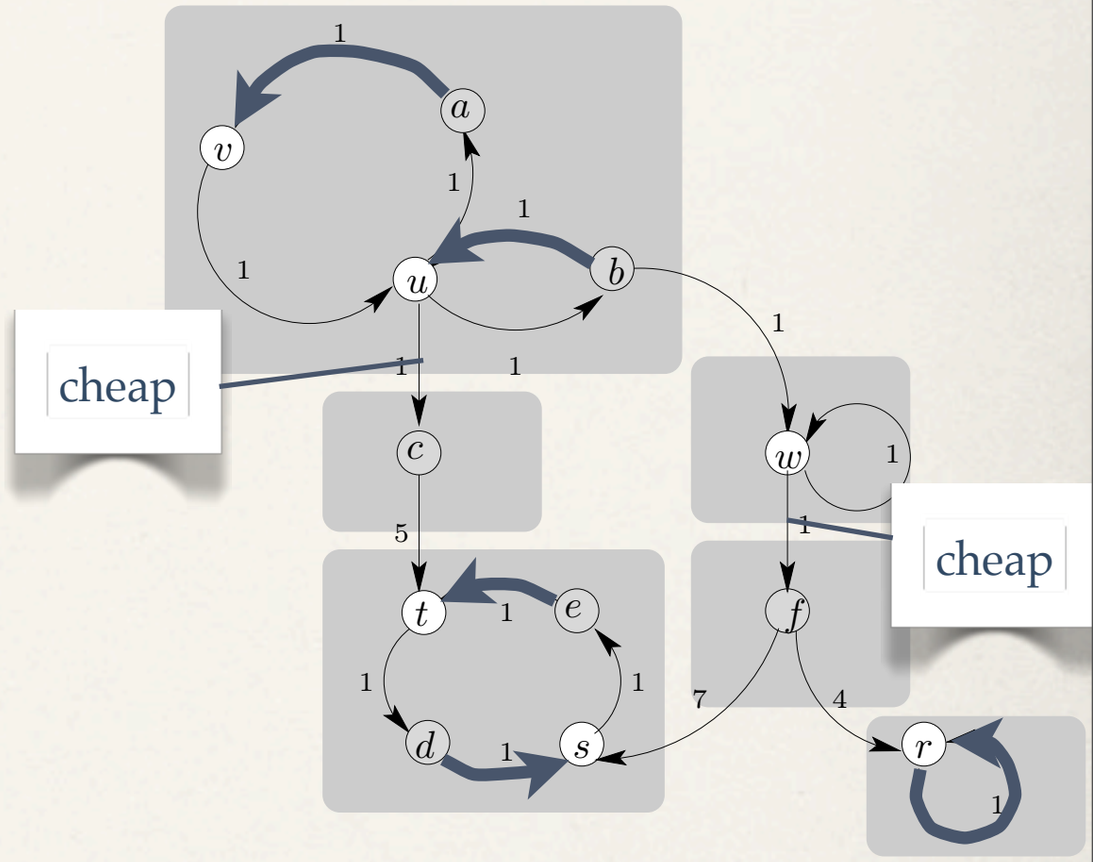

- For a non-trivial SCC A, an edge $u \to v$ going out of A is:
  — **expensive** iff u is a + vertex
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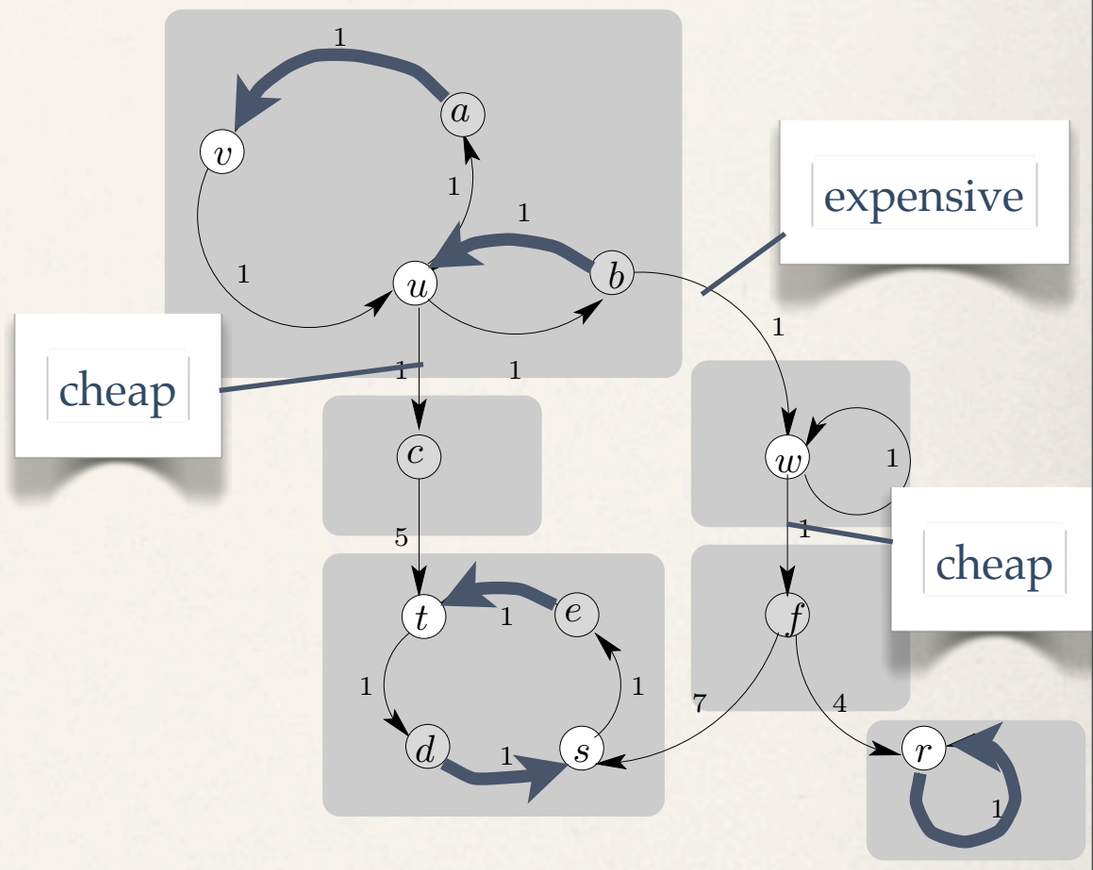

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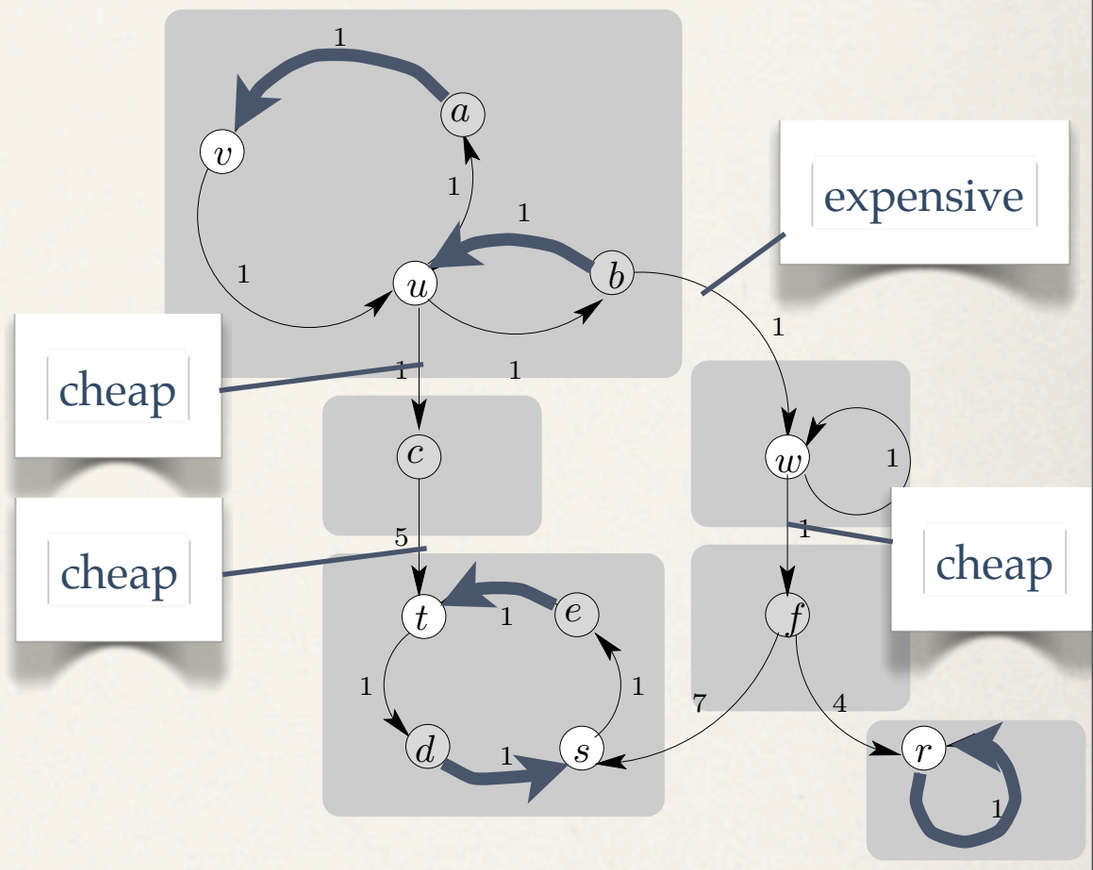

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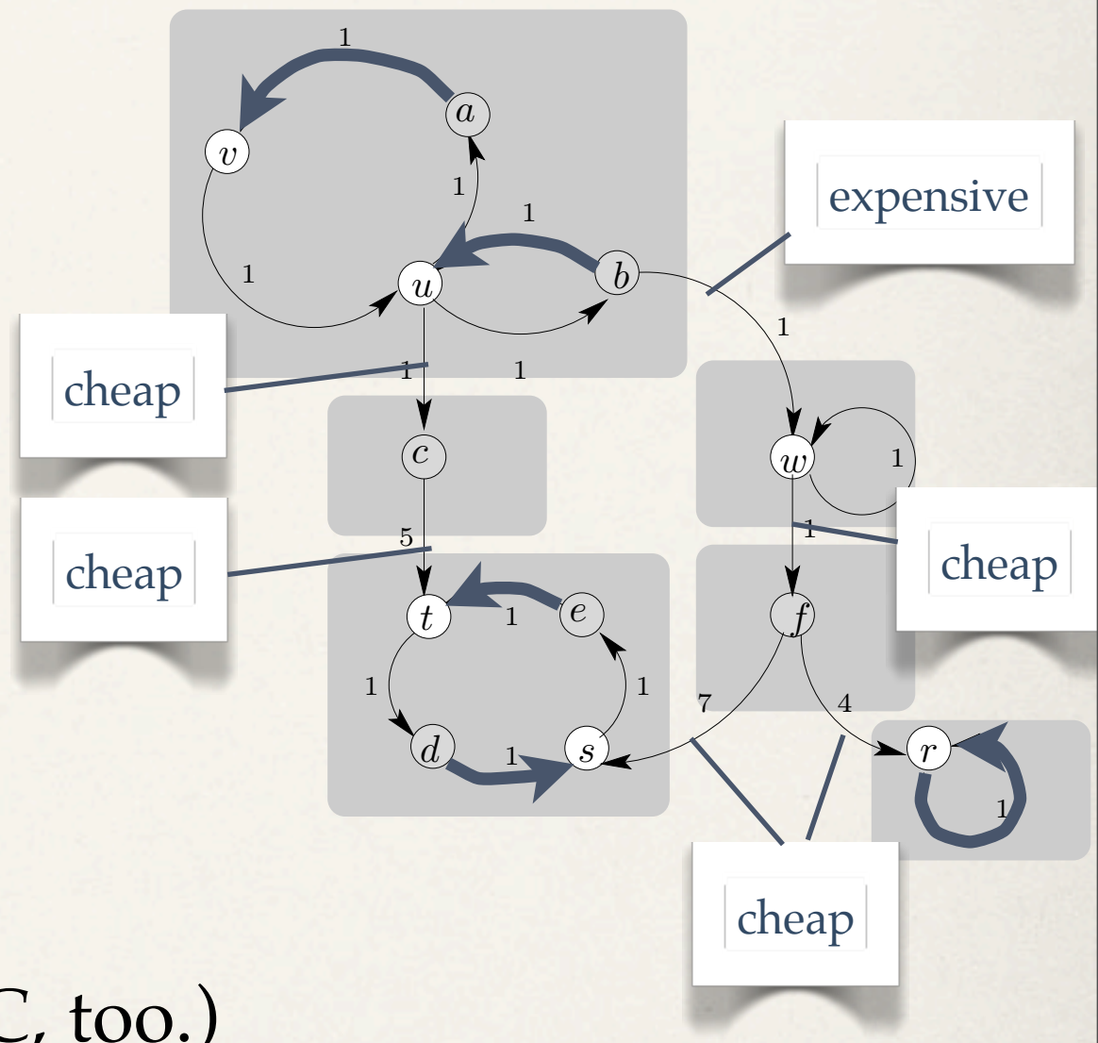

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Polynomial behaviors 3

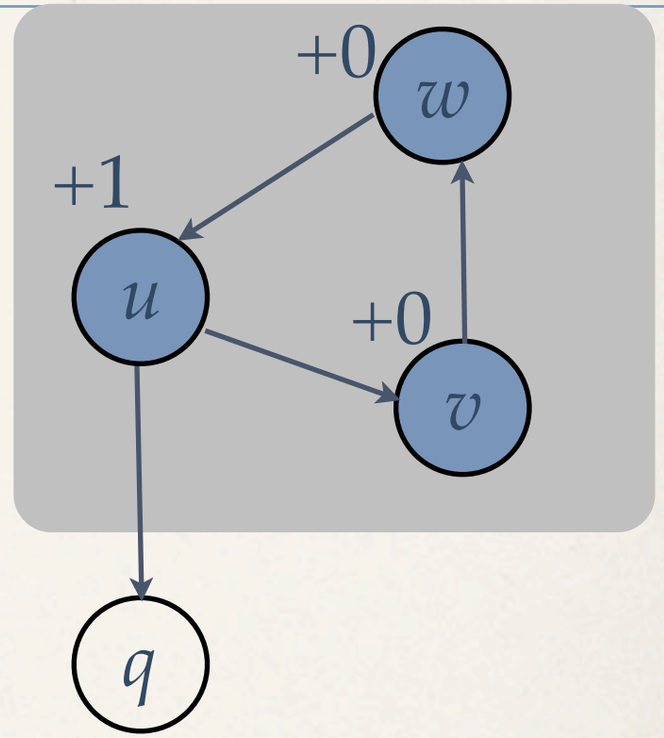
- Say that an SCC A **has degree k** iff every vertex of A is $O(n^k)$.

- **Prop.** Assume:
  — $A \to B_i$ (SCCs) through at least one expensive edge, $i=1...m$,
  — $A \to C_j$ (SCCs) through cheap edges only, $j=1...n$.
  Assume each B_i has degree b_i, each Cj has degree c_j.
  Then A has degree : **$\max(\{b_i + 1 \mid i=1...m\} \cup \{c_j \mid j=1...n\})$.**

- I.e., expensive edges increase degree by 1,
  cheap edges don't.

Polynomial behaviors: the key case

- Recall that in every SCC, every + vertex has at most one outgoing edge that remains in the SCC, and it has label 1.



- In the example to the right: there is a unique cycle inside the SCC.

- From the equations, $u_{n+3}=q_{n+2}+u_n$.
  So $u_{3n+a+1}=q_{3n+a}+q_{3(n-1)+a}+q_{3(n-3)+a}+\ldots+q_a$.
  Let $q'_n=q_{3n+a}$.
  If $q_n=O(n^k)$, then $q'_n=O(n^k)$,
  and therefore $q'_n+q'_{n-1}+\ldots+q'_0=O(n^{k+1})$.
  So $u_n=O(n^{k+1})$. [Increase in degree!]

$u_{n+1}=q_n+v_n$

$v_{n+1}=w_n$

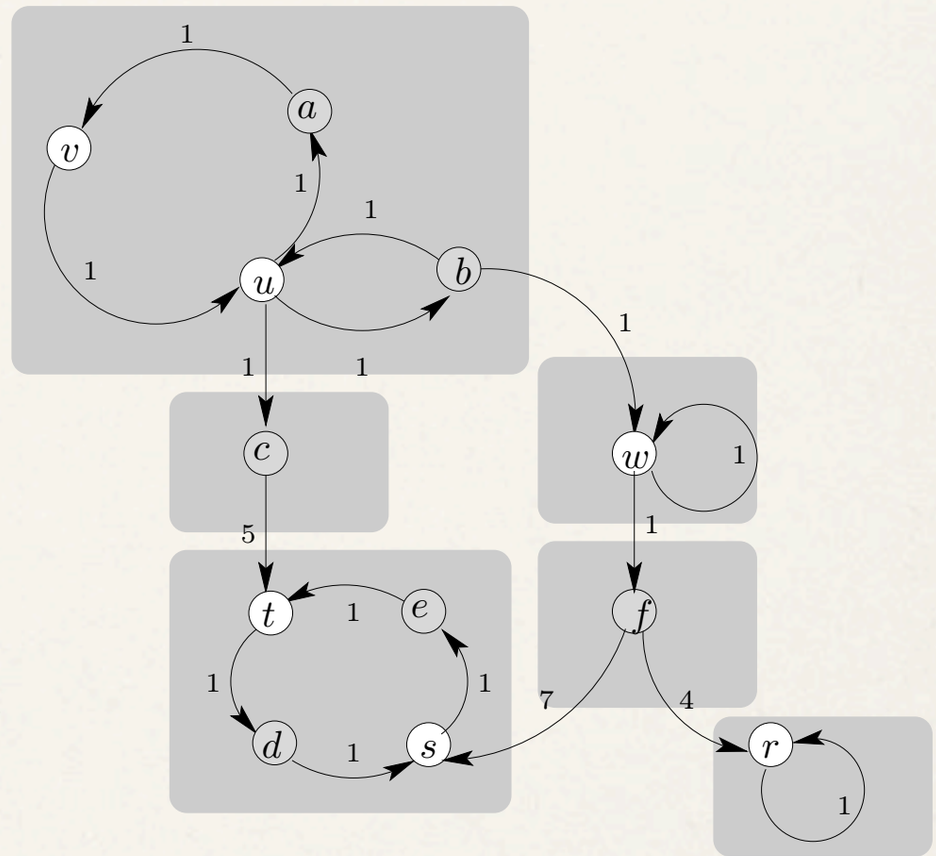
$w_{n+1}=u_n$

The algorithm (a bird's eye view)

- Compute graph, and its SCCs by Tarjan's algorithm

- Map each SCC to its degree, bottom-up:
  — expensive edges raise degree by 1
  — bad vertices set degree to +∞

- Simple modification of Tarjan's algorithm, works in linear time



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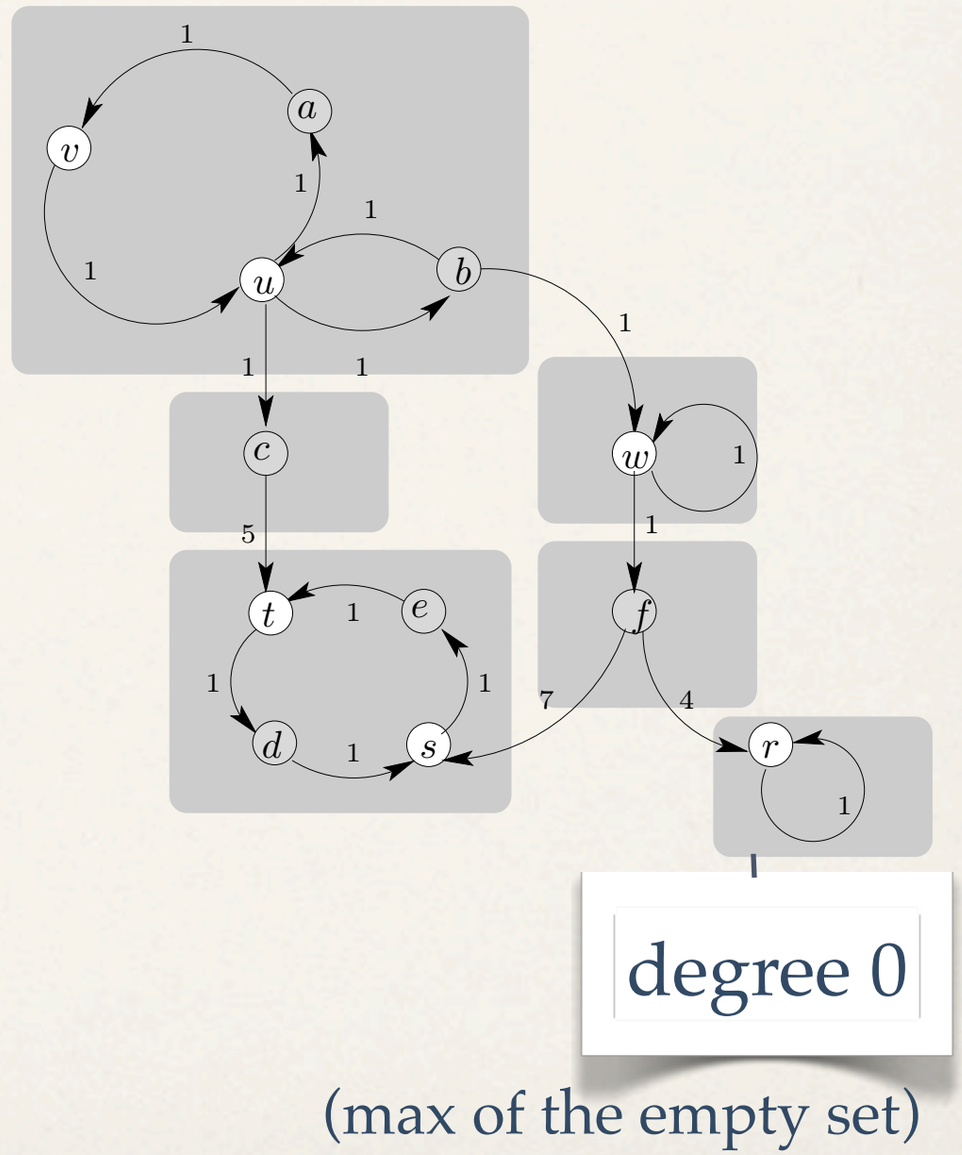

(max of the empty set)

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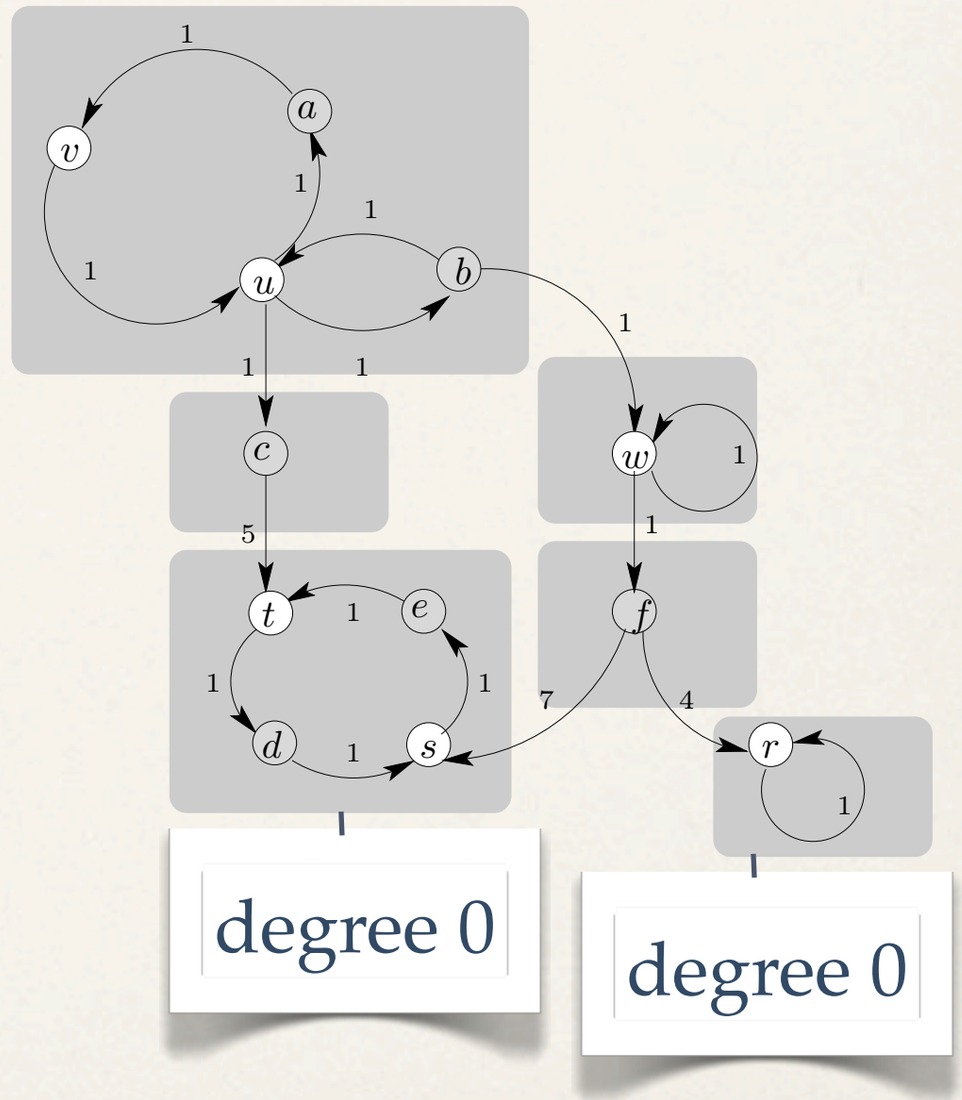

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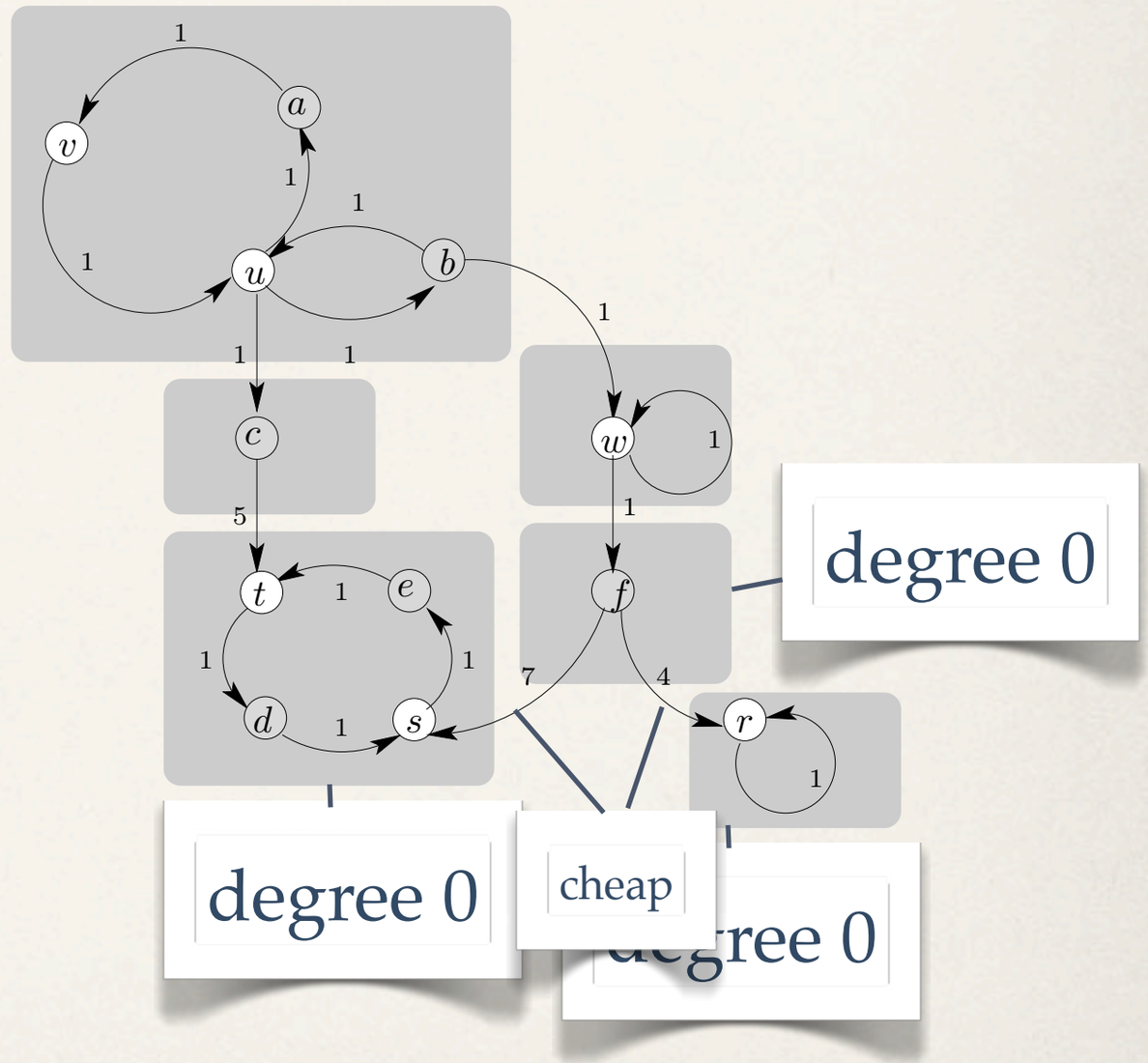

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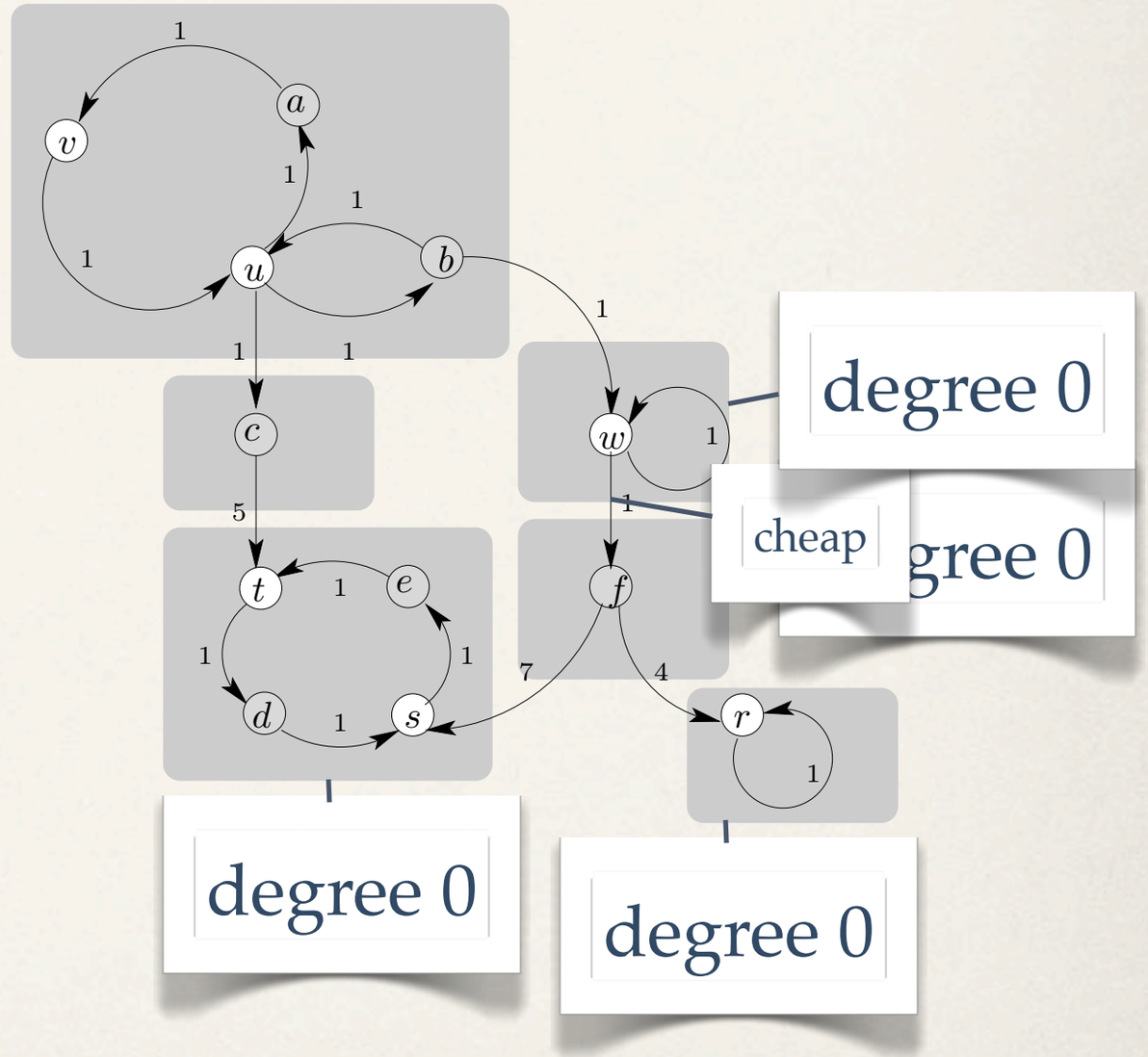

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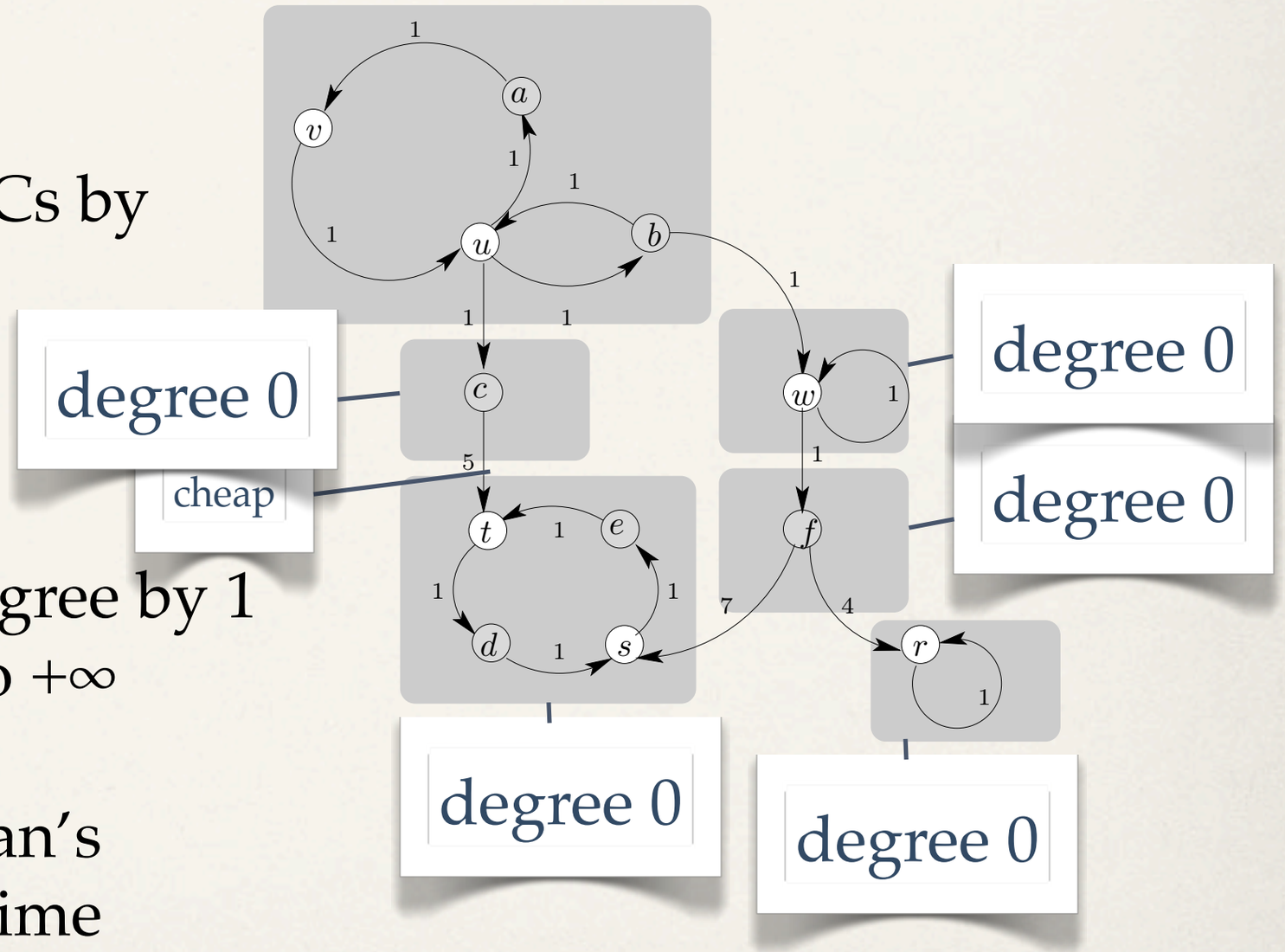

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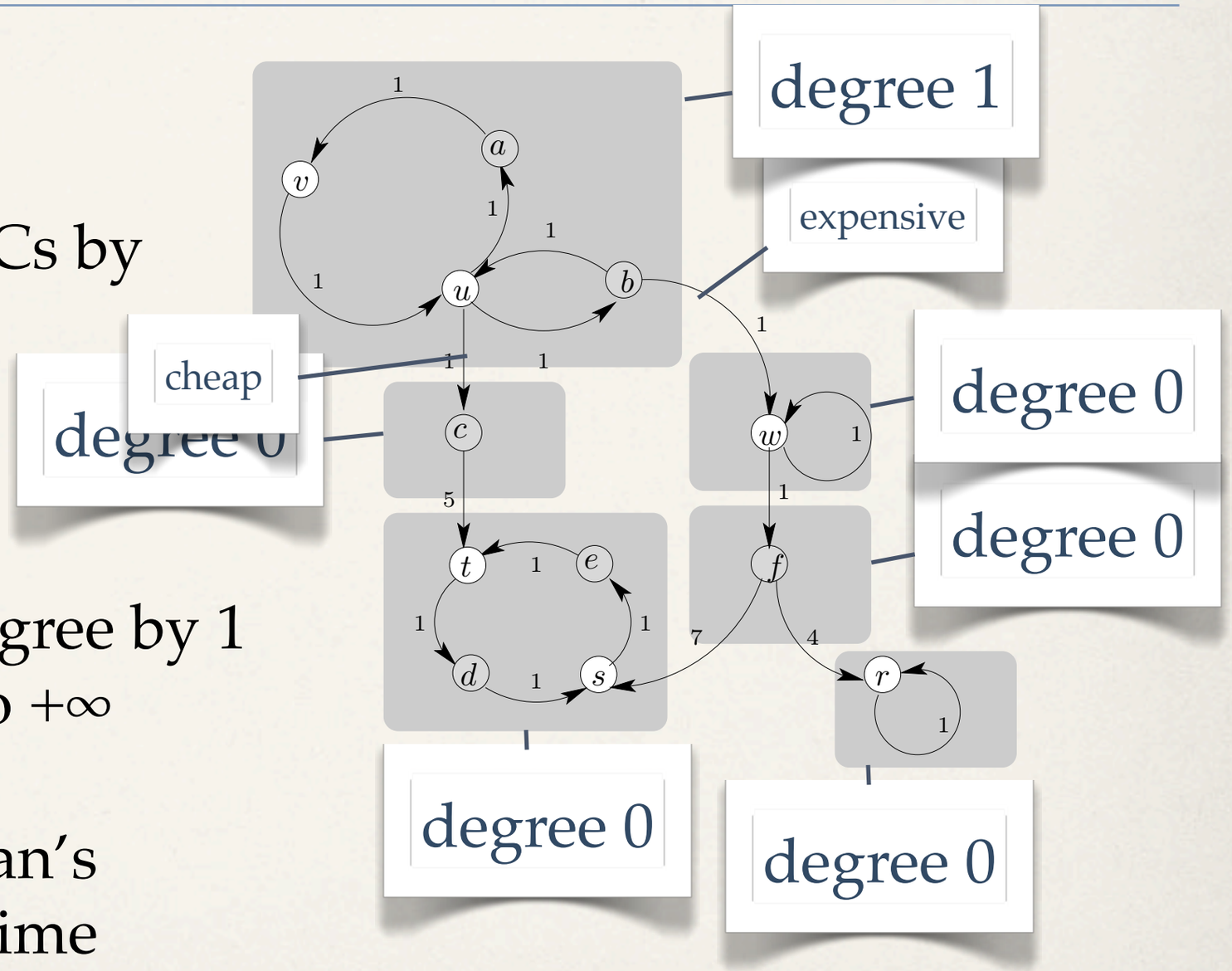
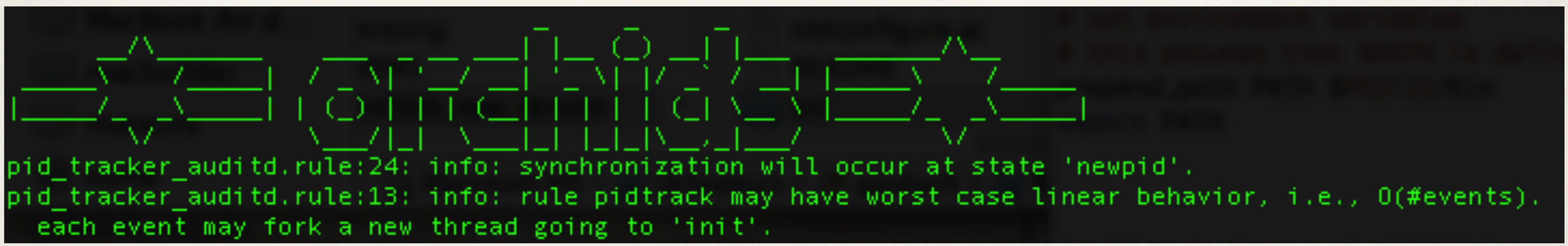


Implementation(s)

- Two early prototypes in 2013. Integrated into Orchids, 2015.

- 7 signatures are O(n), 1 is O(n^2),
  1 is detected as O(n^3) [overapproximated: it is really O(n^2)],
  1 is O(1).



Rule found to be in O(n) — reason explained on last line

Early implementations (2013)

- One early implementation also gave the **coefficient** of the dominant monomial.
  We found later that this is incorrect (see Example 4 in the paper).

- An even earlier implementation compiled the recurrence equations to Sage and to Maple
  — in very special cases (no max)
  — very precise result, but becomes unreadable when output is large.

```
The rule associated to this graph has an polynomial behavior represented by
the dominant monomial 0.16666666666666666 * n^3.0. To approximately reach
this behavior, you first need to launch a series of event in order to follow
the path from qInit to q1 to q2. Once this is done, you have to launch as
much events as you want and each event must match at the time the guard of
each the following transitions :
                                    qInit -> q1
                                     q1 -> q2
                                     q2 -> q3
If this is possible, the number of thread will grow according to the
polynomial solution found.
```

```
rsolve({fq0(n) = fq0(n-1) + fq1(n-1) + fq5(n-1), fq1(n) = fq1(n-1)
+ fq2(n-1) + fq6(n-1), fq5(n) = fq5(n-1), fq2(n) = fq2(n-1) +
fq3(n-1) + fq7(n-1), fq6(n) = fq6(n-1), fq3(n) = fq3(n-1) +
fq4(n-1), fq7(n) = fq7(n-1), fq4(n) = fq4(n-1), fq0(0) = 1, fq1(0)
= 1,  fq5(0) = 1, fq2(0) = 1, fq6(0) = 1, fq3(0) = 1, fq7(0) = 1,
fq4(0) = 1}, {fq0, fq1, fq5, fq2, fq6, fq3, fq7, fq4})
```

Maple

$$f_{q0}(n) = \frac{n^4}{24} + \frac{n^3}{12} + \frac{11*n^2}{24} + \frac{17*n}{12} + 1$$

Conclusion

- A very useful tool for warning signature writers of rules that would take up too many resources...
  which would allow denial-of-service attacks on Orchids itself (!).

- Beyond that, a very general technique for finding asymptotics of certain recurrence equations. Could be used as in [Assaf, PhD, 2015] to deduce quantitative information flow guarantees from an estimation of the number of paths in execution trees?

- Other questions?