

Note to readers:
Please ignore these
sidenotes; they're just
hints to myself for
preparing the index,
and they're often flaky!

KNUTH

THE ART OF COMPUTER PROGRAMMING

VOLUME 4 PRE-FASCICLE 12A

COMPONENTS AND TRAVERSAL (ridiculously preliminary draft)

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ADDISON-WESLEY



September 18, 2026

Internet
Stanford GraphBase
MMIX

Internet page <https://www-cs-faculty.stanford.edu/~knuth/taocp.html> contains current information about this book and related books.

See also <https://www-cs-faculty.stanford.edu/~knuth/sgb.html> for information about *The Stanford GraphBase*, including downloadable software for dealing with the graphs used in many of the examples in Chapter 7.

See also <https://www-cs-faculty.stanford.edu/~knuth/mmixture.html> for downloadable software to simulate the MMIX computer.

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September 18, 2026

PREFACE

*But that is not my point.
I have totally forgotten my point.*

— DAVE BARRY (2012)

THIS BOOKLET contains draft material that I'm circulating to experts in the field, in hopes that they can help remove its most egregious errors before too many other people see it. I am also, however, posting it on the Internet for courageous and/or random readers who don't mind the risk of reading a few pages that have not yet reached a very mature state. *Beware:* This material has not yet been proofread as thoroughly as the manuscripts of Volumes 1, 2, 3, 4A, and 4B were at the time of their first printings. And alas, those carefully checked volumes were subsequently found to contain thousands of mistakes.

Given this caveat, I hope that my errors this time will not be so numerous and/or obtrusive that you will be discouraged from reading the material carefully. I did try to make the text both interesting and authoritative, as far as it goes. But the field is vast; I cannot hope to have surrounded it enough to corral it completely. So I beg you to let me know about any deficiencies that you discover.

To put the material in context, this portion of fascicle 12 previews parts of Section 7.4.1 of Chapter 7 of *The Art of Computer Programming*, entitled "Components and traversal." The first part, Section 7.4.1.1, is about "Union-find algorithms," and it's barely started. The next part, Section 7.4.1.2, deals with "Depth-first search"; I've drafted quite a bit more about that, especially with respect to Tarjan's algorithm for strong components. And there will be at least one more part. But I haven't had time to write much more of 7.4.1 yet — not even this preface!

At present I've only got a few small scraps of copy that I'm occasionally putting into my computer, on days when possibly relevant material occurs to me. Thus almost everything you see here is more or less a place-holder for better things that hopefully will come later. Some day, however, I hope that I'll no longer have to apologize for what is now just a bunch of crumbs.

* * *

The explosion of research in computer science since the 1970s has meant that I cannot hope to be aware of all the important ideas in this field. I've tried

my best to get the story right, yet I fear that in many respects I'm woefully ignorant. So I beg expert readers to steer me in appropriate directions.

Please look, for example, at the exercises that I've classed as research problems (rated with difficulty level 46 or higher), namely exercises 47, . . . ; I've also implicitly mentioned or posed additional unsolved questions in the answers to exercises 75, Are those problems still open? Please inform me if you know of a solution to any of these intriguing questions. And of course if no solution is known today but you do make progress on any of them in the future, I hope you'll let me know.

I urgently need your help also with respect to some exercises that I made up as I was preparing this material. I certainly don't like to receive credit for things that have already been published by others, and most of these results are quite natural "fruits" that were just waiting to be "plucked." Therefore please tell me if you know who deserves to be credited, with respect to the ideas found in exercises 24, 32–34, 37–39, 61, 66, 80, 84, 85, 92, 93, 95, 96, 98, Furthermore I've credited exercises . . . to unpublished work of Have any of those results ever appeared in print, to your knowledge?

As usual, I've written many programs to test the technical details while preparing this material, and I've posted some of the major ones online. For example,

<https://cs.stanford.edu/~knuth/programs/tarjan-strong.w>

<https://cs.stanford.edu/~knuth/programs/tarjan-strong-and-weak.w>

are experimental implementations of Algorithms 7.4.1.2T and 7.4.1.2W.

* * *

Special thanks are due to Svante Janson, Shisheng Li, Filip Stappers, Bob Tarjan, and . . . for their detailed comments on my early attempts at exposition, as well as to numerous other correspondents who have contributed crucial corrections.

I happily offer a "finder's fee" of \$2.56 for each error in this draft when it is first reported to me, whether that error be typographical, technical, or historical. The same reward holds for items that I forgot to put in the index. And valuable suggestions for improvements to the text are worth 32¢ each. (Furthermore, if you find a better solution to an exercise, I'll actually do my best to give you immortal glory, by publishing your name in the eventual book:—)

Cross references to yet-unwritten material sometimes appear as '00'; this impossible value is a placeholder for the actual numbers to be supplied later.

Happy reading!

Stanford, California
99 Umbruary 2021

D. E. K.

*For all such items, my procedure is the same:
I write them down—and then write them up.*

— DON HAUPTMAN (2016)

Janson
Li
Stappers
Tarjan
Knuth
HAUPTMAN

7.4. GRAPH ALGORITHMS

Casting about, as I lay awake in bed one night, to discover some means of conveying an intelligible conception of the objects of modern algebra to a mixed society, mainly composed of physicists, chemists and biologists, ... to which I stood engaged to give some account of my recent researches in this subject of my predilection, ... I was agreeably surprised to find, of a sudden, distinctly pictured on my mental retina a chemico-graphical image ... every bond or connecting line in the graph passes through two atoms.

— J. J. SYLVESTER, *American Journal of Mathematics* (1878)

One can give the problem a geometric form, in which $x_1, x_2, \dots, x_n$ are represented by arbitrary points in the plane, while each factor $x_m - x_p$ is portrayed by an arbitrary connecting line between x_m and x_p

English authors have introduced the name graph for figures like this; I shall retain that name.

— JULIUS PETERSEN, *Acta Mathematica* (1891)

Although algorithmic graph theory was started by Euler, if not earlier, its development in the last ten years has been dramatic and revolutionary.

— SHIMON EVEN, *Graph Algorithms* (1979)

SYLVESTER
PETERSEN
Euler
EVEN
reachable
equivalence relation
connected components
empty graph

GRAPHS HAVE tremendous variety, and can be viewed in many different ways. Therefore we turn now to the study of algorithms that discover structural properties of a given graph. We'll see how to take advantage of various special attributes that a graph might have. For example, many graphs can be decomposed into parts that are either independent or fit together nicely in a simple way that allows problems to be solved more quickly.

7.4.1. Components and traversal

In previous chapters we've already seen many instances of important techniques that have been developed to work with graphs efficiently inside a computer. Now it's time to examine those basic methods in more detail.

7.4.1.1. Union-find algorithms. Let's begin with connectedness, the simplest structural concept of all. A nonempty graph is *connected* if there's a path between any two of its vertices. Thus, if we divide its vertices into two nonempty parts, there's always at least one edge that connects them by having one vertex in each part; every path from one part to the other contains such an edge.

We say that vertex w is *reachable* from vertex v in graph G if $w = v$ or there's a path in G from v to w . Reachability is clearly an equivalence relation; and the equivalence classes of this relation are the *connected components* of G .

(The empty graph has no components, so we don't consider it to be connected. Similarly, the number '1' isn't considered to be prime.)

Long ago, in Algorithm 2.3.3E, we saw that it's not difficult to determine whether or not two elements of a set are equivalent to each other as the result of a given collection of individual equivalences. Such individual equivalences define the edges of a graph; so Algorithm 2.3.3E can be regarded as an algorithm to determine the connected components of a given graph.

There are, in fact, several interesting ways to improve that algorithm.



(Now I'll go into the story of “union-find” algorithms. That will be fun—it's one of my favorite chapters in the early development of computer science!)

EXERCISES

1. [05] Is the one-vertex graph K_1 connected?
99. [00] this is a temporary dummy exercise
999. [M00] this is a temporary exercise (for dummies)

In every affair, consider what precedes and what follows, before acting.

— EPICTETUS, *Discourses* III.xv (c. A.D. 110)

*And in the lowest deep a lower deep
Still threatening to devour me opens wide.*

— JOHN MILTON, *Paradise Lost* IV (1667)

EPICTETUS
MILTON
depth-first search-
worm
bipartite
SGB format
stack
sentinel

7.4.1.2. Depth-first search. Another fundamental problem is to visit every vertex and every arc of a graph. It's analogous to the problem of traversing a forest; see, for example, the “worm” in 7.2.1.6–(3). But graphs are trickier because they can contain cycles. We saw a simple example related to depth-first search near the beginning of Chapter 7: Algorithm 7B tests whether or not a given graph is bipartite, by assigning one of two colors to every vertex unless that task turns out to be impossible.

In the previous section we dealt with situations where we learn one edge of a graph at a time, occasionally making a query to see if the graph-so-far has a particular property. We didn't actually need to remember every edge of that graph.

But now our outlook changes. We're given a prespecified digraph, and we want to walk through it. An undirected graph or multigraph is the special case of a digraph in which every edge is represented by two arcs, one in each direction.

We will assume that the digraph g is represented in SGB format, as discussed just before Algorithm 7B. That is, there are $n = N(g)$ vertices v , each having fields $NAME(v)$ and $ARCS(v)$. Those vertices are $v_0 + k$ for $0 \leq k < n$, where $v_0 = VERTICES(g)$. There are $m = M(g)$ arcs, where the arcs from v begin at $ARCS(v)$. Each arc a has fields $TIP(a)$ and $NEXT(a)$. If the arcs from v are $v \rightarrow w_1, v \rightarrow w_2, \dots, v \rightarrow w_k$, we have $w_1 = TIP(a_1), w_2 = TIP(a_2), \dots$, and $w_k = TIP(a_k)$, where $a_1 = ARCS(v), a_2 = NEXT(a_1), \dots, a_k = NEXT(a_{k-1})$, and $NEXT(a_k) = \Lambda$. (If v has no successors, $k = 0$ and $ARCS(v) = \Lambda$.)

A straightforward way to walk through such a digraph is to use a stack to hold the vertices that we've seen but whose arcs we haven't yet seen. The only complication is that we don't want to put a vertex on that stack more than once.

A neat trick allows us to achieve our goal efficiently by letting the stack links themselves tell us which vertices we've seen:

Algorithm Q (*Quick digraph search*). Given a digraph g in SGB format, this algorithm marks every vertex and visits every arc of g . It uses a utility field in each vertex, called **MARK**, and a pointer variable, called s , which implements a stack.

- Q1.** [Initialize.] Set $MARK(w) \leftarrow \Lambda$ for $VERTICES(g) \leq w < SENT$, until eventually $w = SENT$, where $SENT = VERTICES(g) + N(g)$ is a “sentinel.”
- Q2.** [Done?] (Every vertex $v \geq w$ has now been marked, as well as all vertices reachable from v .) Terminate if $w = VERTICES(g)$. Otherwise set $w \leftarrow w - 1$, and repeat this step if $MARK(w) \neq \Lambda$.
- Q3.** [Begin to explore from v .] Set $v \leftarrow w, MARK(v) \leftarrow s \leftarrow SENT, a \leftarrow ARCS(v)$.
- Q4.** [Visit the next arc from v .] Go to Q6 if $a = \Lambda$. Otherwise set $u \leftarrow TIP(a)$ and $a \leftarrow NEXT(a)$.

Q5. [Mark and stack u , unless it's already marked.] If $\text{MARK}(u) = \Lambda$, set $\text{MARK}(u) \leftarrow s$ and $s \leftarrow u$. Return to Q4.

Q6. [Pop the stack.] Go back to Q2 if $s = \text{SENT}$. Otherwise set $v \leftarrow s$, $s \leftarrow \text{MARK}(v)$, $a \leftarrow \text{ARCS}(v)$, and return to Q4. ■

Consider, for example, the digraph on vertices $\{0, 1, \dots, 9\}$ whose 21 arcs are based on the first 42 digits of π :

$$\begin{aligned} 3 \rightarrow 1, & \ 4 \rightarrow 1, \ 5 \rightarrow 9, \ 2 \rightarrow 6, \ 5 \rightarrow 3, \ 5 \rightarrow 8, \ 9 \rightarrow 7, \\ 9 \rightarrow 3, & \ 2 \rightarrow 3, \ 8 \rightarrow 4, \ 6 \rightarrow 2, \ 6 \rightarrow 4, \ 3 \rightarrow 3, \ 8 \rightarrow 3, \\ 2 \rightarrow 7, & \ 9 \rightarrow 5, \ 0 \rightarrow 2, \ 8 \rightarrow 8, \ 4 \rightarrow 1, \ 9 \rightarrow 7, \ 1 \rightarrow 6. \end{aligned} \quad (1)$$

Algorithm Q visits these arcs by seeing respectively

$$\begin{aligned} 9 \rightarrow 7, & \ 3, \ 5, \ (7); \\ 5 \rightarrow (9), & \ (3), \ 8; \\ 8 \rightarrow 4, & \ (3), \ (8); \\ 4 \rightarrow 1, & \ (1); \end{aligned} \quad (2)$$

and so on, where the parentheses in ‘(7)’ indicate that 7 was not stacked because it had been seen before. (See exercise 1.)

Algorithm Q is refreshingly quick. In fact, exercise 5 shows that it accesses memory fewer than $3m + 5n$ times, when the digraph has m arcs and n vertices. But unfortunately the order in which it traverses g is not the best, from the standpoint of graph algorithms in general. There's another way to do the traversal, called *depth-first search*, which turns out to be far more useful, because it can be extended to help solve a wide variety of more difficult problems on graphs.

Depth-first search is superficially similar to Algorithm Q, yet it's significantly better in many applications, because it implicitly constructs an *oriented spanning forest* of the given digraph. Furthermore, it visits the vertices in a recursive order that corresponds to preorder on that forest. (By contrast, the order of visitation by Algorithm Q doesn't have a clean recursive characterization.)

One good way to visualize depth-first traversal is to imagine that we're playing an adventure game in which we're exploring a cave. The vertices of the digraph are the rooms of the cave, and the arcs are one-way passages from one room to another. We haven't been given a map of the cave; our goal is to pry into every nook and cranny, systematically feeling our way.

Algorithm Q “cheats” when it says $v \leftarrow s$ in step Q6: Cave games rarely allow us to teleport ourselves from one room of a cave to another. A genuine depth-first search moves only through legitimate passageways, except when it enters or leaves the cave, although we do allow it to retrace its steps in the one-way corridors. (In a real game we can't unfall off a cliff.)

Let us therefore go depth-first without lowering our standards.

Algorithm D (*Depth-first search*). Given a digraph g in SGB format, this algorithm traverses g and uses a subset of g 's arcs to construct an oriented spanning forest. (The arcs in this forest lead *away* from the roots.) Every

π
oriented spanning forest
spanning forest
preorder
adventure game
game
cave

vertex is assumed to contain utility fields called **PARENT**, **ARC**, **PRE**, and **POST**. After termination, **PARENT**(v) will be v 's parent in the forest, or the sentinel value **SENT** if v is a root; **PRE**(v) and **POST**(v) will be the indices of v in preorder and postorder of the forest. We use integer variables p and q .

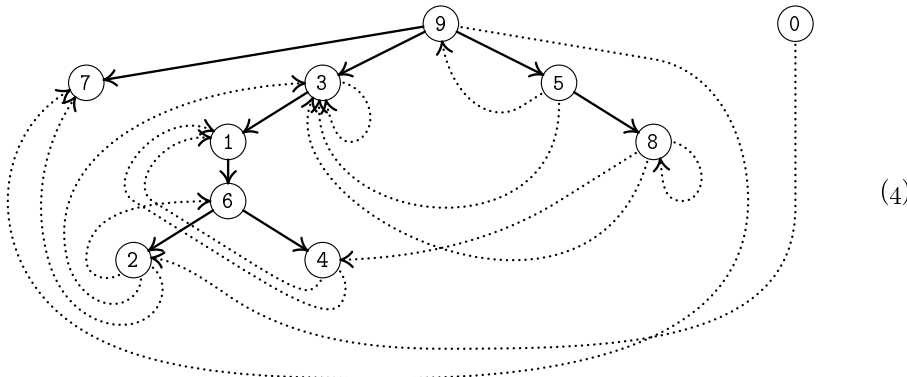
postorder
preorder
postorder

- D1.** [Initialize.] Set **PARENT**(w) $\leftarrow \Lambda$ for **VERTICES**(g) $\leq w < \mathbf{SENT}$, until eventually $w = \mathbf{SENT}$, where $\mathbf{SENT} = \mathbf{VERTICES}(g) + \mathbf{N}(g)$. Also set $p \leftarrow q \leftarrow 0$.
- D2.** [Done?] (Every vertex $v \geq w$ is now in the explored forest, as well as all vertices reachable from v .) Terminate if $w = \mathbf{VERTICES}(g)$. Otherwise set $w \leftarrow w - 1$, and repeat this step if **PARENT**(w) $\neq \Lambda$.
- D3.** [Begin to explore from v .] Set $v \leftarrow w$, **PARENT**(v) $\leftarrow \mathbf{SENT}$, $p \leftarrow p + 1$, **PRE**(v) $\leftarrow p$, and $a \leftarrow \mathbf{ARCS}(v)$. (Vertex v is p th in preorder of the forest.)
- D4.** [Done with v ?] If $a = \Lambda$, set $q \leftarrow q + 1$, **POST**(v) $\leftarrow q$, $v \leftarrow \mathbf{PARENT}(v)$, and go to D8. (Vertex v is q th in postorder of the forest.)
- D5.** [Visit the next arc, $v \rightarrow u$.] Set $u \leftarrow \mathbf{TIP}(a)$ and $a \leftarrow \mathbf{NEXT}(a)$.
- D6.** [If u isn't new, continue at v .] If **PARENT**(u) $\neq \Lambda$, return to D4.
- D7.** [Move to u .] Set **PARENT**(u) $\leftarrow v$, **ARC**(v) $\leftarrow a$, $v \leftarrow u$, $p \leftarrow p + 1$, **PRE**(v) $\leftarrow p$, $a \leftarrow \mathbf{ARCS}(v)$, and go to D4.
- D8.** [Done with tree?] If $v = \mathbf{SENT}$, go back to D2. Otherwise set $a \leftarrow \mathbf{ARC}(v)$ and go to D4. ■

Algorithm D essentially mimics the behavior of a well-organized spelunker. There are three main cases, depending on whether the current position v moves to a newly discovered child (step D7), moves back to a parent (step D8), or stays put (goes from D6 to D4). Step D4 is the main switch: When presented with digraph (1), arc a in that step takes the successive values

$$\begin{aligned} &9 \rightarrow 7; \Lambda \text{ (end 7)}; 9 \rightarrow 3; 3 \rightarrow 1; 1 \rightarrow 6; 6 \rightarrow 2; 2 \rightarrow 6; 2 \rightarrow 3; 2 \rightarrow 7; \\ &\Lambda \text{ (end 2)}; 6 \rightarrow 4; 4 \rightarrow 1; 4 \rightarrow 1; \Lambda \text{ (end 4)}; \Lambda \text{ (end 6)}; \Lambda \text{ (end 1)}; \end{aligned} \quad (3)$$

and so on (see exercise 12). Eventually the oriented forest



is constructed from the arcs $v \rightarrow u$ when step D6 discovers a new vertex u .

The arcs $v \rightarrow u$ that Algorithm D encounters when vertex u has already been seen do not form part of the oriented forest. But they're still in the digraph g , so they are shown as dotted arcs in (4). Nontree arcs come in four flavors:

- “Back arcs” go from a vertex to one of its proper ancestors.
- “Forward arcs” go from a vertex to one of its proper descendants.
- “Loops” go from a vertex to itself.
- “Cross arcs” go from a vertex to a nonancestor, nondescendant.

Can you classify all 13 of the dotted arcs in (4)? (See exercise 13.)

The nontree arcs can in fact be easily classified by looking at PRE and POST:

Theorem D. *After a depth-first search, the nontree arc $v \rightarrow u$ is*

- a back arc if and only if $\text{PRE}(v) > \text{PRE}(u)$ and $\text{POST}(v) < \text{POST}(u)$;*
- a forward arc if and only if $\text{PRE}(v) < \text{PRE}(u)$ and $\text{POST}(v) > \text{POST}(u)$;*
- a cross arc if and only if $\text{PRE}(v) > \text{PRE}(u)$ and $\text{POST}(v) > \text{POST}(u)$;*

the case $\text{PRE}(v) < \text{PRE}(u)$ and $\text{POST}(v) < \text{POST}(u)$ is impossible.

Proof. Every vertex v begins “unseen.” Then $\text{PRE}(v)$ is set, and v becomes “active” while Algorithm D is visiting every unseen vertex reachable from v via a path whose other vertices are currently unseen. Finally, after all of v 's arcs have been examined, v has been “explored” and $\text{POST}(v)$ is set. (See exercise 7.)

Exercise 2.3.2–20 shows that ancestor-descendant relations are characterized by preorder and postorder. Exercise 18 completes the proof. ■

The data structure provided by Algorithm D, which chooses some of the arcs of g to be the tree arcs of an oriented spanning forest, is called the *depth-first jungle* of g . Notice that the jungle is not an inherent property of the graph g itself; isomorphic graphs can have drastically different jungles, because the order in which arcs from a given vertex are examined has a significant effect. The order in which vertices are internally numbered and surveyed in step D2 is also important; for example, the first vertex to be explored is always a root. (See exercise 22.) But we will see that the choice of jungle makes little or no difference to the efficiency of more elaborate algorithms that make use of this structure.

Strong components. In any digraph g , the relation “ u is reachable from v and v is reachable from u ” is clearly an equivalence relation. The equivalence classes of this relation are called the *strong components* of g , and a digraph with only one strong component is called *strongly connected*.

Robert Tarjan discovered that the strong components of any given digraph can actually be discovered “on the fly” while we’re doing a depth-first search,* by making only modest changes to Algorithm D.

* Author’s note: Over the years I’ve often been asked, “What is your favorite algorithm?” Immediately I think to myself, “Uff, how I hate to be asked to choose favorites.” But then I realize that, in this particular case, the answer is quite clear: Tarjan’s algorithm for strong components is, without doubt, the algorithm that I love best. When I learned of this elegant procedure in 1973, I understood for the first time that data structures can also be “deep.”

Back arcs
ancestors
Forward arcs
descendants
Loops
Cross arcs
unseen
active
reachable
explored
depth-first jungle
jungle
strong components—
reachable
equivalence relation
strongly connected
Tarjan
Knuth
algorithm, favorite

In divers Liquors the little surfaces of the component particles are smooth and slippery.

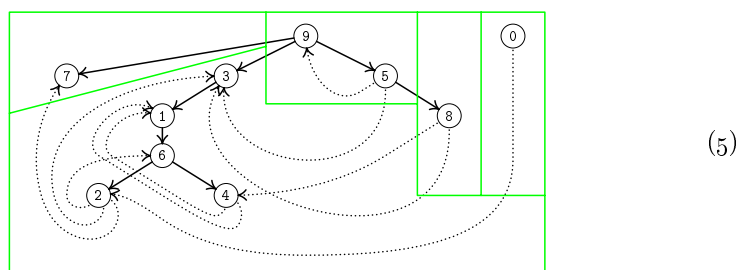
— ROBERT BOYLE, *Certain Physiological Essays* (1661)

*It seems like a circular situation;
in order to compute the lowpoint we need to identify the components,
and in order to find the components we need the lowpoint.
However, Tarjan found a way out.*

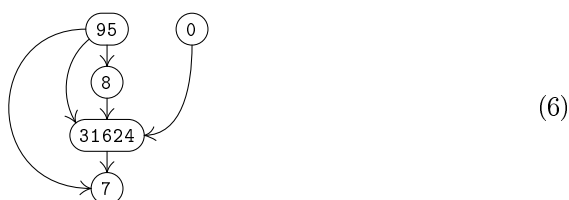
— SHIMON EVEN, *Graph Algorithms* (1979)

supervertices
acyclic
BOYLE
circular situation
Tarjan
EVEN
oriented cycle
shrink
directed acyclic graph
sink

Let's try to see why that's possible, by looking for example at the jungle (4) of the digraph (1) and examining its strong components. Here is (4) again, but the forward arc $9 \rightarrow 7$ and the loops $3 \rightarrow 3$, $8 \rightarrow 8$ are not shown:



(Forward arcs and loops have no effect on strong components, because they can be deleted without affecting reachability.) This jungle has been partitioned into five regions, containing “supervertices” $\{7, 31624, 95, 8, 0\}$; and it's easy to see that the vertices within each region are strongly connected. For example, each of the five vertices $\{3, 1, 6, 2, 4\}$ is reachable from the other four. Furthermore, these regions are in fact the strong components of (1)! For if we shrink the supervertices to single points, the resulting digraph



is acyclic. We can't go from one supervertex to another and back again.

In general, there's a conceptually simple way to find the strong components of *any* digraph: The vertices of an oriented cycle are strongly connected; so they're equivalent, and we can shrink them to a point. Let's do that repeatedly until the digraph no longer has any oriented cycles. The remaining supervertices are the (shrunk) strong components. In (1), for example, we could shrink $4 \rightarrow 1 \rightarrow 6 \rightarrow 4$ into 416; then $5 \rightarrow 9 \rightarrow 5$ into 59; then $2 \rightarrow 3 \rightarrow 416 \rightarrow 2$ into 23416; voilà, we've got (6).

Notice now that every nonempty directed acyclic graph has at least one “sink” vertex, a vertex with out-degree 0. Therefore, by the shrinking mech-

anism just described, *every nonempty digraph has at least one “sink” strong component*, a strong component without arcs to any other strong components.

Let S be a sink strong component of the digraph g . Since there’s no escape from S , we can remove any arcs of g that lead to a vertex of S ; after all, arcs into a “black hole” have no influence on g ’s strong components. Consequently *the strong components of g are S together with the strong components of $g \setminus S$.*

Good—there’s a decent chance that we might discover an efficient method, based on the notion of repeatedly identifying and removing sink components until all components have been found. Depth-first search has the convenient property that it learns about g ’s vertices and arcs one by one; we essentially want to extend it so that it can readily recognize (and remove) sink components.

Recall that all vertices are initially unseen when depth-first search begins. Then they become active, one by one, in preorder of the depth-first forest. Furthermore, a vertex remains active until the moment when we know that we’ve seen all of its outgoing arcs. In other words, every vertex goes through three stages as we perform depth-first search: It’s unseen and inactive, then seen and active, then seen and inactive. We’re going to extend that process by also removing vertices from the graph and calling them “settled,” as soon as we know that they’re part of a sink component with respect to unsettled vertices.

Thus every vertex will go through *four* stages as we search for strong components: First it’s unseen, inactive, unsettled; then it’s seen, active, unsettled; then it’s seen, inactive, unsettled; finally it’s seen, inactive, settled. We know from Algorithm D how to handle the first transitions. The only thing missing is an appropriate way to settle an unsettled vertex.

Let U be the set of all currently seen but unsettled vertices. We can list them

$$u_1, u_2, \dots, u_t, \quad \text{where} \quad \text{PRE}(u_1) < \text{PRE}(u_2) < \dots < \text{PRE}(u_t), \quad (7)$$

according to the order in which we’ve seen them. Some of those vertices might be active, while others might be inactive. If the active ones are $u_{j_1}, u_{j_2}, \dots, u_{j_a}$, with $j_1 < j_2 < \dots < j_a$, the depth-first strategy of Algorithm D tells us that $\text{PARENT}(u_{j_1}) = \text{SENT}$, $\text{PARENT}(u_{j_2}) = u_{j_1}$, $\dots$, $\text{PARENT}(u_{j_a}) = u_{j_{a-1}}$.

We’ve already seen every arc that goes out from the inactive vertices of U . For all we know, however, there may still be lots and lots of yet-unseen arcs, leading from any or all of the active vertices to any vertices whatsoever.

A nice structure does turn out to be present:

Lemma S. *Let $\hat{g}$ be the digraph whose vertices U are listed in (7), and whose arcs are those seen so far from U into U during a depth-first search for the strong components of g . Assume that $t \geq 1$. Also let $S_1, \dots, S_k$ be the strong components of $\hat{g}$. Then the leftmost element of each S_j , called its “leader” and denoted by u'_j , is an active vertex; and if u''_j denotes S_j ’s rightmost active vertex, $\hat{g}$ contains the $k - 1$ tree arcs*

$$u''_1 \rightarrow u'_2, \quad u''_2 \rightarrow u'_3, \quad \dots, \quad u''_{k-1} \rightarrow u'_k, \quad (8)$$

which link those components into a path. All other arcs of $\hat{g}$ lie within the individual strong components S_j , which form consecutive intervals of the list (7).

unseen
active
seen
settled
sink component
leader

Proof. The lemma holds initially, when $\hat{g}$ is a single isolated active vertex, because an isolated vertex u_1 is a strong component S_1 all by itself. We shall prove that the lemma remains true as the computation proceeds.

Let $u = u_{j_a}$ be the active vertex of largest preorder rank. Then $u \in S_k$, and the algorithm looks for the next unseen arc from u .

If there is no such arc, u becomes inactive. The lemma remains true if u isn't the first element of S_k . Otherwise, however, S_k has no remaining active vertices, so the algorithm knows that S_k is a sink component; vertices $\{u_{j_a}, \dots, u_t\}$ become settled, and the lemma remains true with $t \leftarrow j_a - 1$, $k \leftarrow k - 1$.

Suppose the next arc from u is $u \rightarrow v$. We ignore it if v is already settled, or if $v \in S_k$. On the other hand if $v \in S_j$ for $j < k$, we combine $S_j \cup \dots \cup S_k$ into a single strong component and set $k \leftarrow j$; the lemma remains true.

Otherwise v is an unseen vertex, which becomes seen and active. The lemma remains true with $u_{t+1} \leftarrow v$, $u''_k \leftarrow u$, $u'_{k+1} \leftarrow v$, $t \leftarrow t + 1$, $k \leftarrow k + 1$. ■

Corollary S. Suppose digraph g has s strong components $\{C_1, \dots, C_s\}$, and let v_j be the vertex of C_j that is earliest in preorder of g 's depth-first forest. Order the components so that $\text{POST}(v_1) < \dots < \text{POST}(v_s)$. Then the vertices of C_j are

$$\text{desc}(v_j) \setminus (\text{desc}(v_1) \cup \dots \cup \text{desc}(v_{j-1})), \quad \text{for } 1 \leq j \leq s, \quad (9)$$

where $\text{desc}(v)$ denotes the descendants of v in the forest. ■

(Hence the strong components of g are the *connected* components of the digraph obtained by deleting the arcs to $v_1, \dots, v_s$ from g 's depth-first spanning forest.)

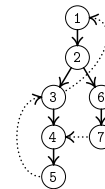
The structure guaranteed by Lemma S almost gives us the efficient algorithm that we want. But one ingredient is still missing, namely a quick way to deal with the boundaries between the current candidates S_j for strong components. Tarjan discovered that an extra field called **LOW** in each vertex is able to do what we need.

The definition of **LOW** is somewhat tricky and technical: When v is seen but unsettled, $\text{LOW}(v)$ is the smallest preorder rank of an unsettled vertex w for which we've seen a "downpath" from v to w , where a downpath is an oriented path

$$v = v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_r = w, \quad \text{for some } r \geq 0, \quad (10)$$

such that $v_j \rightarrow v_{j+1}$ "matured" before $v_{j-1} \rightarrow v_j$ for $0 < j < r$. A tree arc $v \rightarrow u$ matures when u becomes inactive; a nontree arc matures when we first see it.

Consider, for example, the depth-first search that leads to the jungle shown here. At the time vertex 5 has just become seen, we have $\text{LOW}(1) = 1, \dots, \text{LOW}(5) = 5$. Then the arc $5 \rightarrow 3$ is a downpath with $r = 1$, so $\text{LOW}(5) \leftarrow 3$. After 5 becomes inactive, $4 \rightarrow 5$ matures; hence $\text{LOW}(4) \leftarrow 3$ because of the downpath $4 \rightarrow 5 \rightarrow 3$ with $r = 2$. Soon $\text{LOW}(3) \leftarrow 1$; and so on (see exercise 55). The definition ensures that at most one **LOW** value changes at every step of the depth-first process.



Theorem T. When vertex v becomes inactive during a depth-first search, v is the leader of the current sink component if and only if $\text{LOW}(v) = \text{PRE}(v)$.

Proof. (This fact is Tarjan's "secret sauce.") See exercise 60. ■

isolated vertex
Tarjan
LOW
downpath
tree arc
matures
nontree arc
leader

OK, we're ready now for the nitty-gritty details of an efficient algorithm. Algorithm T maintains a stack whose top is SINK, linked together in LINK fields; this stack holds the inactive vertices that aren't yet settled. The algorithm also gives every vertex a REP field for the equivalence class representatives: Vertices v and w are strongly connected if and only if $\text{REP}(v) = \text{REP}(w)$ at termination.

Tarjan
leader
SENT

Tarjan noticed in 2021 that we can save time and space by encoding PRE and LOW in the existing LINK and REP fields, because we need only know whether or not $\text{LOW} = \text{PRE}$. While vertex v is active, we shall therefore let

$$\text{LINK}(v) = \begin{cases} \text{SENT}, & \text{if } \text{LOW}(v) = \text{PRE}(v); \\ \Lambda, & \text{if } \text{LOW}(v) \neq \text{PRE}(v). \end{cases} \quad (11)$$

Moreover, after v has been seen, we shall let

$$\text{REP}(v) = \begin{cases} \text{LOW}(v), & \text{if } v \text{ isn't settled}; \\ \text{SENT} + v', & \text{if } v \text{ is settled with strong component leader } v'. \end{cases} \quad (12)$$

Algorithm T (*Strong components*). Given a digraph g in SGB format, this algorithm determines the strong components of g . Each vertex is assumed to contain utility fields PARENT, ARC, LINK, and REP, as explained above. Auxiliary vertex pointer variables u , v , w , and SINK are used; also an arc pointer a and an integer p . A dummy vertex $\text{SENT} = \text{VERTICES}(g) + \text{N}(g)$ is assumed to be present, with $\text{REP}(\text{SENT}) = 0$.

- T1.** [Initialize.] Set $\text{PARENT}(w) \leftarrow \Lambda$ for $\text{VERTICES}(g) \leq w < \text{SENT}$, until eventually $w = \text{SENT}$. Also set $p \leftarrow 0$ and $\text{SINK} \leftarrow \text{SENT}$.
- T2.** [Done?] (All vertices reachable from a vertex $v \geq w$ are now settled.) Terminate if $w = \text{VERTICES}(g)$. Otherwise set $w \leftarrow w - 1$, and repeat this step if $\text{PARENT}(w) \neq \Lambda$. Otherwise set $v \leftarrow w$ and $\text{PARENT}(v) \leftarrow \text{SENT}$.
- T3.** [Begin to explore from v .] Set $a \leftarrow \text{ARCS}(v)$, $p \leftarrow p + 1$, $\text{REP}(v) \leftarrow p$, and $\text{LINK}(v) \leftarrow \text{SENT}$.
- T4.** [Done with v ?] If $a = \Lambda$, go to T7.
- T5.** [Visit the next arc, $v \rightarrow u$.] Set $u \leftarrow \text{TIP}(a)$ and $a \leftarrow \text{NEXT}(a)$.
- T6.** [If u is new, move to it.] If $\text{PARENT}(u) = \Lambda$, set $\text{PARENT}(u) \leftarrow v$, $\text{ARC}(v) \leftarrow a$, $v \leftarrow u$, and go to T3. Otherwise, if $u = w$ and $p = \text{N}(g)$ (we're in the last component), while $v \neq w$ set $\text{LINK}(v) \leftarrow \text{SINK}$, $\text{SINK} \leftarrow v$, $v \leftarrow \text{PARENT}(v)$; then set $u \leftarrow \text{SENT}$ and go to T8. Otherwise, if $\text{REP}(u) < \text{REP}(v)$, set $\text{REP}(v) \leftarrow \text{REP}(u)$, $\text{LINK}(v) \leftarrow \Lambda$ (see (11) and (12)). Go to T4.
- T7.** [Finish with v .] Set $u \leftarrow \text{PARENT}(v)$. If $\text{LINK}(v) = \text{SENT}$, go to T8. (See Theorem T.) Otherwise, if $\text{REP}(v) < \text{REP}(u)$, set $\text{REP}(u) \leftarrow \text{REP}(v)$ and $\text{LINK}(u) \leftarrow \Lambda$. Then set $\text{LINK}(v) \leftarrow \text{SINK}$, $\text{SINK} \leftarrow v$, and go to T9.
- T8.** [New strong component.] (Now v and its unsettled descendants form a strong component that will be represented by v .) While $\text{REP}(\text{SINK}) \geq \text{REP}(v)$, set $\text{REP}(\text{SINK}) \leftarrow \text{SENT} + v$ and $\text{SINK} \leftarrow \text{LINK}(\text{SINK})$. (See (12).) Finally set $\text{REP}(v) \leftarrow \text{SENT} + v$.
- T9.** [Tree done?] If $u = \text{SENT}$, go back to T2. Otherwise set $v \leftarrow u$, $a \leftarrow \text{ARC}(v)$, and go to T4. ■

Step T6 may terminate the algorithm before all of the arcs have been seen, in cases where the final strong component is already known. (See exercise 62.)

One can only marvel at how everything fits together like clockwork in this algorithm! Algorithm T traverses each vertex and each arc at most once, and whenever it needs to make a crucial decision the necessary information just happens to be right there at its fingertips.

The running time is, of course, linear in the number of vertices and edges. With m edges and n vertices, Algorithm T makes at most $6m + 14n$ accesses to memory (see exercise 63).

And there's also an extra bonus: The strong components $C_1, C_2, \dots, C_s$ of g are not only discovered, they are actually produced in “reverse topological order”: Every arc *not* inside a strong component runs from C_j to a component C_i for which $i < j$. In particular, if g has no cycles, every strong component will contain a single vertex, and the vertices will be *topologically sorted* in the backwards direction. (Algorithm 2.2.3T is a bit faster, in this special case, and it goes forward; but of course it solves a much simpler problem.)

With minor extensions to Algorithm T, we can also (i) compute the dag analogous to (6) that results when strong components shrink to a point; and (ii) compute a subset of the arcs that's sufficient to certify the strength of each strong component. (See exercises 65 and 66.)

Weak components. Let's write ' $v \Rightarrow w$ ' if w is reachable from v , and ' $v \not\Rightarrow w$ ' otherwise. If vertices v and w of a digraph g are mutually reachable from each other (written ' $v \Leftrightarrow w$ '), they lie in the same strong component, so they're “strongly equivalent.” On the other hand if they're *mutually unreachable* (written ' $v \parallel w$ '), meaning that neither one is reachable from the other, we shall regard them as “weakly equivalent.” Two vertices that are called strongly equivalent should naturally also be considered to be weakly equivalent, because strength is stronger than weakness; so let's write ' $v \approx w$ ' to mean that either $v \Leftrightarrow w$ or $v \parallel w$. We can now rely on transitivity to say that v is weakly equivalent to w (written ' $v \asymp w$ ') if and only if there's a chain

$$v = v_0 \approx v_1 \approx \dots \approx v_r = w, \quad \text{for some } r \geq 0. \quad (13)$$

Weak equivalence is obviously an equivalence relation, and the corresponding equivalence classes are called the *weak components* of g . (Some authors define weak components differently, by saying that weak components are simply the components of the undirected graph that's obtained by ignoring the orientations of arcs. It's better, however, to call those the *undirected components* of g .)

Every weak component is clearly a union of strong components. For example, the weak components of the digraph (1) are $\{\{95, 0, 8\}, \{31624\}, \{7\}\}$, obtained by combining the mutually unreachable strong components in (6). In general, *strong components are partially ordered and weak components are totally ordered*, by the reachability relation between their vertices. Indeed, strong components and weak components are perhaps best understood as the most refined set partitions of the vertices for which that statement is true.

topological order
certify
weak components—
mutually unreachable
notation $v \Leftrightarrow w$
notation $v \parallel w$
transitivity
notation $v \asymp w$
weak components
undirected components
partial ordering
total ordering
linear ordering, see total
refinement
set partitions

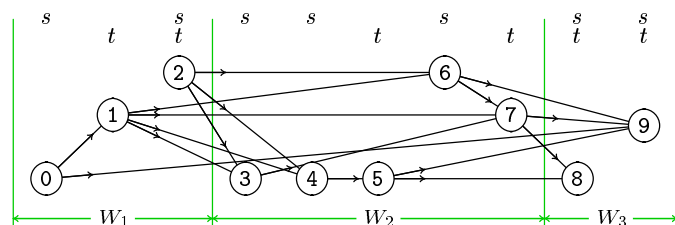


Fig. 600. A directed acyclic graph with ten vertices, seventeen arcs, and three weak components (W_1, W_2, W_3). Each source vertex within a component is marked with ‘s’, and each sink with ‘t’. Weak components are linearly ordered; and when two weak components are adjacent, there are arcs from each sink of W_j to each source of W_{j+1} .

A graph is *weakly connected* if it has only one weak component, which means that $u \asymp v$ for all vertices u and v . Exercises 80–85 discuss alternative ways to define weak equivalence and weak connectedness; one of the most noteworthy is the characterization that’s proved in exercise 84:

Lemma W. A nonempty digraph is weakly connected if and only if we can’t split its vertices into two nonempty parts L and R such that (i) every vertex of R is reachable from every vertex of L ; (ii) no vertex of L is reachable from any vertex of R . ■

(Notice that (ii) characterizes *ordinary* connectedness of *undirected* graphs.)

When we shrink all strong components of a digraph into single loopless vertices, we’re left with a directed *acyclic* graph (dag), whose weak components have important structural properties. Consider, for example, the dag in Fig. 600, whose weak components (W_1, W_2, W_3) are depicted with vertical lines between them. A strong component is called a *source* with respect to weak component W_j if it has no predecessors in W_j ; it’s called a *sink* of W_j if it has no successors in W_j .

A weak component with more than one vertex must have at least two sources, and at least two sinks, because of Lemma W.

In general the weak components of any digraph can always be placed into a linear order and labeled ($W_1, W_2, \dots, W_r$) in such a way that

$$v \Rightarrow w \text{ for all } v \in W_j \text{ and } w \in W_k \text{ with } 1 \leq j < k \leq r. \quad (14)$$

This condition is equivalent to requiring that $t \rightarrow s$ for all sinks t of W_j and all sources s of W_{j+1} , for $1 \leq j < r$. (For example, when $j = 1$ in Fig. 600 we have $1 \rightarrow 3, 1 \rightarrow 4, 1 \rightarrow 6, 2 \rightarrow 3, 2 \rightarrow 4$, and $2 \rightarrow 6$.) Thus all dags with $r > 1$ weak components can be obtained by starting with an arbitrary sequence of r weakly connected dags, then hooking together sinks to sources at the $r - 1$ boundaries between them, and adding optional arcs between W_i and W_j for $i < j$.

Suppose we introduce a new vertex v and insert it at the left of Fig. 600. There are 2^{10} different ways to make a new 11-vertex dag by adding arcs from v to a subset of $\{0, 1, \dots, 9\}$, but only a few essentially different cases arise. For example, Case 1 occurs when there are arcs $v \rightarrow 0$ and $v \rightarrow 2$ to both of the sources in W_1 ; then $\{v\}$ becomes a new weak component W_0 , all by itself, in which v is both a source and a sink. The other weak components don’t change.

weakly connected

dag

source

sink

series decomposition of a poset: see weak compo

Case 2 arises when there are arcs $v \rightarrow 3$, $v \rightarrow 4$, $v \rightarrow 6$ from v to all the sources of W_2 , but no arcs from v into W_1 . Then v becomes part of W_1 , as a new source and sink; W_2 and W_3 remain unchanged.

Tarjan
leader
HIT
WHIT

There's an intermediate Case 1' between Case 1 and Case 2, namely when v "hits" at least one of the vertices $\{0, 1, 2\}$ of W_1 but not both of its sources $\{0, 2\}$. In Case 1', as in Case 2, v joins W_1 as a source vertex, and the other components stay the same. But in this case v is not a sink; furthermore, 0 and 2 will still be sources only if they aren't hit.

Case 3, by analogy with Cases 1 and 2, arises when v hits both sources of W_3 but doesn't touch either W_1 or W_2 . There's also Case 2', analogous to Case 1', when v hits W_2 at least once but without touching W_1 and without hitting all three of W_2 's sources. In both of those cases the weak components W_1 and W_2 will merge together, and together with v they'll become a new W_1 . The former sink vertices of W_1 will no longer be sinks, and the former source vertices of W_2 will no longer be sources. In Case 3 (but not Case 2'), v will be a sink. Weak component W_3 won't change, except that it will get the new name W_2 .

The reader should now be able to guess what happens in the remaining two cases, namely Case 4 and Case 3', after which only one weak component remains.

In all cases it's easy to determine the weak components, sources, and sinks of the new dag, if we know them before v was introduced. In fact, sinks aren't important; we need only keep track of the sources. Exercise 88 has full details.

Algorithm T has the nice property that it discovers the strong components from right to left. Therefore, after each strong component is found, the task of maintaining the current *weak* components is essentially the same as introducing a new vertex v at the left, as we've just discussed! So there's good news: It's actually possible to discover the weak components at the same time as we learn the strong ones, by extending Algorithm T slightly. The following algorithm [R. E. Tarjan, *Information Processing Letters* **3** (1974), 13–15] achieves this while still needing only $O(m + n)$ steps of computation.

Of course we'll need to extend our data structures to include additional fields; each vertex record gains two link fields, **WLINK** and **SRC**. Suppose the strong components discovered so far belong to weak components $(W_1, \dots, W_r)$. The leader of the leftmost strong component of W_j (the one found last) is called the leader of W_j . Let vertex v be that leader; then **WLINK**(v) is the leader of W_{j+1} , or **SENT** if $j = r$. Variable **WP** is the leader of W_1 . Hence, for example, Fig. 600 is represented by **WP** = 0, **WLINK**(0) = 3, **WLINK**(3) = 8, **WLINK**(8) = **SENT**.

The **SRC** fields are similar, but they track sources. If v is the leader of a strong component that's a source of W_j , **SRC**(v) is the next such source to the right, or **SENT** if v is rightmost. In Fig. 600, for example, **SRC**(0) = 2, **SRC**(2) = **SENT**; **SRC**(3) = 4, **SRC**(4) = 6, **SRC**(6) = **SENT**; **SRC**(8) = 9, **SRC**(9) = **SENT**.

The values of **WLINK**(v) and **SRC**(v) are unused, and undefined, unless vertex v plays one of the special roles already described. So we needn't set them.

Each vertex also has two additional 1-bit fields, called **HIT** and **WHIT**; they turn out to be necessary in order to keep the running time down to $O(m + n)$. We have **WHIT**(v) = 1 if and only if there's an arc to v from the current vertex w . And

$\text{HIT}(v) = 1$ implies that vertex v has been hit; hence it's definitely *not* a source, although the SRC links might not yet have been updated to indicate that fact.

The vertex records of our data structure have eight fields so far: PARENT, LINK, REP, ARC, WLINK, SRC, WHIT, and HIT. To round them out, we add a ninth field $\text{SRANK}(v)$, which will hold the serial number of v 's strong component when v is a leader. Every strong component will be assigned a serial number in topological order, ending with $N(g) - 1$; the smallest number will be $N(g) - c$, if c strong components have been identified.

serial number
topological order
SETTLED

Algorithm W (*Weak components*). Given a digraph g in SGB format, this algorithm extends Algorithm T by also identifying g 's weak components. In fact, steps W1–W8 take the place of step T8 in that algorithm. Step T1 should be amended so that it initializes $\text{WHIT}(w) \leftarrow \text{HIT}(w) \leftarrow 0$ at the same time as it sets $\text{PARENT}(w) \leftarrow \Lambda$. Step T1 should also set $\text{WP} \leftarrow \text{PREV} \leftarrow \text{SENT}$, $s \leftarrow \text{SRANK}(\text{SENT}) \leftarrow N(g)$, $\text{HIT}(\text{SENT}) \leftarrow 0$, and $\text{SETTLED} \leftarrow \Lambda$. Upon termination, SETTLED will point to the beginning of a list of all vertices, linked in the LINK fields. The vertices of each component, whether strong or weak, will appear consecutively in that list, beginning with the component leader.

- W1.** [Begin new strong component v .] Set $u'' \leftarrow u$, $s \leftarrow s - 1$, $\text{SRANK}(v) \leftarrow s$, $\text{SRC}(v) \leftarrow \text{PREV}$, $\text{PREV} \leftarrow v$, $\text{LINK}(v) \leftarrow \text{SINK}$, $t \leftarrow v$. Perform step T8 of Algorithm T, also setting $t \leftarrow \text{SINK}$ just before $\text{SINK} \leftarrow \text{LINK}(\text{SINK})$ in that loop. Finally set $\text{LINK}(t) \leftarrow \text{SETTLED}$ and $\text{SETTLED} \leftarrow v$.
- W2.** [Find v 's least successor, v' .] Set $w' \leftarrow \text{SETTLED}$ and $v' \leftarrow \text{SENT}$. (We will reexamine all arcs that lead from strong component v .) For $a \leftarrow \text{ARCS}(w')$, while $a \neq \Lambda$, set $u \leftarrow \text{REP}(\text{TIP}(a)) - \text{SENT}$ and $a \leftarrow \text{NEXT}(a)$; if $u \neq v$, set $\text{WHIT}(u) \leftarrow 1$ and if $\text{SRANK}(u) < \text{SRANK}(v')$ also set $v' \leftarrow u$. Then if $w' \neq t$, set $w' \leftarrow \text{LINK}(w')$ and run through all arcs of w' in the same way.
- W3.** [Find w' , the weak component of v' .] (Now v' is the leader of the successor strong component of v that has smallest SRANK.) If $v' = \text{SENT}$, set $\text{WP} \leftarrow \text{SENT}$ and go to W6. Otherwise set $w' \leftarrow \text{SRC}(v)$, and while $\text{SRANK}(\text{WP}) \leq \text{SRANK}(v')$ set $w' \leftarrow \text{WP}$ and $\text{WP} \leftarrow \text{WLINK}(w')$. Finally set $u \leftarrow w'$.
- W4.** [All sources of w' hit?] If $u = \text{SENT}$, go to W5. Otherwise, if $\text{WHIT}(u) = 0$, go to W6. Otherwise set $u' \leftarrow u$, $u \leftarrow \text{SRC}(u)$, and while $\text{HIT}(u) = 1$ set $u \leftarrow \text{SRC}(u)$ and $\text{SRC}(u') \leftarrow u$; then repeat step W4. (See exercise 90.)
- W5.** [Move WP back one.] Set $\text{WP} \leftarrow w'$. If $w' = \text{SRC}(v)$, also set $\text{SRC}(v) \leftarrow \text{SENT}$.
- W6.** [Finish $\text{WLINK}(v)$.] Set $\text{WLINK}(v) \leftarrow \text{WP}$.
- W7.** [Reset WHITs.] Set $w' \leftarrow \text{SETTLED}$. (This step is similar to W2.) For $a \leftarrow \text{ARCS}(w')$, while $a \neq \Lambda$, set $u \leftarrow \text{REP}(\text{TIP}(a)) - \text{SENT}$ and $a \leftarrow \text{NEXT}(a)$; if $u \neq v$, set $\text{WHIT}(u) \leftarrow 0$ and if $\text{SRANK}(u) < \text{SRANK}(\text{WP})$ also set $\text{HIT}(u) \leftarrow 1$. Then if $w' \neq t$, set $w' \leftarrow \text{LINK}(w')$ and run through all arcs of w' in the same way.
- W8.** [Finish component v .] Set $\text{WP} \leftarrow v$, $u \leftarrow u''$, and go to step T9. ■

The reader will find it instructive to compare this algorithm to exercise 88, in order to see how the current weak components are updated efficiently in each

of the various cases that can arise. Once again, the information that we need to make each decision is “magically” present at our fingertips in the data structures.

Exercises 92 and 93 mention minor improvements to Algorithm W.

data structures
biconnected components–
biconnectivity
strong connectivity
TARJAN



(Who knows what I might say next?)

Biconnected components.



Some day this section will include another major algorithm (Algorithm 7.4.1.2B), namely the Hopcroft–Tarjan for biconnected components.

The similarity between biconnectivity and strong connectivity revealed by the depth-first search approach is striking.
— ROBERT TARJAN, *SIAM Journal on Computing* (1972)

Historical notes. The term depth-first search was introduced by Nils Nilsson in a literature review [*IEEE Trans.* **C-18** (1969), 963–964] and popularized in his classic book *Problem-Solving Methods in Artificial Intelligence* (New York: McGraw–Hill, 1971). His methods resembled Algorithm Q. He was particularly interested in “state spaces”: graphs for which the vertices are the configurations of some model and the arcs are the allowable transitions; he focussed on searching for good ways to get from an initial state to a goal state.

The special case of depth-first search in which the given digraph is a connected and undirected graph was devised in the 19th century by C. P. Trémaux, in the context of a person who is able to drop pebbles while exploring the tunnels of a mine. The problem was to start at an arbitrary point and to traverse every passage exactly twice, once in each direction, eventually returning to the start; thus it was to find an Eulerian trail in a balanced digraph, whose existence is guaranteed by Theorem 2.3.4.2G. [See É. Lucas, *Récréations Mathématiques* **1** (Paris: Gauthier-Villars, 1882), 47–50.] A similar but less efficient procedure had previously been published by C. Wiener [*Mathematische Annalen* **6** (1873), 29–30]. The validity of Trémaux’s algorithm was first proved rigorously by D. König, *Theorie der endlichen und unendlichen Graphen* (1936), Chapter 3.

The fact that depth-first search is extremely useful for graph algorithms was discovered by John Hopcroft and Robert Tarjan when they shared an office at Stanford University during Hopcroft’s first sabbatical year. After discovering Algorithm B, they continued to develop related methods for planarity testing and other problems; see ACM Algorithm 447, *CACM* **16** (1973), 372–378.

The concept of a strongly connected digraph seems to have arisen gradually. H. E. Robbins introduced “orientable graphs” by considering a city that wants to convert all of its roads to one-way streets on weekends during football season [*AMM* **46** (1939), 281–283]. R. D. Luce developed the theory of digraphs that remain strongly connected after k arcs are removed [*American J. Math.* **74** (1952), 701–722]. He called them “networks that are connected”; the term “strongly connected” was introduced by F. Harary [*Trans. Amer. Math. Soc.* **78** (1955), 459].

R. E. Tarjan described the beauties of the depth-first jungle and introduced a precursor to Algorithm T in *SICOMP* **1** (1972), 146–160. His original algorithm used a different definition of LOW; the present version was inspired in part by J. Eve and R. Kurki-Suonio [*Acta Informatica* **8** (1977), 303–314]. Lemma S is based largely on ideas developed by E. W. Dijkstra in *A Discipline of Programming* (Prentice–Hall, 1976), Chapter 25. Interesting but less efficient algorithms had been published previously by R. W. H. Sargent and A. W. Westerberg [*Transactions of the Institution of Chemical Engineers* **42** (1964), 190–197]; L. Ya. Leifman [*Kibernetika* **2**, 5 (1966), 19–23]; P. Purdom Jr. [*BIT* **10** (1970), 76–94]; I. Munro [*Information Processing Letters* **1** (1971), 56–58].

Tarjan revisited this work 50 years later, in a review paper written with Uri Zwick [*European Journal of Combinatorics* **119** (2024), 103815, 24 pages].

Historical notes
depth-first search
Nilsson
state spaces
Trémaux
Eulerian trail
Lucas
Wiener, Ludwig Christian
König
Hopcroft
Tarjan
Stanford University
planarity testing
strongly connected digraph
Robbins
orientable graphs
football
Luce
Harary
Tarjan
jungle
Eve
Kurki-Suonio
Dijkstra
Sargent
Westerberg
Leifman
Purdom Jr.
Munro
Zwick

EXERCISES

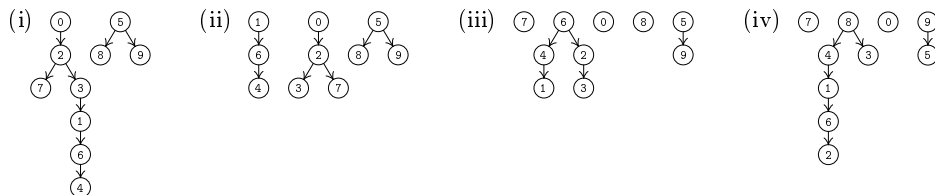
1. [16] Complete (2). Also show the stack contents at the beginning of step Q6.
3. [18] Instead of using the linked mechanism **ARCS**, **TIP**, **NEXT** of SGB format, the arcs of digraphs are sometimes represented sequentially in a single array called, say, **TIP**. The arcs from vertex v then are $v \rightarrow \text{TIP}[k]$ for $\text{ARCS}[v] \leq k < \text{ARCS}[v+1]$, where $\text{ARCS}[v_0 + n]$ is suitably defined. Modify Algorithm Q to work with this convention.
5. [M20] Exactly how often are each of the operations or tests (a) $\text{MARK}(w) \leftarrow \Lambda$, (b) $\text{MARK}(w) \neq \Lambda$, (c) $\text{MARK}(v) \leftarrow \text{SENT}$, (d) $a \leftarrow \text{ARCS}(v)$, (e) $u \leftarrow \text{TIP}(a)$, (f) $a \leftarrow \text{NEXT}(a)$, (g) $\text{MARK}(u) = \Lambda$, (h) $\text{MARK}(u) \leftarrow s$, and (i) $s \leftarrow \text{MARK}(v)$ performed by Algorithm Q? Express your answers in terms of $m = M(g)$, $n = N(g)$, and the number r of times that step Q3 is executed.
- 7. [20] (*Breadth-first search.*) Whenever we traverse a digraph, its vertices begin “unseen”; then they’re “active”; and finally they’re “explored.” A general search procedure operates repeatedly as follows, until all vertices have been explored:

Choose an active vertex, v ; or if none are active, activate an unseen vertex v .
 If v has no unseen arcs, call it explored. Otherwise let $v \rightarrow u$ be an unseen arc;
 if vertex u is unseen, add the arc $v \rightarrow u$ to the spanning forest and activate u .

Algorithm D is the special case where we always choose the most recently activated v .

By contrast, breadth-first search, which we’ve used for example in Section 7.3 to find the shortest paths from a root vertex, always chooses the *least* recently activated v . Show that simple changes to Algorithm Q will implement breadth-first search efficiently.

8. [17] What spanning forest does the algorithm of exercise 7 construct from (1)?
10. [M20] Count exercise 7’s memory references, in comparison with exercise 5.
12. [18] Complete (3) by listing *all* of the arcs a that are seen in step D4.
13. [16] Identify the back arcs, forward arcs, loops, and cross arcs in (4).
- 15. [M20] Prove that a digraph is acyclic if and only if it has no back arcs or loops.
16. [20] Sometimes we know that every vertex of a digraph is reachable from a single vertex v_0 . Show that Algorithm D can be simplified in such cases.
18. [20] Prove that $\text{PRE}(v) < \text{PRE}(u)$ implies $\text{POST}(v) > \text{POST}(u)$ in Theorem D.
- 19. [M21] Count Algorithm D’s memory references, in comparison with exercise 5.
20. [20] Rewrite Algorithm D as a recursive procedure. (In this formulation, the **PARENT** and **ARC** fields won’t be needed.)
- 21. [21] Modify Algorithm D so that it classifies every arc a in step D5 as either a tree arc, a back arc, a forward arc, a loop, or a cross arc.
22. [20] Which of the following oriented forests could be produced by Algorithm D from the digraph (1), if the internal orderings of arcs and vertices are changed?



ARCS
TIP
NEXT
 SGB format
 sequentially
 Breadth-first search
 unseen
 active
 explored
 general search procedure
 back arcs
 forward arcs
 loops
 cross arcs
 acyclic
 reachable
 recursive procedure
 tree arc

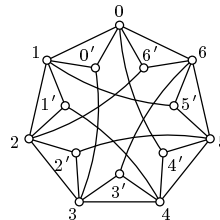
- **24.** [20] (*Vertex heights.*) Extend Algorithm D so that it (i) removes all back arcs and loops from g ; and (ii) introduces a new field $\text{HT}(v)$ for each vertex v , setting it to the length of the longest path from v in the resulting acyclic digraph.

- **25.** [M23] An undirected graph G with m edges can be converted to a digraph g in 2^m ways by orienting each edge, changing $u - v$ into either $u \rightarrow v$ or $v \rightarrow u$. Prove that (i) G has an orientation for which no simple directed path has length $\geq k \iff$ (ii) G is k -colorable $\iff$ (iii) G has an acyclic orientation for which the height of every vertex is less than k . *Hint:* Use the algorithm of exercise 24.

- 26.** [22] Show that the vertex heights found by the algorithm of exercise 24 can depend on the order in which arcs are examined: Construct a digraph on vertices $\{0, 1, \dots, 9\}$ for which $\text{HT}(9) = 9$ when the arcs are processed in one order, but all heights are ≤ 5 when that order is reversed.

- 27.** [24] The *Youngs graph* Y consists of a cycle of seven vertices $0 - 1 - 2 - 3 - 4 - 5 - 6 - 0$ joined to seven other vertices of degree 3, with $x - x'$, $x - ((x-1) \bmod 7)'$, $x - ((x-3) \bmod 7)'$.

- a) Show that Y is “4-critical”: Its chromatic number is 4, but it can be 3-colored when any edge is removed.
b) Find all orientations of Y that have at most two simple oriented paths of length 3, and no simple oriented paths of length 4.



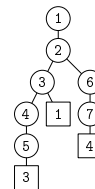
- **28.** [M21] A subset S of a partially ordered set P is called a *chain* if its elements are pairwise comparable; that is, if $x \in S$ and $y \in S$ and $x \neq y$ implies that $x \prec y$ or $y \prec x$ in P . It's called an *antichain* if its elements are pairwise incomparable; that is, if $x \in S$ and $y \in S$ and $x \neq y$ implies that $x \not\prec y$ and $y \not\prec x$ in P .

- a) Assuming that P is finite, let s be the size of its largest chain or chains. Explain how to determine s using exercise 24.
b) Prove that s is also the minimum number of antichains into which P can be partitioned.

- **30.** [21] The *depth-first jungle forest* of a digraph g is obtained as follows: Start with one internal node for each vertex, represented as a circle labeled with the name of that vertex. The k th child of internal node v is internal node w , if the k th arc $v \rightarrow w$ is a tree arc; otherwise that k th child is an external node, represented as a square labeled with w .

For example, the depth-first jungle forest for the digraph whose depth-first jungle appears after (10) in the text is shown here.

- a) Draw the depth-first jungle forest that corresponds to (4).
b) How many digraphs have exactly the same depth-first jungle forest as (a), except for the labels in the external nodes?
c) How many digraphs have exactly the same depth-first jungle forest as (a), except for the node labels (either internal or external)?



- 31.** [M22] Generalize the results of exercise 30, considering all possible digraphs.

- 32.** [22] Test Algorithm D empirically on random digraphs with $n = 1000000$ vertices, where each of $m = 5n$ arcs goes from a uniformly random vertex v to a uniformly random vertex u . How many tree arcs, back arcs, forward arcs, and cross arcs are formed?

- 33.** [22] Continuing exercise 32, test Algorithm D when the arcs from each vertex v are obtained as follows: “With probability $p = 5/6$, generate a uniformly random vertex u , create the arc $v \rightarrow u$, and repeat this process. Otherwise stop.” (The expected number of arcs from v will be $(p + 2p^2 + 3p^3 + \dots)(1-p) = p/(1-p) = 5$.)

heights
dag
longest path
acyclic digraph
digraph
orienting each edge
graph, orientation
simple directed path
 k -colorable
path length
coloring a graph
acyclic orientation
Youngs graph
critical
 k -critical graph
chromatic number
partially ordered set
chain
comparable
antichain
incomparable
partition of a set
depth-first jungle forest
internal node
external node
random digraphs
random digraphs, uniform model
uniform model of random digraphs
random digraphs, geometric model
geometric model of random digraphs

- **34.** [HM27] At first glance the “uniform” model of random digraphs in exercise 32 might seem to be roughly equivalent to the “geometric” model in exercise 33, when $m = pn/(1 - p)$ and $n \rightarrow \infty$. Prove, however, that the models are actually quite different, by explaining how to compute the probability that a given depth-first jungle forest with m edges is obtained with (a) the uniform model; (b) the geometric model when $p = m/(m + n)$. Evaluate those probabilities for the forest of exercise 30(a).

35. [HM21] What is the probability that a random digraph has exactly k loops $v \rightarrow v$, under the (a) uniform (b) geometric model, assuming that $p = m/(m + n)$?

36. [M22] (P. Jacquet.) Generalize the geometric model of exercise 33 as follows: Every vertex v independently has out-degree d with probability π_d , where $(\pi_0, \pi_1, \dots)$ is an *arbitrary* probability distribution with finite mean. Once d has been chosen, each arc $v \rightarrow w_j$ for $1 \leq j \leq d$ then goes to a uniformly random vertex w_j .

Show that a random depth-first jungle forest with n internal nodes, conforming to this model, can be generated with the following simple algorithm. (There's an auxiliary array $\mathbf{V}$, where $\mathbf{V}[p]$ will be the p th vertex in preorder of the forest, for $1 \leq p \leq n$, as well as an auxiliary stack $\mathbf{S}$ of potentially unbounded size.)

- J1.** [Initialize.] Set $\mathbf{V}[j] \leftarrow j - 1$ for $1 \leq j \leq n$. Also set $p \leftarrow s \leftarrow 0$.
- J2.** [Start a tree.] Set $p \leftarrow p + 1$, let $\mathbf{V}[j] = \max\{\mathbf{V}[p], \dots, \mathbf{V}[n]\}$, swap $\mathbf{V}[p] \leftrightarrow \mathbf{V}[j]$.
- J3.** [Choose D .] Let D be an independent random integer, with $\Pr(D = d) = \pi_d$. (It will be the out-degree of $\mathbf{V}[p]$.) Set $\mathbf{S}[s + j] \leftarrow p$ for $0 \leq j < D$, then $s \leftarrow s + D$.
- J4.** [Choose X .] If $p = n$, set $X \leftarrow s$. Else let X be an independent random integer with the geometric distribution $\Pr(X = x) = (p/n)^x(1 - p/n)$. If $X > s$, set $X \leftarrow s$.
- J5.** [Define nontree arcs.] Let $\mathbf{V}[\mathbf{S}[s - j]] \rightarrow \mathbf{V}[P_j]$ be arcs for $1 \leq j \leq X$, where P_j (for each j) is an independent uniform random integer in the range $1 \leq P_j \leq p$.
- J6.** [Define a tree arc.] If $X = s$, go to step J7. Otherwise set $s \leftarrow s - X - 1$ and let $\mathbf{V}[\mathbf{S}[s]] \rightarrow \mathbf{V}[j]$ be an arc, where j is an independent uniform random integer in the range $p < j \leq n$. Then set $p \leftarrow p + 1$, swap $\mathbf{V}[p] \leftrightarrow \mathbf{V}[j]$, and return to J3.
- J7.** [Finish a tree.] Terminate if $p = n$. Otherwise set $s \leftarrow 0$ and return to J2. ■

- **37.** [HM30] Given a forest F with n nodes, explain how to construct the multivariate generating function g_F for which $[v^l w^t x^b y^f z^c] g_F(v, w, x, y, z)$ is the probability that the geometric model of exercise 33 will produce a random digraph whose depth-first forest is F and whose depth-first jungle contains exactly l loops, t tree arcs, b back arcs, f forward arcs, and c cross arcs. For example, there are two possibilities when $n = 2$:

$$g_F = \begin{cases} (1 - p)^2 pw / (2(1 - (v + x)p/2)(1 - vp/2)(1 - (v + y)p/2)), & \text{if } F = \mathbf{!}; \\ (1 - p)^2 / ((1 - vp/2)(1 - (v + z)p/2)), & \text{if } F = \bullet\bullet. \end{cases}$$

Notice that g_F is a function of the geometric probability parameter p .

38. [HM23] Exercise 37 allows us to compute the probability $g_F(1, 1, 1, 1, 1)$ that a geometrically random digraph will have F as its depth-first forest. When $n = 2$, for example, that forest will be $\mathbf{!}$ with probability $(1 - p)^2 p / (2(1 - p)(1 - p/2)(1 - p)) = p/(2 - p)$; thus $\mathbf{!}$ is more likely than $\bullet\bullet$ if and only if the parameter p exceeds $\frac{2}{3}$.

There are 14 possible forests when $n = 4$ (see Tables 1–3 in Section 7.2.1.6). Which of them is (a) most (b) least likely to be the depth-first forest, as p increases from 0 to 1?

39. [HM23] Continuing exercise 37, let g_n be the sum of g_F over all n -node forests F . Also let $g_n^a(z) = g_n(z, 1, 1, 1, 1)$, $g_n^b(z) = g_n(1, z, 1, 1, 1)$, $g_n^c(z) = g_n(1, 1, z, 1, 1)$,

depth-first jungle forest
loops
analysis of algorithms+
Jacquet
random
geometric distribution
forest
multivariate generating function
generating function
geometric model

$g_n^f(z) = g_n(1, 1, 1, z, 1)$, and $g_n^c(z) = g_n(1, 1, 1, 1, z)$ be the univariate generating functions for the loops, tree arcs, back arcs, forward arcs, and cross arcs in isolation. (Of course $g_n(1, 1, 1, 1, 1) = g_n^l(1) = \cdots = g_n^c(1) = 1$. Exercise 35(b) analyzes g_n^l .)

- a) What are $g_2^l(z)$, $g_2^t(z)$, $g_2^b(z)$, $g_2^f(z)$, and $g_2^c(z)$?
- b) What is $g_n(z, z, z, z, z)$?
- c) Find surprises in $g_4^l(1)$, $g_4^t(1)$, $g_4^b(1)$, $g_4^f(1)$, and $g_4^c(1)$.
- d) For what values of p does the average number of back arcs exceed the average number of tree arcs, in the geometric model when $n = 4$?

40. [M28] Exercise 39 mentions that $g_2^b(z) = g_2^f(z)$. Prove that, for all n , the number of back arcs has the same mean as the number of forward arcs, in the depth-first jungles of random digraphs generated by the geometric model of exercise 33 with probability p . Furthermore the number of tree arcs has the same mean as the number of cross arcs.

41. [HM37] Continuing exercise 40, prove that in fact the joint probability distribution of the random variables $(L, F, B+C, T)$ is exactly the same as the joint probability distribution of $(L, B, F+C, T)$, where L, B, F, C , and T are respectively the numbers of loops, back arcs, forward arcs, cross arcs, and tree arcs of random geometric depth-first forests, for all n and p .

42. [HM30] Study the depth-first jungles of random mappings (random “functional digraphs”). How many tree arcs, back arcs, $\dots$, cross arcs do they have, asymptotically?

- 43. [HM40] Determine the asymptotic number of arcs of different kinds, in the depth-first jungles of random digraphs defined by the geometric model with probability p .
- 44. [HM31] Algorithm J (exercise 36) can be analyzed by computing several interesting generating functions, defined by recurrences. Let $G(z) = \sum_{k=0}^{\infty} \pi_k z^k$ be the probability generating function for out-degrees, and let ϕ_p denote the fraction p/n .
 - a) Let $S_p(z) = \sum_k \Pr(s = k) z^k$ be the distribution of stack sizes at the beginning of step J3, and let $\zeta_p = \Pr(X = s \text{ in step J6})$. Show that $\zeta_p = S_p(\phi_p)G(\phi_p)$.
 - b) Furthermore $S_1(z) = 1$ and $S_{p+1}(z) = (1 - \phi_p)(S_p(z)G(z) - \zeta_p)/(z - \phi_p) + \zeta_p$.
 - c) Find a simple formula for $S'_p(1)$, the average stack size.
 - d) Relate $S'_p(1)$ to the number of forward arcs that go to $V[p]$.
 - e) Prove that if $G(z)$ is a polynomial with rational coefficients, so is $S_p(z)$. And $S_p(z)$ can be computed by working only with polynomials that have integer coefficients.
 - f) Let the coefficient of z^k in the generating function $A_{p',p}(z)$ be the probability that $V[p']$ is an ancestor of $V[p]$ in step J3, and the stack contains exactly k items $V[p_j]$ for which $p' \leq p_j < p$. Show that these functions obey the recurrence $A_{p,p}(z) = 1$ and $A_{p',p+1}(z) = (1 - \phi_p)(A_{p',p}(z)G(z) - A_{p',p}(\phi_p)G(\phi_p))/(z - \phi_p)$.
 - g) Interpret the “meaning” of $A_{p',p}(1)$. (We define $A_{p',p}(z) = 0$ when $p' > p$.)
 - h) Find a simple recurrence for the generating function $A_p(z) = \sum_{p'=1}^{p-1} A_{p',p}(z)$.

- 45. [HM42] Extend the analysis of exercise 43 to the generalized model of exercise 36.

46. [HM41] Carry out an analysis analogous to exercise 43, but for random digraphs generated by the *uniform* model of exercise 32 with λn arcs.

47. [HM46] The maximum value of $\text{HT}(v)$ computed by the algorithm of exercise 24, over all vertices v , is greater than or equal to the maximum depth of a vertex in the depth-first jungle. Analyze the asymptotic gap between maximum vertex height and maximum tree depth, on large random digraphs that use (a) the uniform model of exercise 32; (b) the geometric model of exercise 33.

random mappings
functional digraphs
analysis of algs
generating functions
recurrences
probability generating function
ancestor
random digraphs
digraphs
uniform model
vertex height
maximum tree depth
uniform model
geometric model

48. [HM41] Analyze the expected number of arcs of different kinds in the depth-first jungle when the generating function for out-degrees is $(1+z^2)/2$. That is, every vertex v either has no outgoing arcs (with probability $\frac{1}{2}$), or it has exactly two outgoing arcs $v \rightarrow w$ and $v \rightarrow w'$, where w and w' are independently and uniformly random.

49. [15] What are the strong components of the “Orient Express” digraph of Fig. 3, near the beginning of Chapter 7? (These are the groups of murder suspects whose alibis depend on each other. Answer the question without computer help.)

50. [M20] A *Markov process* is an algorithm that performs a random walk on a set of states. If there are n states it can be defined by an $n \times n$ matrix (p_{ij}) , where p_{ij} is the probability of going from state i to state j at each step.

In exercise 2.3.4.2–26 we studied Markov processes that terminate with probability 1; however, it is more usual to assume that $p_{i1} + \dots + p_{in} = 1$ for $1 \leq i \leq n$. Thus the process *never* terminates, although it might reach an “absorbing” state in which it remains forever. The digraph g on vertices $\{1, \dots, n\}$ whose arcs are $i \rightarrow j$ when $p_{ij} > 0$ represents all possible walks of the process.

State j is called *transient* if there's positive probability that a walk starting at j will never return to j ; otherwise state j is called *recurrent*. Characterize transient and recurrent states in terms of the strong components of g .

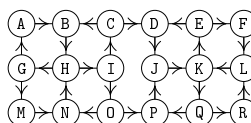
- 51. [22] Rewrite Algorithm T as a recursive procedure. (Compare with exercise 20.) However, omit the shortcut that tests for $u = w$ and $p = N(g)$ in step T6.

53. [20] In what order do the arcs of digraph (1) mature during a depth-first search? (See (10) for the definition of “maturing.”)

- 54. [21] Extend Algorithm D by including a **TIME** field in each arc record. If a is the r th arc to mature, your algorithm should set $\text{TIME}(a) \leftarrow r$.

55. [20] Describe all the LOW computations in the 7-vertex digraph following (10).

57. [21] What are the preorder and postorder of the depth-first forest when g is the digraph shown? (Begin at vertex A. Go left before right and up before down. Notice that every vertex has out-degree and in-degree 1 or 2.) What are the strong components? What are the final values of $\text{LOW}(v)$ at the end of Algorithm T?



58. [20] How many strong components does the digraph of exercise 57 have when one of its arcs has been removed? (Answer this question for each of the 26 arcs.)

- 60. [M25] Prove Theorem T, which justifies step T7 of Algorithm T.
61. [18] Why is it important to have $\text{REP}(\text{SENT}) = 0$ in Algorithm T?
62. [20] Why is it sometimes permissible for step T6 to go directly to step T8?
63. [M24] Count Algorithm T's memory references, in comparison with exercise 19.
64. [20] Extend Algorithm T so that it prints out the vertices of each strong component, preceded by their leader. In what order are strongly equivalent vertices printed?
- 65. [25] Let $\hat{g}$ be the directed acyclic graph whose vertices are the strong components of g and whose arcs correspond to directly related components, as in (6). Extend Algorithm T so that it prints out exactly one arc of g for each arc of $\hat{g}$.
- 66. [30] Extend Algorithm T so that it prints out a subset of the arcs for which the resulting subgraph has the same strong components as g . Make the subset as small as you can without losing efficiency.

Orient Express
Markov process
random walk
absorbing
transient
recurrent
strong components
recursive procedure
mature
LOW
preorder
postorder
directed acyclic graph

- **68.** [M30] The *period* of vertex v in a digraph is the greatest common divisor of the lengths of all oriented cycles that contain v (not necessarily simple).
- Find the periods of the vertices in the digraph whose arcs are $A \rightarrow B$, $A \rightarrow E$, $B \rightarrow C$, $B \rightarrow G$, $C \rightarrow A$, $C \rightarrow F$, $D \rightarrow H$, $E \rightarrow C$, $F \rightarrow B$, $F \rightarrow D$, $H \rightarrow A$, $H \rightarrow F$.
 - Show that vertices in the same strong component have the same period.
 - Extend Algorithm T so that it computes the period of every vertex. Illustrate your algorithm by applying it to the digraph in (a). *Hint:* Give each vertex a DEPTH field, representing its distance from the root of a tree in the depth-first jungle.

period
greatest common divisor
simple
whirlpool maze
maze
pi, for random example
giant strong component
strong components
tournament
nonpath
Topological sorting

- **71.** [22] (*A whirlpool maze.*) The 11×11 matrix (a_{ij}) shown here represents a digraph with $11^2 + 1$ vertices, named (i, j) for $0 \leq i, j < 11$ and OUT. There's an arc from (i, j) to (i', j') if and only if (i', j') is a_{ij} steps away from (i, j) in a horizontal, vertical, or diagonal direction. And there's an arc from (i, j) to OUT if and only if either i or j is either $a_{ij} - 1$ or $11 - a_{ij}$. For example, the legal moves from $(1, 2)$ are to $(1, 5)$, $(4, 2)$, $(4, 5)$, and OUT. There are eight legal moves from the '2' in the center cell $(5, 5)$.

3	1	4	1	5	9	6	5	3	5	9
7	9	3	2	3	8	4	6	2	6	4
5	8	8	4	6	5	8	5	4	8	6
6	9	7	6	6	5	6	5	5	5	5
9	8	8	6	6	2	6	4	4	8	8
9	9	4	7	5	2	6	7	8	8	3
9	9	9	3	2	4	3	4	8	4	4
3	9	5	3	5	5	3	5	9	3	5
5	6	6	5	6	5	6	6	5	5	5
3	9	2	6	6	1	3	1	5	5	6
3	4	7	3	8	8	8	9	1	7	8

- Can you find (by hand) a path from $(5, 5)$ to OUT?
 - Use Algorithm T to find the strong components of this digraph.
 - What subgraph does the extended algorithm in exercise 66 give?
- 75.** [22] Study Algorithm T empirically by using the random digraph models of exercises 32 and 33. Estimate the number of strong components, the size of the largest strong component, the number of arcs actually examined in step T5, and the number of times REP changes in steps T6 and T7.
- 78.** [M21] Say something interesting about the strong components of a tournament.
- **80.** [M20] True or false (see (13)): $v \asymp w$ if and only if either $v \Leftrightarrow w$ or there's a chain

$$v = v_0 \parallel v_1 \parallel \cdots \parallel v_r = w, \quad \text{for some } r \geq 0.$$

- 81.** [M21] Prove that $v \asymp w$ if and only if either $v \Leftrightarrow w$ or there's a nonpath from v to w and a nonpath from w to v , where a *nonpath* from v to w is a sequence

$$v = v_0 \not\rightarrow v_1 \not\rightarrow \cdots \not\rightarrow v_r = w, \quad \text{for some } r \geq 1.$$

- 82.** [M20] Construct a weakly connected digraph that contains two vertices v and w for which the relation of exercise 80 holds between v and w only when $r \geq 1000000$.
- 83.** [M22] True or false: $u \asymp v$ and $v \Rightarrow w$ and $u \not\rightarrow w$ implies $u \asymp w$.
- 84.** [M21] Prove Lemma W.
- **85.** [M27] Prove that a dag with $n > 1$ vertices is weakly connected if and only if its vertices can be topologically sorted in two ways $u_1 u_2 \dots u_n$ and $v_1 v_2 \dots v_n$, such that $\{u_1, \dots, u_l\} \neq \{v_1, \dots, v_l\}$ for $1 \leq l < n$. (Topological sorting means that $u_i \rightarrow u_j$ or $v_i \rightarrow v_j$ implies $i < j$.)
- 86.** [16] If a digraph has r weak components, in how many ways can its vertices be divided into nonempty parts L and R that satisfy conditions (i) and (ii) of Lemma W?
- 88.** [M22] Let D be a dag with n vertices and weak components $(W_1, \dots, W_r)$. Suppose we augment D by introducing an $(n+1)$ st vertex v at the left, together with optional arcs from v . Say that vertex w is "hit" if there's a new arc $v \rightarrow w$; otherwise w is "missed." Case j , for $1 \leq j \leq r$, arises when all the sources of W_j are hit, but all

vertices of $W_1 \cup \dots \cup W_{j-1}$ are missed. Case j' is similar, but at least one source of W_j is missed while W_j isn't missed entirely. Finally, Case $r+1$ arises when v hits nothing.

- a) Exactly how many of the 2^n possible augmentations belong to each case, when each weak component W_j has exactly s_j sources and n_j vertices?
- b) In each case, explain how the weak components, sources, and sinks are changed.

89. [21] What vertices are strong and weak leaders when Algorithm W terminates?

- **90.** [25] Prove that the running time of Algorithm W is linear in the number of vertices and arcs of g , and explain why the HIT fields enable such efficiency.

92. [20] Show that the operation ' $\text{WP} \leftarrow v$ ' could be omitted from step W8.

- **93.** [22] The HIT field of a vertex is set nonzero by Algorithm W only in step W7.
- a) Show that the operation ' $\text{HIT}(u) \leftarrow 1$ ' could be omitted from that step, whenever the algorithm isn't dealing with what exercise 88 calls Case 1'.
 - b) Suggest how to use this observation to make Algorithm W faster.

95. [25] Show that the number of sequences $(s_1, n_1; \dots; s_r, n_r)$ with $1 \leq s_j \leq n_j$ for $1 \leq j \leq r$ and $n_1 + \dots + n_r = n$ is the Fibonacci number F_{2n} . Also devise an easily computed one-to-one correspondence between such sequences and the integers $[0 \dots F_{2n})$.

- **96.** [M29] For each sequence $\sigma = (s_1, n_1; \dots; s_r, n_r)$ considered in exercise 95, let $g_\sigma(z)$ be the generating function $\sum_{m \geq 0} a_{\sigma m} z^m$, where $a_{\sigma m}$ is the number of subgraphs of the transitive tournament $K_n^\rightarrow$ that have m arcs and r weak components $(W_1, \dots, W_r)$, where each W_j has exactly s_j sources and n_j vertices.

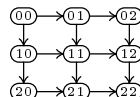
- a) Compute $g_\sigma(z)$ for all σ with $n \leq 16$.
- b) Use (a) to count the number of weakly connected dags on $\{1, \dots, n\}$ for $n \leq 16$. (Every arc $u \rightarrow v$ has $u < v$. For example, the single arc $2 \rightarrow 4$ works for $n \geq 4$.)
- c) Use (a) to determine the probability that a random subgraph of $K_{16}^\rightarrow$ has exactly r weak components, for $1 \leq r \leq 16$, where each arc is independently present with probability (i) $2/3$; (ii) $1/2$; (iii) $1/3$; (iv) $1/16$.

- **98.** [M33] Prove that a weakly connected subgraph of the transitive tournament $K_n^\rightarrow$ cannot have more than $\binom{n-1}{2}$ arcs. Furthermore, when $n > 1$, exactly 3^{n-2} such (labeled) subgraphs have exactly $\binom{n-1}{2}$ arcs, and there's a nice one-to-one correspondence between them and ternary sequences $a_2 \dots a_{n-1}$, where $a_j \in \{-, 0, +\}$ for $1 < j < n$.

100. [M21] An *order ideal*, in a partial ordering on the set X , is a subset $I \subseteq X$ for which $x \preceq y$ and $y \in I$ implies that $x \in I$. It's easy to see that $I \cup I'$ and $I \cap I'$ are order ideals whenever both I and I' are order ideals; therefore the order ideals of any partial order form a distributive lattice with respect to set inclusion.

Every dag implicitly defines a partial ordering when we stipulate that $x \preceq y$ if and only if y is reachable from x , namely that there's a k -step sequence $x = x_0 \rightarrow x_1 \rightarrow \dots \rightarrow x_k = y$ for some $k \geq 0$. (In other words, ' $\preceq$ ' is ' $\rightarrow^*$ ', the *transitive completion* of the binary relation ' $\rightarrow$ '.) We can therefore say that I is an order ideal of the dag when it has the property that $x \rightarrow y$ and $y \in I$ implies $x \in I$.

- a) If X has n elements, prove that $x_1 x_2 \dots x_n$ is a topological sort of the partial order if and only if $\emptyset, \{x_1\}, \{x_1, x_2\}, \dots, \{x_1, \dots, x_k\}, \dots, \{x_1, \dots, x_n\}$ is a path of length n in the lattice of order ideals.
- b) Prove that the directed $m \times n$ grid $P_m^\rightarrow \square P_n^\rightarrow$ has exactly $\binom{m+n}{m}$ order ideals. (The case $m = n = 3$ is shown here.)
- c) Draw a picture of the lattice of order ideals for $P_3^\rightarrow \square P_3^\rightarrow$.



leaders
analysis of algorithms
linear
HIT
Fibonacci number
generating function
weakly connected
random subgraph
transitive tournament
 $K_n^\rightarrow$
ternary sequences
order ideal
partial ordering
distributive lattice
lattice
reachable
transitive completion
binary relation
relation
topological sort
directed $m \times n$ grid

- **101.** [M30] Given a directed acyclic graph, use depth-first search to construct its lattice of order ideals. Your algorithm should also compute, for each I , the number of upward paths from I to the top of the lattice. *Hint:* The ideals just above I are $I \cup \{s\}$, where s is a “source” vertex (with in-degree 0) after all vertices in I have been removed.
- 102.** [21] Use the results of exercise 101 to generate uniformly random topological sorts of a given partial ordering.
- **103.** [25] Use exercise 101 to compute, for each pair $x \neq y$, the number of topological sorts of a given partial ordering where x occurs before y . (These topological sorts will survive if we add the arc $x \rightarrow y$; see the discussion of optimum sorting in Section 5.3.1.)
- 104.** [M10] Describe the order ideal lattice of a partially ordered set that has weak components $(W_1, \dots, W_t)$ in terms of the order ideal lattices of $W_1, \dots, W_t$.
- 999.** [M00] this is a temporary dummy exercise

depth-first search
 “source” vertex
 in-degree
 uniformly random
 random
 topological sorts
 optimum sorting
 sorting
 weak components

SECTION 7.4.1.1

1. Yes. Indeed, any isolated vertices of a graph are among its connected components.

99. ...

999. ...

SECTION 7.4.1.2

Stack	Arcs	Stack	Arcs
Begin 9	$9 \rightarrow 7, 3, 5, (7)$	736	$6 \rightarrow 2, (4)$
735	$5 \rightarrow (9), (3), 8$	732	$2 \rightarrow (6), (3), (7)$
738	$8 \rightarrow 4, (3), (8)$	73	$3 \rightarrow (1), (3)$
734	$4 \rightarrow 1, (1)$	7	$7 \rightarrow$
731	$1 \rightarrow 6$	Begin 0	$0 \rightarrow (2)$

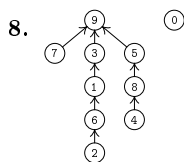
3. (The TIP array for (i) would be (2, 6, 6, ..., 5, 7), and the ARCS array would be (0, 1, 2, 5, ..., 17, 21).) Change “ARCS(v)” to “ARCS[v]” in steps Q3 and Q6. Step Q4 becomes “Go to Q6 if $a = \text{ARCS}[v + 1]$. Otherwise set $u \leftarrow \text{TIP}[a]$ and $a \leftarrow a + 1$.”

[Of course the sequential convention makes the task of visiting every arc trivial, so we wouldn't really be using Algorithm Q! But a similar change applies to Algorithm D and many others. Notice that we avoid fetching $\text{NEXT}(a)$; but we need an extra memory reference to fetch $\text{ARCS}[v + 1]$. On the other hand, $\text{TIP}(a)$ and $\text{NEXT}(a)$ are typically fetched *simultaneously* with SGB format, as in the MMIX program of exercise 7-71.]

5. (a, b) n . (c) r . (d) n (r in step Q3 and $n - r$ in step Q6). (e, f, g) m . (h, i) $n - r$.

7. (Solution by Peter Weigel.) Introduce a new pointer t . Change ‘MARK(v) $\leftarrow s \leftarrow \text{SENT}$ ’ to ‘ $s \leftarrow t \leftarrow v$ ’ in step Q3. Change ‘MARK(u) $\leftarrow s$ and $s \leftarrow u$ ’ to ‘MARK(t) $\leftarrow u$ and $t \leftarrow u$ ’ in step Q5. And in step Q6, ‘Go back to Q2 if $s = \text{SENT}$ ’ $\searrow$ ‘If $s = t$, set MARK(t) $\leftarrow t$ and go back to Q2.’ Also ‘ $v \leftarrow s, s \leftarrow \text{MARK}(v)$ ’ $\searrow$ ‘ $s \leftarrow \text{MARK}(v), v \leftarrow s$ ’.

(We've essentially changed the stack into a queue. Notice that vertex t , at the tail of the queue, has been seen but perhaps not yet marked.)



10. The total number of memory references remains unchanged. (The r that we avoid in step Q3 eventually occur in step Q6.)

12. ... Λ (end 1); $3 \rightarrow 3$; Λ (end 3); $9 \rightarrow 5$; $5 \rightarrow 9$; $5 \rightarrow 3$; $5 \rightarrow 8$; $8 \rightarrow 4$; $8 \rightarrow 3$; $8 \rightarrow 8$; Λ (end 8); Λ (end 5); $9 \rightarrow 7$; Λ (end 9); $0 \rightarrow 2$; Λ (end 0).

13. Back arcs: $2 \rightarrow 3$; $2 \rightarrow 6$; $4 \rightarrow 1$; $4 \rightarrow 1$; $5 \rightarrow 9$. Forward arcs: $9 \rightarrow 7$. Loops: $3 \rightarrow 3$; $8 \rightarrow 8$. Cross arcs: $0 \rightarrow 2$; $2 \rightarrow 7$; $5 \rightarrow 3$; $8 \rightarrow 3$; $8 \rightarrow 4$.

15. A back arc or loop certainly makes a cycle. Conversely, if there's a cycle $v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_{t-1} \rightarrow v_0$, with v_0 smallest in preorder, each of $v_1, \dots, v_{t-1}$ is reachable from v_0 but was unseen when v_0 was first seen. Hence they are descendants of v_0 . It follows that $v_{t-1} \rightarrow v_0$ is either a back arc or a loop.

16. Change step D2 so that it simply sets $w \leftarrow v_0$. Terminate when $v = \text{SENT}$ in step D8. (Similar changes will also simplify Algorithm T.)

isolated vertices
MMIX
Weigel
stack
queue
preorder
reachable
unseen
descendants

18. If $\text{PRE}(v) < \text{PRE}(u)$, vertex u was unseen when v became active. And if $v \rightarrow u$ is a nontree arc of g , vertex u must be reachable by tree arcs. Thus u is a proper descendant of v , and $v \rightarrow u$ is a forward arc. Apply exercise 2.3.2–20.

19. (ARC, ARCS, NEXT, PARENT, TIP) are fetched respectively $(n - r, n, m, m + 2n, m)$ times; we store into (ARC, PARENT, POST, PRE) respectively $(n - r, 2n, n, n)$ times. (So it's $< 4n$ more memory accesses than in Algorithm Q, and we've got PRE and POST.)

20. Set $\text{PRE}(w) \leftarrow 0$ for $\text{VERTICES}(g) \leq w < \text{VERTICES}(g) + N(g)$, and $p \leftarrow q \leftarrow 0$, where p and q are global variables. Then, while $w > \text{VERTICES}(g)$, set $w \leftarrow w - 1$ and execute $\text{dfs}(w)$ if $\text{PRE}(w) = 0$, where $\text{dfs}(v)$ is the following procedure: “Set $p \leftarrow p + 1$, $\text{PRE}(v) \leftarrow p$, and $a \leftarrow \text{ARCS}(v)$, where a is a local variable. While $a \neq \Lambda$, set $u \leftarrow \text{TIP}(a)$, $a \leftarrow \text{NEXT}(a)$, and execute $\text{dfs}(u)$ if $\text{PRE}(u) = 0$. Finally set $q \leftarrow q + 1$ and $\text{POST}(v) \leftarrow q$.”

21. Set $\text{POST}(w) \leftarrow 0$ for all w in step D1. Then, at the end of step D5, if $\text{PARENT}(u) = \Lambda$, a is a tree arc; otherwise if $u = v$, a is a loop; otherwise if $\text{PRE}(u) > \text{PRE}(v)$, a is a forward arc; otherwise if $\text{POST}(u) = 0$, a is a back arc; otherwise a is a cross arc.

22. (i) results when all the orderings used in (4) are reversed. (iii) might also occur. But (ii) and (iv) violate Theorem D with respect to nontree arcs $6 \rightarrow 2$ and $2 \rightarrow 3$. [Tarjan proved that any oriented spanning forest consistent with Theorem D is possible. The jungle (4) is obtained from $9!$ different orderings of the vertices and respectively $(1, 1, 6, 2, 1, 6, 2, 1, 6, 3)$ independently different orderings of the arcs from $(0, \dots, 9)$.]

24. In step D1, also set $\text{POST}(w) \leftarrow \text{HT}(w) \leftarrow 0$ for all w . Add ‘ $b \leftarrow \Lambda$ ’ to step D3. Replace steps D4–D6 by:

D4’. [Done with v ?] If $a \neq \Lambda$, go to D5’. Otherwise set $q \leftarrow q + 1$, $\text{POST}(v) \leftarrow q$, and $v' \leftarrow \text{PARENT}(v)$. If $v' \neq \text{SENT}$, set $\text{HT}(v') \leftarrow \max(\text{HT}(v'), 1 + \text{HT}(v))$. Then set $v \leftarrow v'$ and go to D8.

D5’. [Visit the next arc, $v \rightarrow u$.] Set $u \leftarrow \text{TIP}(a)$ and $a' \leftarrow \text{NEXT}(a)$. If $\text{POST}(u) = 0$ and $\text{PARENT}(u) \neq \Lambda$ and $\text{PRE}(u) \leq \text{PRE}(v)$ (see answer 21), remove the arc $v \rightarrow u$: Set $a \leftarrow a'$ and either $\text{NEXT}(b) \leftarrow a'$ (if $b \neq \Lambda$) or $\text{ARCS}(v) \leftarrow a'$ (if $b = \Lambda$), then return to D4’. Otherwise set $b \leftarrow a$ and $a \leftarrow a'$.

D6’. [If u isn’t new, continue at v .] If $\text{PARENT}(u) \neq \Lambda$, set $\text{HT}(v) \leftarrow \max(\text{HT}(v), 1 + \text{HT}(u))$ and return to D4’.

[Vertices $(0, \dots, 9)$ of (4) have heights $(2, 3, 1, 4, 0, 6, 2, 0, 5, 7)$.]

25. (i) $\Rightarrow$ (ii): Apply exercise 24 to g , and color every vertex with its height. This is a valid k -coloring because all heights are less than k , and every arc (deleted or not) joins vertices of different heights. (ii) $\Rightarrow$ (iii): Given a coloring with colors $\{0, 1, \dots, k - 1\}$, orient each edge from higher to lower color. (iii) $\Rightarrow$ (i): This is obvious.

[This connection between coloring and path length is called the Gallai–Hasse–Roy–Vitaver Theorem because it was discovered independently by many people: L. M. Vitaver, *Doklady Akad. Nauk SSSR* **147** (1962), 758–759; M. Hasse, *Math. Nachrichten* **28** (1965), 275–290; B. Roy, *Rev. Française d’Informatique et de Recherche Opérationnelle* **1** (1967), 129–132; T. Gallai, *Theory of Graphs* (Academic Press, 1968), 115–118.]

26. For example, from ‘ $9 \rightarrow 8, 8 \rightarrow 7, \dots, 1 \rightarrow 0, 9 \rightarrow 6, 6 \rightarrow 3, 3 \rightarrow 0, 6 \rightarrow 8, 3 \rightarrow 5, 0 \rightarrow 2$ ’ the final three back arcs are removed. In the reverse order ‘ $0 \rightarrow 2, \dots, 9 \rightarrow 8$ ’, however, the algorithm sees $9 \rightarrow 6, 6 \rightarrow 8, 8 \rightarrow 7$, drops $7 \rightarrow 6$, sees $6 \rightarrow 3, 3 \rightarrow 5, 5 \rightarrow 4$, drops $4 \rightarrow 3$, sees $3 \rightarrow 0, 0 \rightarrow 2, 2 \rightarrow 1$, drops $1 \rightarrow 0$; $\text{HT}(9 - 3k) = 5 - k$, $\text{HT}(8 - 3k) = 1$, $\text{HT}(7 - 3k) = 0$.

Tarjan
Gallai
Hasse
Roy
Vitaver
historical notes
Vitaver
Hasse
Roy
Gallai

27. (a) Use 7-fold symmetry. The 3-coloring $0 \equiv 2 \equiv 4 \equiv 6$, $1 \equiv 3 \equiv 5$, $0' \equiv 1' \equiv \dots \equiv 6'$ works when $6 \not\equiv 0$. From $0 \equiv 2 \equiv 4 \equiv 5'$, $1 \equiv 3 \equiv 5 \equiv 6'$, $6 \equiv 0' \equiv 1' \equiv 2' \equiv 4'$ we can color $3'$ when $3' \not\equiv 4$, $3' \not\equiv 3$, $3' \not\equiv 6$.

(b) Only $5 \cdot 2^{21}$ symmetrically distinct orientations avoid a 4-path on the outer cycle; and only 392 of those orientations avoid 4-paths everywhere. When the 392 winners are processed by exercise 24, only nine of them have at most two 3-paths; and those nine are acyclic, so their HT values aren't ambiguous as in exercise 26. All nine have $0 \rightarrow 1 \rightarrow 2 \leftarrow 3 \rightarrow 4 \leftarrow 5 \rightarrow 6 \leftarrow 0$ and exactly two 3-paths. For example, we can achieve this when $x' \rightarrow y$ iff $x = 1$ or $y = 2$.

28. (a) The digraph for which $x \rightarrow y$ if and only if $x \prec y$ is acyclic. So the algorithm of exercise 24 won't delete any arcs, and we clearly have $s = 1 + \max_{x \in P} \text{HT}(x)$.

(b) The antichains $A_k = \{x \mid \text{HT}(x) = k\}$ for $0 \leq k < s$ partition P . We can't have fewer than s , because a chain of size s must have one element in every antichain.

[L. Mirsky, in *AMM* **78** (1971), 876–877, noted that this result is “dual” to a deeper theorem of R. P. Dilworth, who proved that the maximum size of an antichain is the minimum size of a partition into chains; see *Annals of Math.* (2) **51** (1950), 161–166.]

30. (a) Notice that the jungle forest carries more information than the jungle itself, because it encodes the order of the arcs as well as their initial and final vertices.

(b) The label in every external node must agree with the label of some internal node that precedes it in preorder of the forest. Thus, the first three external nodes in (a), according to preorder, could be labeled in six ways (either 9 or 7 or 3 or ... or 2); the next three in seven ways (also 4); and so on. The total number of possible labelings is therefore $6^3 7^3 8^2 9^4 10^1 = 311098475520$.

(c) The internal labels can be any permutation of the vertex names, except that the root of each forest must be labeled with the first vertex of its tree that is encountered in step D1; the roots must also be in “encounter-order” from left to right. In (a) this means only that the first root must be labeled 9. Hence the total number of possibilities for a depth-first jungle forest of that shape is $311098475520 \cdot 9! = 112891414796697600$.

31. In general, the depth-first jungle forest for a digraph with m arcs and n vertices has m edges and n internal nodes. If it contains r trees, it has $m + r$ nodes altogether. Hence it has $m + r - n$ external nodes, none of which are roots and all of which are leaves.

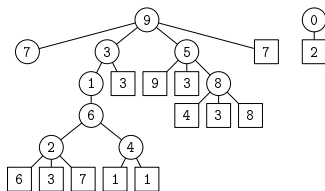
Conversely, if we start with *any* forest of r trees and $m + r$ nodes, where $m + r - n$ nonroot leaves are designated “external,” the resulting structure can be labeled so that it becomes the depth-first jungle forest of a digraph with m arcs and n vertices.

The number of ways to label the external nodes is the product, over all external nodes, of the number of internal predecessors in preorder. The number of ways to label the internal nodes is $n!/(s_1 \dots s_r)$, where $s_j = t_j + \dots + t_r$ and t_j is the number of the internal nodes of the j th tree (see exercise 5.1.4–20).

32. First generate m random vertices and count how many times a_v each v occurs. Then set $\text{ARCS}[v] \leftarrow a_0 + \dots + a_{v-1}$ for $0 \leq v \leq n$. Generate m more random vertices $\text{TIP}[k]$ for $0 \leq k < m$, and use the convention of exercise 3.

The number of tree arcs is n minus the number of roots. Several thousand trials gave approximately 6860 ± 80 roots, $2.036 \cdot 10^6 \pm 1200$ back arcs, $1.507 \cdot 10^6 \pm 1100$ forward arcs, and $0.464 \cdot 10^6 \pm 1250$ cross arcs. (The forward arcs included 5 ± 2 loops. The maximum tree depth was $0.6725 \cdot 10^6 \pm 500$.)

symmetry
acyclic
Mirsky
Dilworth
maximum tree depth



33. With this random model it's not necessary to store individual arcs. Several thousand trials now gave approximately 6850 ± 90 roots, $1.507 \cdot 10^6 \pm 3300$ back arcs, $1.507 \cdot 10^6 \pm 3300$ forward arcs, and $0.993 \cdot 10^6 \pm 2200$ cross arcs. (The forward arcs included 5 ± 2 loops. The maximum tree depth was $0.4782 \cdot 10^6 \pm 700$.)

34. (a) Let $d_k = \text{out-degree}(v_k)$. There are $\binom{m}{d_1, \dots, d_n}$ admissible orderings of the m arcs, and this should be multiplied by the probability n^{-2m} of obtaining them. In exercise 30 this comes to $21!/(1!1!3!2!2!3!2!0!3!4!10^{42}) = 1.23193822752 \times 10^{-27}$.

(b) All depth-first jungle forests with n internal nodes can be generated by a finite-state automaton whose states (d, t) represent the current depth and the number of internal nodes generated so far. Begin in state $(0, 0)$ and stop when state $(0, n)$ is reached. When in state $(0, t)$ for $t < n$, generate a new internal node, which will be the root of a new tree, and go to state $(1, t + 1)$; there are $n - t$ candidate labels for that new node. When in state (d, t) for $d > 0$, there are three choices: We either go to state $(d - 1, t)$, meaning that the current node has no further children; or we remain in state (d, t) after generating a new external child of the current node; or we go to state $(d + 1, t + 1)$ after generating a new internal child. In the second case there are t candidate labels; in the third case there are $n - t$.

In the geometric model the automaton corresponds to a Markov process in which the transition probabilities are 1 for $(0, t) \rightarrow (1, t + 1)$, $1 - p$ for $(d, t) \rightarrow (d - 1, t)$, tp/n for $(d, t) \rightarrow (d, t)$, and $(n - t)p/n$ for $(d, t) \rightarrow (d + 1, t + 1)$. That produces a random depth-first jungle forest whose node labels are randomized as in exercise 30(c).

However, to match a given forest, the transition probabilities for both $(d, t) \rightarrow (d, t)$ and $(d, t) \rightarrow (d + 1, t + 1)$ become p/n , and the process terminates unsuccessfully if an incorrect label is generated. So the overall probability reduces to $(p/n)^m(1 - p)^n$, which comes to $(21/310)^{21}(10/31)^{10} \approx 3.4 \cdot 10^{-30}$ in the forest of exercise 30. (The probability of getting a forest with exactly m arcs is $[z^m]((1 - p)/(1 - pz))^n = \binom{n + m - 1}{m} p^m(1 - p)^n$; in exercise 30 it's $\binom{30}{21}(21/31)^{21}(10/31)^{10} \approx .049$.)

[Another way to explain the discrepancies between the empirical results of exercises 32 and 33 is to note that each vertex in the uniform model has the same distribution for its in-degree and out-degree, but that is far from true in the geometric model. Indeed, the probability of in-degree k in that model is $[z^k]((1 - p)/(1 - p(1 + (z - 1)/n)))^n$; for fixed p and k it's $e^{-\mu} \mu^k/k! + O(1/n)$, strongly concentrated about its mean $\mu = p/(1 - p)$.]

35. (a) Each arc is a loop with probability $1/n$, so the answer is $[z^k](n - 1 + z)^m/n^m = \binom{m}{k}(n - 1)^{m - k}/n^m$; mean m/n , variance $m(n - 1)/n^2$. (A binomial distribution.)

(b) Each vertex has j loops with probability $[z^j](1 - p)/(1 - (n - 1 + z)p/n)$, so the answer is $[z^k]((1 - p)/(1 - (n - 1 + z)p/n))^n$; mean $p/(1 - p) = m/n$, variance $(n - (n - 1)p)p/(n(1 - p)^2) = m(m + n^2)/n^3$. (A negative binomial distribution.)

(In the generalized model defined in the following exercise, the probability generating function for the number of loops is $G((n - 1 + z)/n)^n$, where $G(z) = \sum_{k=0}^{\infty} \pi_k z^k$.)

36. The basic idea is that the stack holds future arcs $v \rightarrow w$ where v is known but w isn't. Notice that it's convenient to implement steps J4 and J5 as follows (even if $p = n$): "Set $X \leftarrow 0$; while $X < s$, let i be independently uniform with $1 \leq i \leq n$; break out of the loop if $i > p$; otherwise set $X \leftarrow X + 1$ and let $\mathbf{V}[s - X] \rightarrow \mathbf{V}[i]$ be an arc." The arc in step J6 can then be $\mathbf{V}[s] \rightarrow \mathbf{V}[i]$.

[Actually there's a much, much simpler way to generate a random jungle forest: We can decide all out-degrees in advance, and build an ARCS array as in exercise 3; the TIP array can then be filled at random. However, Algorithm J is significant because it is a Markov process whose behavior can be analyzed. Philippe Jacquet and Svante

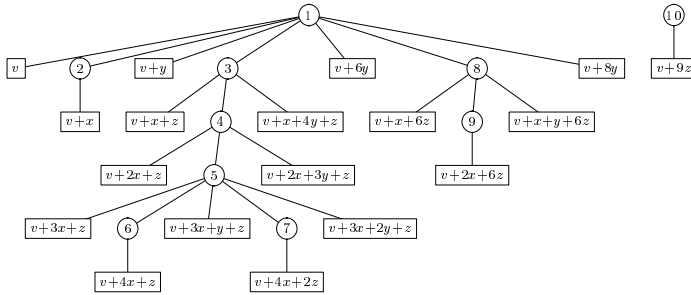
finite-state automaton
Markov process
in-degree
out-degree
Poisson distribution
binomial distribution
negative binomial distribution
probability generating function
generating function
Markov process
Jacquet

Janson showed in *LIPICs* **302** (2024), 30:1–30:15, that the algorithm has several nice properties: Let s_p be the stack size s at the beginning of step J3; let D_p be the out-degree chosen in that step; let X_p be the geometric random variate X in step J4 (before changing X to $\min(X, s_p + D_p)$); and let $Z_p = D_p - 1 - X_p$. They observe that $s_p = \Sigma_p - \Sigma_p^{\min}$, where $\Sigma_p = Z_1 + \dots + Z_{p-1}$ and $\Sigma_p^{\min} = \min\{\Sigma_1, \dots, \Sigma_p\}$. A new tree begins with $\mathbb{V}[p]$ if and only if $\Sigma_p^{\min} \neq \Sigma_{p-1}^{\min}$. (In particular, $\Sigma_1^{\min} = 0$ and $\Sigma_0^{\min} = \infty$; we always get a new tree when $p = 1$.) Furthermore, $\mathbb{V}[p]$ is an ancestor of $\mathbb{V}[p']$ if and only if $p \leq p'$ and $\Sigma_p \leq \Sigma_t$ for $p < t \leq p'$; $\mathbb{V}[p]$ is the parent of $\mathbb{V}[p']$ if and only if $p < p'$, $\Sigma_p \leq \Sigma_{p'}$, and $\Sigma_{p'} < \Sigma_t$ for $p < t < p'$.

Janson
extended forest
preorder

37. Every forest F with m edges and n nodes yields an *extended* forest F^+ with n internal nodes, $m + n$ external nodes, and $2m + n$ edges, if we insert an external leaf node before, between, and after every child of an internal node. (Thus a node q with k children $q_1, \dots, q_k$ in F becomes an internal node q with $2k + 1$ children $q'_0, q_1, q'_1, \dots, q_k, q'_k$ in F^+ , where $\{q_1, \dots, q_k\}$ are internal and $\{q'_0, \dots, q'_k\}$ are external.) Label every internal node of F^+ with its rank in preorder. Label every external child q'_j of q with the sum $\alpha_1 + \dots + \alpha_t$, where t is the number of internal nodes that precede q'_j in preorder of F^+ , and α_i is respectively (v, x, y, z) if a nontree arc from internal node q to internal node i is respectively a (loop, back arc, forward arc, cross arc).

For example, here's F^+ when F is the forest of (4):



The generating function g_F is then $(1-p)^n (wp/n)^{n-r} (n!/(s_1 \dots s_r))$ divided by the product of $(1-p\alpha/n)$ taken over all external labels α of F^+ , where r is the number of trees and $(s_1 \dots s_r)$ is defined in answer 31.

38. Of course the disconnected forest $\dots$ is forced when $p = 0$. It remains most likely until $p = \frac{2}{35}(16 - 4\sqrt[3]{6} + \sqrt[3]{36}) \approx .69$, after which the tallest forest $\ddagger$ takes the lead.

The five least likely forests, when $p = \epsilon$ and ϵ is very tiny, are $\mathfrak{A} < \mathfrak{f} < \mathfrak{A} < \mathfrak{A} < \mathfrak{f}$. They retain this relative order as p increases to $1 - \epsilon$, when they have in fact become five of the six *most* likely forests. An eight-way tie arises when $p = \frac{4}{5}$, at which point each of $\mathfrak{f}, \mathfrak{f}, \mathfrak{A}, \mathfrak{A}, \mathfrak{f}, \mathfrak{f}, \mathfrak{A}, \mathfrak{A}$ occurs with probability $\frac{1}{24}$. Ultimately, when $p > \frac{4}{5}$, the disconnected forest $\dots$ becomes the least likely.

[Curiously, it turns out that $\mathfrak{f}, \mathfrak{f}$ is less likely than $\mathfrak{A}, \mathfrak{A}$ if and only if $\frac{2}{3} < p < \frac{4}{5}$. And $\mathfrak{f}, \mathfrak{f}$ is less likely than $\mathfrak{f}, \mathfrak{f}$ if and only if $.52 \approx \frac{4}{33}(6 - \sqrt{3}) < p < \frac{4}{33}(6 + \sqrt{3}) \approx .94$.]

39. (a) By exercise 37, $g_2^i(z) = 4(1-p)^2/(2-p-pz)^2$; $g_2^t(z) = (2-2p+pz)/(2-p)$; $g_2^b(z) = 2(1-p)(2-pz)/((2-p)(2-p-pz))$; $g_2^f(z) = 2(1-p)(2-pz)/((2-p)(2-p-pz))$; and $g_2^c(z) = (4-6p+3p^2-p^2z)/((2-p)(2-p-pz))$. Notice that $g_2^f(z) = g_2^b(z)$.

(b) The generating function for total arcs is $((1-p)/(1-pz))^n$.

(c) After calculating 14 generating functions g_F as in exercise 38, we find $g_4^{i'}(1) = p/(1-p)$; but that's no surprise (see exercise 35). Also $g_4^{t'}(1) = (1536p - 4224p^2 +$

$4384p^3 - 2160p^4 + 536p^5 - 63p^6)/((4-p)(4-3p)^3(2-p)^2)$; and $g_4^{b'}(1) = (768p^2 - 1856p^3 + 1664p^4 - 748p^5 + 226p^6 - 45p^7)/(2(4-p)(4-3p)^3(2-p)^2(1-p))$. The surprises are that $g_4^{f'}(1) = g_4^{b'}(1)$ and $g_4^{c'}(1) = g_4^{t'}(1)$. (See exercise 40 — and also exercise 41!)

(d) When $p > p_0$, where $p_0 \approx .732792$ is the root of a sixth-degree polynomial.

40. (Solution by S. Janson.) Whenever vertex v has a new descendant w , we generate arcs from w with the geometric distribution, and each of those arcs goes back to v with probability $1/n$. Hence the mean number of back arcs from w to v is $p/(n(1-p))$. Later on, we generate further arcs from v with the geometric distribution, each of which goes to w with probability $1/n$; the mean number of forward arcs from v to w is therefore also $p/(n(1-p))$. These expectations are independent of the past history. Summing over all v and w , with v a proper ancestor of w , we find $E(\text{back arcs}) = E(\text{forward arcs})$, namely $p/(1-p)$ times the average number of ancestors of a random vertex.

Notice further that the expected number of arcs to a previous vertex in preorder is the expected number of arcs to a later vertex: $E(\text{back} + \text{cross}) = E(\text{tree} + \text{forward})$. This holds even in the much more general model of exercise 36 (see answer 45).

41. Let $\hat{G}_1(w, x, z) = \check{G}_1(w, x, z) = 1/(1-w)$ and, for $n > 1$,

$$\hat{G}_n(w, x, z) = \sum_{k=1}^{n-1} \frac{\hat{G}_k(w, x, z) \hat{G}_{n-k}(w + kz, x, z)}{1 - w - (n-1)x},$$

$$\check{G}_n(w, x, z) = \sum_{k=1}^{n-1} \frac{\check{G}_k(w + x, x, z) \check{G}_{n-k}(w + kz, x, z)}{1 - w}.$$

S. Janson, in arXiv:2301.04131 [math.CO] (2023), 6 pages, showed that the desired result is equivalent to the identity $\hat{G}_n(w, x, z) = \check{G}_n(w, x, z)$ for all $n \geq 1$; then Z. Nie, in arXiv:2301.05704 [math.CO] (2023), 6 pages, proved that identity and a bit more.

42. There clearly are no forward arcs. Loops have the probability generating function $((n-1+z)/n)^n$, with mean 1 and variance $1 - 1/n$.

Arcs are learned one at a time in step D5. The k th arc learned is a tree arc with probability $(n-k)/n$; hence $\prod_{k=1}^n ((k+(n-k)z)/n)$ is the generating function for tree arcs, with mean $(n-1)/2$ and variance $(n^2-1)/(6n)$. [Interesting connections of this generating function to other combinatorial problems have been found by I. Gessel and S. Seo, *Electronic Journal of Combinatorics* **11**, 2 (2004–6), #R27, 1–23.]

Each component of a functional digraph is a cycle with trees feeding into it; hence there's exactly one back arc or loop in every component. The generating function for back arcs plus loops is therefore the generating function for components, namely $t_n(z)/n^n$, where $t_n(z) = n![w^n](1-T(w))^{-z}$ is the so-called tree polynomial and $T(w) = \sum_{n \geq 1} n^{n-1}w^n/n!$ is the tree function, 2.3.4.4–(30). We have, for example, $t_1(z) = z$, $t_2(z) = z^2 + 3z$, $t_3(z) = z^3 + 9z^2 + 17z$. See D. E. Knuth and B. Pittel, *Proc. Amer. Math. Soc.* **105** (1989), 335–349, who showed that the mean value $t'_n(1)/n^n$ is $\frac{1}{2}H_{2n} + O(n^{-1/2})$ and that the variance is also $O(\log n)$. (See also exercise 3.1–14.)

Finally, the number of cross arcs is n minus the number of arcs of other kinds. So its mean value is $n - \frac{1}{2}(n-1) - \frac{1}{2}H_{2n} + O(n^{-1/2}) = \frac{1}{2}(n+1 - H_{2n}) + O(n^{-1/2})$.

43. Philippe Jacquet and Svante Janson [*La Matematica* **3** (2024), 262–292] have carried out a very instructive and comprehensive asymptotic analysis of depth-first search in the geometric model. Let $\lambda = p/(1-p)$ be the average out-degree of each vertex, and let $\theta = \tau(\lambda)$ be the largest number such that $1 - \theta = e^{-\lambda\theta}$. (For example, $\theta = \frac{1}{2}$ when $\lambda = 2 \ln 2 \approx 1.3863$; $\theta = \frac{4}{5}$ when $\lambda = \frac{5}{4} \ln 5 \approx 2.0118$; and in general,

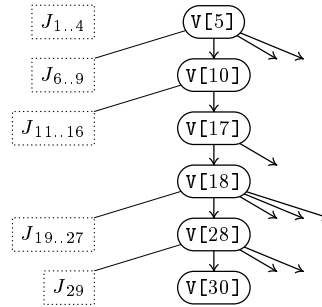
Janson
Janson
recurrence
Nie
probability generating function
generating function
Gessel
Seo
component
tree polynomial
tree function
Knuth
Pittel
Jacquet
Janson

$\tau(\lambda) = 1 - T(\lambda e^{-\lambda})/\lambda$ when $\lambda > 1$, where T is the tree function.) If $p \leq \frac{1}{2}$, or equivalently if $\lambda \leq 1$, or equivalently if $\theta = 0$, the trees of the forest a.s. never get very large. Otherwise depth-first search will a.s. construct a tree with $\theta n + \overline{O}(\sqrt{n})$ vertices and max depth $(\lambda - 1 - \ln \lambda)n/\lambda + \overline{O}(\sqrt{n})$, where $\overline{O}(\sqrt{n})$ means $O(\sqrt{n}\omega(n))$ for every function $\omega(n)$ that increases monotonically to ∞ as $n \rightarrow \infty$ (however slowly). This “giant” tree will be the only one in the forest with $\Omega(n)$ nodes. Many small trees will follow it, and few might also precede it.

The average number of trees in the forest is a.s. $\rho n + \overline{O}(\sqrt{n})$, where $\rho = 1 - \theta - \frac{\lambda}{2}(1-\theta)^2$. The average number of back arcs is a.s. $\beta n + \overline{O}(\sqrt{n})$, where $\beta = (\lambda-1)\theta - \frac{\lambda}{2}\theta^2$. The average number of tree arcs is a.s. $(1-\rho)n + \overline{O}(\sqrt{n})$. Loops are analyzed in exercise 35(b). The average total number of arcs is, of course λn ; notice that $\beta + 1 - \rho = \frac{\lambda}{2}$.

44. (a) Consider, for example, the jungle being formed in Fig. A-100, when $p = 30$:

Fig. A-100. In this typical scenario, Algorithm J is about to choose the out-degree of $V[30]$, which will be a descendant of $V[5]$, $V[10]$, $\dots$, $V[28]$. A jungle $J_{1..4}$ on the vertices $\{V[1], V[2], V[3], V[4]\}$ has already been completed, and so have the subjungles $J_{6..9}, \dots, J_{29}$. Tree arcs run from $V[5]$ to the roots of $J_{6..9}$, which are left siblings of $V[10]$; and so on. Nontree arcs aren't shown — except that eight yet-to-be-created arcs, like the two from $V[5]$, might become nontree arcs. (Nontree arcs from $V[17]$ may precede the tree arc to $V[18]$.)



tree function
a.s.
giant
probability generating function

This is one of the cases whose probability is part of the coefficient of z^8 in $S_{30}(z)$. Notice that $S_p(z)G(z)$ is the distribution of stack sizes at the beginning of step J4. If step J3 chooses $d = 3$, say (which happens with probability π_3), we'll have three incomplete arrows below $V[30]$; and our case will be part of $[z^{11}]S_{30}(z)G(z)$. The eleven items on the stack will be $\{V[5], V[5], V[17], \dots, V[28], V[30], V[30], V[30]\}$.

A random target is now selected for the first arrow below $V[30]$. With probability $1 - \phi_p = 1 - \frac{30}{n}$, it will be a previously unseen vertex, and we'll have a tree arc to $V[31]$. Otherwise it'll be a nontree arc, and we'll fill in the second arrow below $V[30]$. If that doesn't give us $V[31]$, we'll try again; and if necessary we'll finish up the arcs from $V[28]$, $V[28]$, $V[18]$, $\dots$, until we either find a tree arc or fail eleven times in a row.

The probability of total failure (stack exhaustion) is ζ_p . For in general, if $H(z)$ is any probability generating function for a random variable Q , we have $H(z) = E z^Q$.

(b) So z^{11} in step J4 becomes $(1 - \phi_p)(z^{10} + \phi_p z^9 + \phi_p^2 z^8 + \dots + \phi_p^{10}) + \phi_p^{11} = (1 - \phi_p)(z^{11} - \phi_p^{11})/(z - \phi_p) + \phi_p^{11}$ when p becomes $p + 1$ in step J6 or J2.

(A new tree enters the jungle in step J7. Therefore, if we change $+\zeta_p$ to $+y\zeta_p$ in the formula for S_{p+1} , the coefficient of $y^j z^k$ in $S_p(z)$ will be the probability that $s = k$ and that j trees have been completed so far. At the end, $S_{n+1}(z)$ will then be the probability generating function for trees, $\sum_j \Pr(\text{the jungle has } j \text{ trees}) y^j$.)

(c) Since $S'_1(1) = 0$ and $S'_{p+1}(1) = S'_p(1) + G'(1) - (1 - \zeta_p)/(1 - \phi_p)$, we have $S'_p(1) = (p-1)\lambda + \sum_{k=1}^{p-1} \frac{n}{n-k} \zeta_k - n(H_{n-1} - H_{n-p})$. (Notice that $(1 - \zeta_p)/(1 - \phi_p)$ is the expected number of arcs generated during round p and removed from the stack.)

(d) $S'_p(1)/n$ is the expected number of forward arcs to $\mathbf{V}[p]$, because each item on the stack has probability $1/n$ of becoming such an arc.

(e) In fact, if $G(z)$ is a polynomial of degree d , $S_p(z)$ will have degree $(p-1)(d-1)$.

Now suppose we want to compute $Q(z) = (H(z) - H(p/n))/(z - p/n)$, where the coefficients of $\overline{H}(z) = n^d H(z/n)$ are integers. Polynomial division by $z - p$ gives $\overline{H}(z) = \overline{Q}(z)(z - p) + \overline{H}(p)$. Hence $n^d Q(z/n) = n\overline{Q}(z)$.

For example, if $G(z) = (1+z^2)/2$ we can work entirely with the integer polynomials $\overline{S}_p(z) = 2^{p-1} n^{2p-2} S_p(z/n)$. The recurrence becomes $\overline{S}_{p+1}(z) = (n-p)\overline{Q}_p(z) + \overline{R}_p$, where $\overline{Q}_p(z)$ and $\overline{R}_p$ are the quotient and remainder of $(n^2 + z^2)\overline{S}_p(z)$ divided by $z - p$.

(f) For example, Fig. A-100 is a case that contributes to the respective coefficients of $(z^8, z^6, z^5, z^4, z^3, z^2, z^0)$ in $A_{p',30}(z)$, for $p' = (5, 10, 17, 18, 28, 30)$. Argue as above.

(g) It's the probability that $\mathbf{V}[p']$ is an ancestor of $\mathbf{V}[p]$.

(h) $A_1(z) = 0$; $A_{p+1}(z) = (1 - \phi_p)((A_p(z) + 1)G(z) - (A_p(\phi_p) + 1)G(\phi_p))/(z - \phi_p)$. [By (g), $A_p(1)$ is the average *depth* of $\mathbf{V}[p]$. The "meaning" of $[z^k]A_p(z)$ is, however, *not* easy to interpret! For example, Fig. A-100 contributes twice to the coefficient of z^6 .]

[Claude Opus 5 devised these recurrences and contributed the next three answers.]

45. The paper of Jacquet and Janson cited above proves that the depth-first forest always has at most one giant tree, of size $\theta n + \overline{O}(\sqrt{n})$, and a total of $\rho n + \overline{O}(\sqrt{n})$ trees on average, *whenever* the out-degree distribution has mean λ and finite variance. (Mainly because the average stack size, $S'_p(1)$ in exercise 44, depends only on λ .)

Let Δ be any integer $\leq \lambda$, and d any integer $\geq \mu = \lambda - \Delta$. Interesting out-degree distributions with mean λ arise, for example, when the probability generating function $G(z) = \sum_{d=0}^{\infty} \pi_d z^d$ has one of the following special forms: (i) $z^\Delta(1 + \mu(z^d - 1)/d)$ (shifted two-valued); (ii) $z^\Delta(1 + (\mu/d)(z - 1))^d$ (shifted binomial); (iii) $z^\Delta(q/(1 - pz))^{\mu q/p}$ when $0 < p < 1$ and $p + q = 1$ (shifted negative binomial); (iv) $z^\Delta e^{\mu(z-1)}$ (shifted Poisson).

We know that the number of tree arcs is n minus the number of trees; hence it is approximately $(1 - \rho)n$. It's also true that $E(\text{tree} + \text{forward}) = E(\text{back} + \text{cross}) = \frac{n-1}{2}\lambda$: Theorem D tells us that $\mathbf{V}[p] \rightarrow \mathbf{V}[q]$ is a back arc or cross arc if and only if $p > q$; and for fixed p that occurs with probability ϕ_{p-1} .

Other statistics depend on details of the distribution. Consider first the case that $\lambda > 1$. If $0 \leq y \leq 1 - \frac{1}{\lambda}$, let $\beta(y)$ be the positive root of the equation $1 - \beta(y) = G(1 - (1 - y)\beta(y))$. For example, when $G(z) = z^2$ we have $\beta(y) = (1 - 2y)/(1 - y)^2$; when $G(z)$ is the geometric distribution $1/(\lambda + 1 - \lambda z)$ we have $\beta(y) = 1 - 1/(\lambda(1 - y))$; and when $G(z)$ is the Poisson distribution $e^{\lambda(z-1)}$ we have $\beta(y) = \tau(\lambda(1 - y))$, where τ is defined in answer 43. In general it can be shown that the maximum depth, divided by n , approaches $\int_0^{1-1/\lambda} \beta(y) dy$. The number of back arcs, divided by n , is similar but more complicated: Its limit is $\lambda \int_0^{1-1/\lambda} \beta(y)(1 - y)\tau(\lambda(1 - y)) dy$.

When $\lambda \leq 1$, we have $\theta = 0$. So there are $\approx \frac{\lambda}{2}n$ tree arcs, and hardly any forward arcs. Similarly, it turns out that there are hardly any back arcs, hence $\approx \frac{\lambda}{2}n$ cross arcs. Closer analysis gives an average of just $r(\lambda) = \ln(1/(1 - \lambda)) - \lambda$ back arcs, and $G''(1)r(\lambda)/(2\lambda^2)$ forward arcs, when $\lambda < 1$; and $r(\lambda)$ grows to $\approx \frac{1}{3} \ln n$ when $\lambda \rightarrow 1$. (However, the limit is $\approx \frac{1}{2} \ln n$ in the special case of random mappings, exercise 42.)

46. The uniform model can be regarded as a special case of the general model in exercise 45, if every vertex independently has the Poisson distribution with mean λ for its out-degrees, and if we condition the results by requiring the total number of arcs to be λn ; that gives precisely the correct probabilities for each out-degree. (In fact, we don't even need such conditioning: The total number of arcs is λn on average anyway, and conditioning a sum of independent out-degrees on its own mean perturbs each

ancestor
depth
Claude Opus 5
Jacquet
Janson
giant
probability generating function
two-valued
shifted distribs
binomial
negative binomial
Poisson
geometric distribution
Poisson distribution
random mappings
Poisson distribution

remaining out-degree distribution by only $O(n^{-1/2})$. Hence sufficiently large limits are unaffected. (The dependence on n does affect the argument that $E(\text{tree} + \text{forward}) = \frac{n-1}{2}\lambda$; however, that identity has another proof in the uniform case.)

The only nontrivial computations for this special case are the respective integrals $\int_0^{1-1/\lambda} \beta(y) dy = \int_0^{1-1/\lambda} \tau(\lambda(1-y)) dy$ and $\lambda \int_0^{1-1/\lambda} (1-y)\tau(\lambda(1-y))^2 dy$ for (max depth)/ n and (back arcs)/ n . Let $u = \lambda(1-y)$. Then the first integral becomes $\frac{1}{\lambda} \int_1^\lambda \tau(u) du$; and $w = u\tau(u) = u(1-e^{-w})$ reduces this to $\frac{1}{\lambda} \int_0^{\lambda\theta} (1-w/(e^w-1)) dw = \theta - \frac{1}{\lambda} \text{Li}_2(1-e^{-\lambda\theta})$. Similarly, the second integral becomes $\frac{1}{\lambda} \int_0^{\lambda\theta} (w-w^2/(e^w-1)) dw$. And the identity $\int w^2 dw/(e^w-1) = w^2 \ln(1-e^{-w}) - 2w \text{Li}_2(e^{-w}) - 2 \text{Li}_3(e^{-w})$ handles it.

[These results on max depth have also been obtained by N. Enriquez, G. Faraud, and L. Ménard, *Random Structures & Algorithms* **56** (2020), 501–516, with respect to a strongly related model of random graphs.]

47. (This gap is typically very small. For example, empirical tests using the uniform parameters of exercise 32 give gaps that are only 162 ± 72 ; with the geometric parameters of exercise 33 they're only 137 ± 55 ; and both may merely be noise. There's theoretical and empirical support for the conjecture that the gap size is $\Theta(n\lambda/G''(1))^{1/3}$.)

48. (When $n = 10^6$, 10000 trials lead to 500004 ± 709 trees, 499996 ± 709 tree arcs, 2.37 ± 1.68 forward arcs, 4.73 ± 2.53 back arcs, 500001 ± 715 cross arcs, 1.01 ± 1.01 loops, max depth 245 ± 89.6 .) The first recurrence in exercise 44 shows that the exact expected number of trees, $1 + \zeta_1 + \dots + \zeta_{n-1}$, is ≈ 500002.87 when $n = 10^6$. Hence there are ≈ 499997.13 tree arcs and ≈ 2.37 forward arcs. (To do these computations, the all-integer polynomials of answer 44(e) are not actually useful. But the coefficients of z^k for large k turn out to be negligible. Therefore a good strategy is to work with the scaled and truncated polynomials $\hat{S}_p(z) = \sum_k \lfloor 2^B \Pr(s_p = k) \rfloor z^k$, for sufficiently large B ; these polynomials empirically have degree $O(n^{1/3})$. To divide by $z - \phi_p$, we can map $x \mapsto \lfloor x\phi_p \rfloor$, which is approximately a “high multiplication” by $\lfloor 2^{64}p/n \rfloor$. We'll know that B is large enough when $2B$ doesn't change the answer.)

It's even better to use the recurrence of answer 44(c), to show that the average number of forward arcs, $\frac{1}{n} \sum_{p=1}^n S'_p(1) = \sum_{p=1}^n (\zeta_p - \phi_p)$, is ≈ 2.36878087 when $n = 10^6$. That tells us the expected number of tree arcs with greater precision.

Similarly, we learn from exercise 44(h) that $(A_1(1) + \dots + A_n(1))/n \approx 4.73146527$ is the exact expected number of back arcs. That leaves ≈ 499994.77 cross arcs.

For general n , the theory in answer 45 says that we should expect $\frac{1}{6} \ln n + O(1)$ forward arcs and $\frac{1}{3} \ln n + O(1)$ back arcs, nicely confirming the empirical statistics. (In fact, those $O(1)$ terms are $\frac{1}{2}c + O(n^{-1/3})$ and $c + O(n^{-1/3})$, where $c \approx 0.1352851560853329010$ is the solution to a certain differential equation.) This example has about twice as many back arcs as forward arcs, because a back arc can be a “left child”; a forward arc can't.

49. $\{4, 5\}$, $\{6, 15\}$, $\{8, 14\}$, $\{10, 11\}$, and nine singleton components $\{0\}, \dots, \{16\}$.

50. Recurrent states are the elements of strong components that are sinks.

51. Set $\text{REP}(w) \leftarrow 0$ for $\text{VERTICES}(g) \leq w \leq \text{SENT}$; also $p \leftarrow 0$ and $w \leftarrow \text{SINK} \leftarrow \text{SENT}$, where p , w , and SINK are global variables. Then, while $w > \text{VERTICES}(g)$, set $w \leftarrow w - 1$ and execute $\text{dfs}(w)$ if $\text{REP}(w) = 0$, where $\text{dfs}(v)$ is the following procedure: “Set $p \leftarrow p + 1$, $\text{REP}(v) \leftarrow p$, $\text{LINK}(v) \leftarrow \text{SENT}$, and $a \leftarrow \text{ARCS}(v)$, where a is a local variable. While $a \neq \Lambda$, set $u \leftarrow \text{TIP}(a)$, $a \leftarrow \text{NEXT}(a)$, execute $\text{dfs}(u)$ if $\text{REP}(u) = 0$, and then if $\text{REP}(u) < \text{REP}(v)$ set $\text{REP}(v) \leftarrow \text{REP}(u)$ and $\text{LINK}(v) \leftarrow \Lambda$. Finally if $\text{LINK}(v) = \text{SENT}$, do step T8; otherwise set $\text{LINK}(v) \leftarrow \text{SINK}$ and $\text{SINK} \leftarrow v$.”

(The shortcut from T6 to T8 does not fit nicely into a recursive formulation.)

dilogarithm Li_2
trilogarithm Li_3
polylogarithms Li_k
Enriquez
Faraud
Ménard
polynomial evaluation
polynomial division, approximate
high multiplication:
 $\lfloor xy/W \rfloor$ when $0 \leq x, y < W$
sinks

53. $9 \rightarrow 7, 2 \rightarrow 6, 2 \rightarrow 3, 2 \rightarrow 7, 6 \rightarrow 2, 4 \rightarrow 1, 4 \rightarrow 1, 6 \rightarrow 4, 1 \rightarrow 6, 3 \rightarrow 1, 3 \rightarrow 3, 9 \rightarrow 3, 5 \rightarrow 9, 5 \rightarrow 3, 8 \rightarrow 4, 8 \rightarrow 3, 8 \rightarrow 8, 5 \rightarrow 8, 9 \rightarrow 5, 9 \rightarrow 7, 0 \rightarrow 2$.
(Tree arcs $v \rightarrow w$ mature in postorder of w ; nontree arcs mature as in answer 12.)

active vertices
shortcut
dense graphs

54. Set $r \leftarrow 0$ in step D1. Omit ' $a \leftarrow \text{NEXT}(a)$ ' from step D5. Replace step D6 by

D6.0. [If u is new, don't continue at v .] If $\text{PARENT}(u) = \Lambda$, go to D7.

D6.1. [Stamp a .] Set $r \leftarrow r + 1$, $\text{TIME}(a) \leftarrow r$, $a \leftarrow \text{NEXT}(a)$, and go to D4.

And in step D8, go to D6.1 instead of to D4.

55. Begin 1 $\text{LOW}(1) \leftarrow 1$ $(5 \rightarrow 3)$ $\text{LOW}(5) \leftarrow 3$ $2 \rightarrow 6$ $\text{LOW}(6) \leftarrow 6$
 1 $\rightarrow 2$ $\text{LOW}(2) \leftarrow 2$ $(4 \rightarrow 5)$ $\text{LOW}(4) \leftarrow 3$ $6 \rightarrow 7$ $\text{LOW}(7) \leftarrow 7$
 2 $\rightarrow 3$ $\text{LOW}(3) \leftarrow 3$ $(3 \rightarrow 4)$ $\text{LOW}(3) = 3$ $(7 \rightarrow 4)$ $\text{LOW}(7) \leftarrow 3$
 3 $\rightarrow 4$ $\text{LOW}(4) \leftarrow 4$ $(3 \rightarrow 1)$ $\text{LOW}(3) \leftarrow 1$ $(6 \rightarrow 7)$ $\text{LOW}(6) \leftarrow 3$
 4 $\rightarrow 5$ $\text{LOW}(5) \leftarrow 5$ $(2 \rightarrow 3)$ $\text{LOW}(2) \leftarrow 1$ $(2 \rightarrow 6)$ $\text{LOW}(2) = 1$

Here ' $(u \rightarrow v)$ ' means that the arc is maturing. At the end, after $(1 \rightarrow 2)$, a strong component will be recognized because $\text{LOW}(1) = 1 = \text{PRE}(1)$.

57. Preorder ABHGMNICDJKFLQPRO; postorder NMGLFEPRQKJDCOIHBA; strong components DEFJKLPQR, ABCGHIMNO; $(\text{LOW}(A), \dots, \text{LOW}(R)) = (1, 1, 2, 9, 9, 11, 1, 1, 2, 9, 9, 11, 3, 3, 3, 10, 10, 11)$. (Of course the LOW values are actually encoded in REP, via (12), until they are obliterated in step T8.)

58. Deleting $B \rightarrow H, H \rightarrow G, H \rightarrow I, N \rightarrow H, K \rightarrow E, J \rightarrow K, L \rightarrow K$ or $K \rightarrow Q$ eliminates two cycles, leaving five strong components (three singletons). Deleting $C \rightarrow D$ or $O \rightarrow P$ retains two. Otherwise one cycle is broken, leaving three (one of which is a singleton).

60. At step T7, the active vertices are precisely the ancestors of v , and v is becoming inactive. According to Lemma S, a new strong component should be identified at the moment when the first vertex of the sink component of $\hat{g}$ becomes inactive. If $\text{LOW}(v) < \text{PRE}(v)$, there's a downpath from v to an earlier vertex; hence v can't be that first vertex. Conversely, if v is not that first vertex, there's at least one "escape path" $v = v_0 \rightarrow v_1 \rightarrow \dots \rightarrow v_r$ without forward arcs for which $\text{PRE}(v_r) < \text{PRE}(v)$. We will show that the lexicographically smallest escape path, with respect to $(\text{PRE}(v_0), \text{PRE}(v_1), \dots)$, is in fact a downpath; hence $\text{LOW}(v) < \text{PRE}(v)$ and $\text{LINK}(v) \neq \text{SENT}$.

Indeed, let $v_{j-1} \rightarrow v_j$ be the first nontree arc on that escape path. If $\text{PRE}(v_j)$ were greater than $\text{PRE}(v)$, v_j would be a descendant of v , and there'd be a lexicographically earlier path from v to v_j . Hence $\text{PRE}(v_j) < \text{PRE}(v)$, $j = r$, and we have a downpath.

61. Step T8 mustn't find $\text{REP}(\text{SINK}) \geq \text{REP}(v)$ when $\text{SINK} = \text{SENT}$.

62. If all vertices have been seen and an arc goes from an active vertex to the current root, all remaining vertices belong to a strong component whose leader is w . (In practice this shortcut often reduces the running time to $O(n)$ on dense graphs.)

[Notice that it is possible to have $u = v = w$ in unusual cases. There also are cases when early termination is valid but not detected in step T6, such as $1 \rightarrow 2, 2 \rightarrow 3, 3 \rightarrow 4, 4 \rightarrow 2, 3 \rightarrow 1, 2 \rightarrow 5, 5 \rightarrow 4, \dots$, when $N(g) = 5$.]

63. It's possible to keep $\text{REP}(v)$ in a register without fetching it from memory each time. (If so, that register should be set to $\text{REP}(u)$ just before entering step T9.) Then, if step T6 doesn't go to T8, (ARC, ARCS, LINK, NEXT, PARENT, REP, TIP) are fetched respectively $(n - r, n, 2n - s, m, m + 2n, m + n + r, m)$ times; we store into (ARC, LINK, PARENT, REP) respectively $(n - r, 2n - s + t_6 + t_7, 2n, 2n + t_6 + t_7)$ times. Here r is the number of roots, s is the number of strong components, and t_j is the number of times REP is changed in step Tj. Note that $t_6 \leq m - n + r$, $t_7 \leq n - s$, and $r \leq s$.

Or, if we don't store into **REP** unless necessary, we store it $3n - r - s + t_7$ times. That's better in the worst case, but not often actually better.

(Incidentally, t_6 isn't always $O(n)$. For example, suppose arcs are revealed in the order $v_1 \rightarrow v_2$, $v_2 \rightarrow v_3$, $v_3 \rightarrow v_2$, $v_3 \rightarrow v_1$, $v_3 \rightarrow v_4$, and $(v_{2k} \rightarrow v_{2k+1}, v_{2k+1} \rightarrow v_{2k}, v_{2k+1} \rightarrow v_{2k-2}, \dots, v_{2k+1} \rightarrow v_2, v_{2k+1} \rightarrow v_1, v_{2k+1} \rightarrow v_{2k+2})$ for $2 \leq k < \lfloor n/2 \rfloor$.)

A slightly faster (but trickier) implementation uses **REP** alone to encode **PRE** and **LOW**: Instead of (12), if v has been seen but not settled, we can let $\text{REP}(v)$ be $2 \cdot \text{LOW}(v) - 2 + \lfloor \text{LOW}(v) \neq \text{PRE}(v) \rfloor$; also $\text{REP}(v) = \text{SENT} + \text{N}(g) + v'$ after v is settled. Then $\text{REP}(v) \leftarrow \text{REP}(u) \mid 1$ in T6, $\text{REP}(u) \leftarrow \text{REP}(v) \mid 1$ in T7, and T7 goes to T8 if $\text{REP}(v)$ is even.

[See D. J. Pearce, *Information Processing Letters* **116** (2016), 47–52.]

64. Print **NAME**(v) at the beginning of step T8, then **NAME**(**SINK**) while $\text{REP}(\text{SINK}) \geq \text{REP}(v)$. The vertices appear in reverse postorder of the depth-first forest, because the **SINK** stack is in postorder from bottom to top.

65. Set **SETTLED** $\leftarrow \Lambda$ in step T1, where **SETTLED** heads a new stack. Change step T8 to

T8'. [New strong component.] If $\text{REP}(\text{SINK}) < \text{REP}(v)$, set $\text{REP}(v) \leftarrow \text{SENT} + v$, $\text{LINK}(v) \leftarrow \text{SETTLED}$, and **SETTLED** $\leftarrow v$ (a singleton component). Otherwise set $\text{LINK}(v) \leftarrow \text{SETTLED}$, **SETTLED** $\leftarrow \text{SINK}$; then while $\text{REP}(\text{SINK}) \geq \text{REP}(v)$, set $t \leftarrow \text{SINK}$, $\text{REP}(\text{SINK}) \leftarrow \text{SENT} + v$ and $\text{SINK} \leftarrow \text{LINK}(\text{SINK})$; finally set $\text{REP}(v) \leftarrow \text{SENT} + v$ and $\text{LINK}(t) \leftarrow v$. (We've essentially moved vertices from **SINK** to **SETTLED**, together with v , using the ordering of exercise 64 in reverse.)

Let each vertex have a field called **FROM**. (This field could share space with **ARC**.) After Algorithm T terminates, set $\text{FROM}(v) \leftarrow \Lambda$ for all v . Then set $v \leftarrow \text{SETTLED}$, and do the following while $v \neq \Lambda$: Set $u \leftarrow \text{REP}(v) - \text{SENT}$ and $\text{FROM}(u) \leftarrow u$. For $a \leftarrow \text{ARCS}(v)$, while $a \neq \Lambda$ set $w \leftarrow \text{REP}(\text{TIP}(a)) - \text{SENT}$ and, if $\text{FROM}(w) \neq u$, set $\text{FROM}(w) \leftarrow u$ and print $\text{NAME}(v) \rightarrow \text{NAME}(\text{TIP}(a))$ as a representative of the arc in $\hat{g}$ from component $\text{NAME}(u)$ to component $\text{NAME}(w)$, then set $a \leftarrow \text{NEXT}(a)$. Finally set $v \leftarrow \text{LINK}(v)$.

[See *The Stanford GraphBase* (1993), *roget_components*, §17.]

66. Change (11) so that, if $\text{LOW}(v) < \text{PRE}(v)$ and $\text{LOW}(v)$ was determined by the nontree arc $v \rightarrow u$, then $\text{LINK}(v) = u$. In step T6, change ' $\text{LINK}(v) \leftarrow \Lambda$ ' to ' $\text{LINK}(v) \leftarrow u$ '. [But keep ' $\text{LINK}(u) \leftarrow \Lambda$ ' in step T7.] If step T6 takes the "last component" shortcut, print the nontree arc $\text{NAME}(v) \rightarrow \text{NAME}(w)$ if $v \neq w$. Just after finding $\text{LINK}(v) \neq \text{SENT}$ in step T7, print the nontree arc $\text{NAME}(v) \rightarrow \text{NAME}(\text{LINK}(v))$ if $\text{LINK}(v) \neq \Lambda$.

Those nontree arcs (part of an "ear decomposition") suffice to preserve the **LOW** values within strong components. Also print the tree arcs within strong components, by printing $\text{NAME}(\text{PARENT}(\text{SINK})) \rightarrow \text{NAME}(\text{SINK})$ in the while loop of step T8 or T8'.

These nontree and tree arcs within strong components, together with the arcs between components in exercise 65, give the desired subgraph.

This efficiently found subgraph isn't always minimum. For example, it removes no arcs from the digraph $4 \rightarrow 3$, $3 \rightarrow 2$, $3 \rightarrow 1$, $2 \rightarrow 4$, $1 \rightarrow 2$, although a clairvoyant algorithm could remove $3 \rightarrow 2$. Indeed, the problem of minimizing arcs is NP-complete, because n arcs suffice to make g strongly connected if and only if g has a Hamiltonian cycle.

The subgraph that's found isn't even minimum, in general, if we start with a given depth-first jungle and insist on including all of its tree arcs within strong components. (Consider, for example, $3 \rightarrow 2$, $2 \rightarrow 3$, $2 \rightarrow 1$, $1 \rightarrow 3$.) But it's pretty good.

68. (a) Vertex **G** is in no cycle, so its period is ∞ . But the others all have period 3, since the arcs not involving **G** are a subset of $\{\mathbf{A}, \mathbf{F}\} \rightarrow \{\mathbf{B}, \mathbf{D}, \mathbf{E}\} \rightarrow \{\mathbf{C}, \mathbf{H}\} \rightarrow \{\mathbf{A}, \mathbf{F}\}$.

(b) Let v have period $p = \gcd P$, where $P = \{p_1, p_2, \dots\}$ is the set of lengths of cycles containing v . Similarly, let w have period $q = \gcd Q$, where $Q = \{q_1, q_2, \dots\}$;

worst case
Pearce
SETTLED
Stanford GraphBase
ear decomposition
NP-complete
Hamiltonian cycle
depth-first jungle

and assume that there are paths $v \rightarrow^* w$ and $w \rightarrow^* v$ of lengths a and b . Every cycle $w \rightarrow^* w$ of length q_k containing w is part of a cycle $v \rightarrow^* w \rightarrow^* w \rightarrow^* v$ of length $a + q_k + b$ containing v . Since p divides both $a + q_k + b$ and $a + b$, it divides q_k . Hence p is a common divisor of Q , and $p \leq q$. Similarly $q \leq p$. (Notice that we can also partition v 's strong component into a cycle of p disjoint “strata,” as we did for $p = 3$ in (a).)

(c) Say that the arc $v \rightarrow u$ of a depth-first jungle is a *cycle arc* if it's neither a tree arc nor a link between different strong components. (This condition holds if and only if $\text{PARENT}(u) \neq \Lambda$ and $\text{REP}(u) < \text{SENT}$ in step T6.) Then every cycle arc is part of some cycle; and every cycle $w = w_0 \rightarrow w_1 \rightarrow \dots \rightarrow w_t = w$ is composed entirely of tree arcs and cycle arcs. Let $T(w) = \{t \mid w \text{ is in a cycle of length } t\}$ and $J(w) = \{\text{jump}(v, u) \mid v \rightarrow u \text{ is a cycle arc in the strong component of } w\}$, where

$$\text{jump}(v, u) = \text{DEPTH}(v) + 1 - \text{DEPTH}(u).$$

Lemma: $\gcd T(w) = \gcd J(w)$. *Proof:* Let $v \rightarrow u$ be a cycle arc. By (b) we may assume that w is the leader of its strong component, so that there are paths $w \rightarrow^* u$ and $w \rightarrow^* v$ by tree arcs alone, and w is reachable from u . Let the cycle $w \rightarrow^* u \rightarrow^* w$ have length t . Then the cycle $w \rightarrow^* v \rightarrow u \rightarrow^* w$ has length $t + \text{jump}(v, u)$; hence any common divisor of $T(w)$ divides the difference between these lengths, and must be a common divisor of $J(w)$. Conversely, given any cycle of length t containing w , we have $\text{jump}(w_j, w_{j+1}) = 0$ when $w_j \rightarrow w_{j+1}$ is a tree arc. Hence any common divisor of $J(w)$ divides $\sum_{j=0}^{t-1} \text{jump}(w_j, w_{j+1}) = t$, and must be a common divisor of $T(w)$.

The desired algorithm extends Algorithm T, but without the “shortcut” to T8 in step T6. Every vertex has two new fields, **GCD** and **DEPTH**; we initialize $\text{GCD}(v) \leftarrow 0$ and $\text{DEPTH}(v) \leftarrow \text{DEPTH}(\text{PARENT}(v)) + 1$ in step T3, where $\text{DEPTH}(\text{SENT}) = 0$. In step T6 we set $\text{GCD}(v) \leftarrow \gcd(\text{GCD}(v), \text{jump}(v, u))$ whenever $\text{PARENT}(u) \neq \Lambda$ and $\text{REP}(u) < \text{SENT}$. In step T8 we calculate $\gcd\{\text{GCD}(w) \mid w \in S\}$, where $S = \{w \mid w \text{ is removed from SINK}\} \cup v$ is the new strong component; this gcd is the period of S , and it can be stored in the **GCD** fields. Step T9 becomes ‘If $u = \text{SENT}$, go back to T2. Otherwise if $\text{REP}(v) < \text{SENT}$, set $\text{GCD}(u) \leftarrow \gcd(\text{GCD}(u), \text{GCD}(v))$. Then set $v \leftarrow u$, $a \leftarrow \text{ARC}(v)$, and go to T4.’

In digraph (a), for example, beginning in T2 with vertex H, we find $(\text{DEPTH}(\text{A}), \text{DEPTH}(\text{B}), \dots, \text{DEPTH}(\text{H})) = (2, 3, 4, 6, 3, 5, 4, 1)$. The jumps at cycle arcs $\text{C} \rightarrow \text{A}$, $\text{F} \rightarrow \text{B}$, $\text{D} \rightarrow \text{H}$, $\text{E} \rightarrow \text{C}$, $\text{H} \rightarrow \text{F}$ are respectively $5 - 2$, $6 - 3$, $7 - 1$, $4 - 4$, $2 - 5$.

[This algorithm appeared in D. Knuth, *Lecture Note 2* (Inst. of Math., Univ. of Oslo, 1973), 14–17. R. E. Tarjan, in unpublished lecture notes (CS259, Stanford, Spring 1976), observed that the worst-case running time is $O(m + n)$, because the gcd of a set $D \subseteq \{1, \dots, n\}$ can be computed in $O(n)$ steps from the formula $\gcd(D) = \gcd(D \setminus x \cup (x - y))$, where x and y are the largest and second-largest elements of D . See also M. J. Atallah, *SICOMP* 11 (1982), 567–570.]

strata
cycle arc
leader
Historical notes
Knuth
Tarjan
gcd
Atallah

71. (a) The only such oriented paths (*not* easy to find by hand!) are $(5, 5) \rightarrow (3, 7) \rightarrow ((8, 2) \rightarrow (2, 8) \rightarrow (6, 4) \rightarrow)^p (6, 2) \rightarrow \text{OUT}$, for $p \geq 1$.

(b) The results shown here are obtained when arcs are visited in lexicographically decreasing order (for example, $(1, 2) \rightarrow (4, 5)$, $(1, 2) \rightarrow (4, 2)$, $(1, 2) \rightarrow (1, 5)$, $(1, 2) \rightarrow \text{OUT}$). There are 38 strong components, whose leaders are indicated in bold type. The largest is **aa** (50 vertices); then **a7**, **5a**, **04**, **77**, **82**, **83**, **49**, **4a**, **87**, **91**, **a6**, **a8**, with respectively $(18, 5, 3, 3, 3, 3, 2, 2, 2, 2, 2)$ vertices; and 25 singletons including **OUT**.

a7	01	a7	a7	04	05	a7	a7	08	04	91
10	a7	a7	a7	a7	15	a7	a7	18	19	a7
aa	aa	aa	a7	aa	aa	a6	77	82	aa	aa
aa	31	aa	aa	aa	aa	aa	37	83	aa	aa
40	49	4a	aa	aa	a7	aa	a7	48	49	4a
5a	5a	a7	53	04	55	56	5a	58	5a	5a
aa	aa	62	aa	82	aa	aa	a7	68	aa	aa
aa	71	77	aa	74	aa	aa	77	78	aa	aa
aa	87	82	83	aa	aa	86	87	83	aa	aa
aa	91	92	aa	aa	95	aa	a8	98	aa	aa
aa	aa	aa	aa	aa	aa	a6	a7	a8	aa	aa

historical notes
Loyd
Klondike
Gardner
Li
coupon collecting
linearly ordered
weak components
generating functions
Wright
Graham
Knuth
Motzkin
historical note

(c) The strong components contain $122 - 38 = 84$ tree arcs such as $(1, 2) \rightarrow (4, 5)$. The digraph g has 424 arcs, of which 183 are links between different components. That leaves $424 - 183 - 84 = 157$ nontree arcs within components; answer 66 prints 40 of them, such as $(2, 3) \rightarrow (6, 7)$ within **a7**. The reduced graph $\hat{g}$ has 97 arcs; answer 65 prints 97 representative arcs from g , such as $(1, 2) \rightarrow (4, 2)$ from **a7** to **4a**.

[This exercise was inspired by Sam Loyd's original whirlpool maze in *Tit-Bits* **32** (31 July 1897), 327, later refashioned as his famous "Back from the Klondike" prize puzzle in *New York Journal and Advertiser* (24 April 1898), 32. See Martin Gardner, *Scientific American* **235**, 4 (October 1976), 131–132.]

75. Several thousand trials with the parameters of exercise 32 (or 33) gave 13900 ± 120 (or 205600 ± 530) strong components of maximum size 986100 ± 120 (or 794400 ± 530); $t_6 = 789100 \pm 3100$ (or 611500 ± 1770), $t_7 = 827300 \pm 710$ (or 636000 ± 680). Essentially all 5000000 arcs were examined. But if we have, say, only 100000 vertices (and change p to 50/51), the number of arcs examined drops to 1300000 ± 160000 . Shisheng Li has observed that we can expect to examine $\min(H_{n-1} + 1, \lambda)n$ arcs in general, based on the theory of coupon collecting (Section 3.3.2).

78. Suppose X and Y are different strong components of a tournament. If $x \in X$ and $y \in Y$ we have either $x \rightarrow y$ or $y \rightarrow x$; say $x \rightarrow y$. Then we must have $x' \rightarrow y'$ for every $x' \in X$ and $y' \in Y$. Consequently the strong components can be linearly ordered, from least to greatest; all arcs between components go "the same way." And the strong components are the same as the weak components.

[Hence there are $n! [z^n] (2 - 1/\sum_{k \geq 0} 2^{\binom{k}{2}} z^k/k!)$ strongly connected tournaments on n labeled vertices. See E. M. Wright, *Glasgow Math. J.* **11** (1970), 97–101.]

80. True: Clearly $u \Leftrightarrow v \Leftrightarrow w$ implies $u \Leftrightarrow w$; $u \Leftrightarrow v \parallel w$ implies $u \parallel w$; and $u \parallel v \Leftrightarrow w$ implies $u \parallel w$. The *shortest* chains (13) will therefore have the stated form.

[This is Lemma 2 in the paper by R. L. Graham, D. E. Knuth, and T. S. Motzkin, *Discrete Mathematics* **2** (1972), 17–29, where weak components were first defined. See also the notion of "weak ordering" in exercise 5.3.1–3.]

81. Since $v \parallel w$ if and only if $v \not\Rightarrow w$ and $w \not\Rightarrow v$, answer 80 proves the “only if” part.

Suppose there are nonpaths both ways. If the shortest nonpath from v to w has $r \geq 2$, we actually have $v_j \parallel v_{j+1}$ for $0 \leq j < r$, because $u \not\Rightarrow v \not\Rightarrow w$ and $u \Rightarrow w$ implies $v \not\Rightarrow u$ and $w \not\Rightarrow v$. Therefore we have $v \asymp w$ whenever the shortest nonpath in either direction has length exceeding 1. Otherwise, however, $v \not\Rightarrow w$ and $w \not\Rightarrow v$.

82. Let the vertices be $\{0, 1, \dots, 1000000\}$, with $v \rightarrow w$ if and only if $w \geq v + 2$. Then $v \parallel w$ if and only if $|v - w| = 1$.

83. True. (Assume that $u \asymp v$, $v \Rightarrow w$, and $u \not\Rightarrow w$. If $u \Leftrightarrow v$ then $u \Rightarrow w$. Hence $u = u_0 \parallel \dots \parallel u_{r-1} \parallel u_r = v$ for some $r \geq 1$. If $v \Leftrightarrow w$ then $u_{r-1} \parallel w$. Otherwise $w \not\Rightarrow u_r \not\Rightarrow \dots \not\Rightarrow u_0$ is a nonpath from w to u , and $u \not\Rightarrow w$ is a nonpath the other way.)

84. A digraph with such an (L, R) partition never has $u \Leftrightarrow v$ or $u \parallel v$ when u and v lie in different parts; hence it isn't weakly connected.

Conversely, if $v \not\asymp u$ and $v \not\Rightarrow u$, let L be the set of all vertices w such that, whenever $v \asymp v'$, we have $w \Rightarrow v'$ but $v' \not\Rightarrow w$; and let R be the other vertices. Suppose $w \in L$ and $w' \in R$. Then there's a $v' \asymp v$ such that either (a) $w' \not\Rightarrow v'$ or (b) $w' \Leftrightarrow v'$. Case (b), or case (a) with $v' \not\Rightarrow w'$, give $w' \asymp v$; then (i) and (ii) hold by definition of L . Otherwise $w \Rightarrow v' \Rightarrow w'$ proves (i); and (ii) must also be true, lest $w' \Rightarrow w \Rightarrow v'$.

Clearly $v \in R \neq \emptyset$, since $v \not\Rightarrow v$ is false. Finally, $u \in L \neq \emptyset$: For if $v \asymp v' \Rightarrow u$ and $v \not\Rightarrow u$, exercise 83 tells us $u \asymp v$. Hence $v' \not\Rightarrow u$, and we must have $u \Rightarrow v'$ lest $u \asymp v$.

85. If a dag D is not weakly connected, the (L, R) partition of Lemma W shows that the first $|L|$ elements of any topological sort are the elements of L .

Conversely, if D is weakly connected and $\{u_1, v_1\}$ are any two of its sources, we will show by induction on n that such sequences $u_1 \dots u_n$ and $v_1 \dots v_n$ exist. The result is clear if $n = 2$. If $n > 2$, let s be a source, and let $(W_1, \dots, W_r)$ be the weak components of $D \setminus s$. If $r = 1$, suppose $u_1 \dots u_{n-1}$ and $v_1 \dots v_{n-1}$ work for $D \setminus s$. If u_1 and v_1 are sources of D , then $u_1 s u_2 \dots u_{n-1}$ and $v_1 s v_2 \dots v_{n-1}$ work for D . Otherwise we can assume $s \rightarrow u_1$ and $s \not\rightarrow v_1$; then $s u_1 \dots u_{n-1}$ and $v_1 s v_2 \dots v_{n-1}$ work.

If $r > 1$, the sources of D are s and the sources of W_1 ; also $s \rightarrow w$ implies $w \in W_r$. Let $u_1 \dots u_{n-1}$ and $v_1 \dots v_{n-1}$ be any two topological sorts of $D \setminus s$. If W_r is a single vertex t , we can use $s u_1 \dots u_{n-1}$ and $v_1 \dots v_{n-1} s$; also $u_1 s u_2 \dots u_{n-1}$ and $v_1 \dots v_{n-1} s$ if $u_1 \neq v_1$. Otherwise W_r has at least two sources, u' and v' , with $s \not\rightarrow v'$, and two topological sorts $(u' \dots u'', v' \dots v'')$. We can assume that $u_1 \dots u_{n-1}$ ends with $u' \dots u''$ and $v_1 \dots v_{n-1}$ ends with $v' \dots v''$. Then $s u_1 \dots u_{n-1}$ or perhaps $u_1 s u_2 \dots u_{n-1}$ can be used with $v_1 \dots v' s \dots v''$ (meaning that s is inserted just after v' in $v_1 \dots v_{n-1}$).

(In exercise 82, use 021...1000000999999 and 10...9999999999981000000.)

86. In $r - 1$ ways, with $L = W_1 \cup \dots \cup W_j$ and $R = W_{j+1} \cup \dots \cup W_r$ for $1 \leq j < r$.

88. (a) Cases j and j' together arise in $2^{n_j + \dots + n_r} - 2^{n_{j+1} + \dots + n_r}$ ways. Case j accounts for $2^{n_j - s_j + n_{j+1} + \dots + n_r}$ of these. (And of course Case $r + 1$ occurs in just one way.)

(b) In Case 1, $\{v\}$ becomes a singleton weak component, with v as both source and sink; all else stays unchanged (except each W_j becomes W_{j+1}). In Cases j' and $j + 1$, a new weak component is formed from vertices $\{v\} \cup W_1 \cup \dots \cup W_j$; its sources are v and the unhit sources of W_1 ; its sinks are the sinks of W_j , together with v in Case $j + 1$ only. Components $W_{j+1}, \dots, W_r$ are unchanged, but their “subscript” decreases by $j - 1$.

89. In the SETTLED list, strong components begin at vertices v with $\text{REP}(v) = \text{SENT} + v$. Weak components begin at vertices WP, WLINK(WP), and so on until SENT occurs.

90. All steps clearly take linear time except perhaps W3 and W4. Step W3 is linear because we lose a weak component whenever WP advances.

sources
SETTLED

The interesting case is step W4, which would be nonlinear if we traversed a long list in order to purge unhit sources. Tarjan achieved linearity by introducing a clever “lazy deletion” method, which uses two fields WHIT and HIT. Every weak component W_j has a list L_j of strong components, which begins at the leader and continues through SRC links until reaching SENT. A strong component u is a source of W_j if and only if u is in L_j and $\text{HIT}(u) = 0$. (Thus L_j contains all sources and possibly some nonsources.)

When the loop W4 looks at vertex u , we’ve either had an arc $v \rightarrow u$ ($\text{WHIT}(u) = 1$), or we exit because $\text{WHIT}(u) = 0$, or we remove u from its list L_j because $\text{HIT}(u) = 1$. A vertex is never removed from such a list twice.

[*Historical note:* Tarjan’s Algorithm W was inspired by J. F. Pacault’s linear-time algorithm in *SICOMP* **3** (1974), 56–61.]

92. The effect is that WP points to the leader of the *second* component W_2 (if any), instead of to the leader of W_1 . When Algorithm W is called the next time, step W3 will then perform the operation ‘ $w' \leftarrow \text{WP}$ ’ once less often.

93. (a) In Case j , the operation ‘ $\text{HIT}(u) \leftarrow 1$ ’ is never performed. In Case j' for $j > 1$, that operation has no effect, because vertex u doesn’t appear in the list L_1 of the new component W_1 .

(b) Keep the value of $\text{SRANK}(\text{WP})$ in a register. Recognize Case 1’ by two events: (i) Step W3 doesn’t set $w' \leftarrow \text{WP}$ (assuming that the optimization of exercise 92 is used). (ii) Step W5 isn’t performed.

95. If we map $(s_j, n_j) \mapsto (10)^{s_j-1}(01)^{n_j-s_j}00$, we obtain a one-to-one correspondence between such sequences and binary strings of length $2n$ that have no consecutive 1s and end with 00. And there’s a well-known “Morse code” correspondence between $[0 \dots F_n]$ and 11-free binary strings of length $n-2$; see, for example, *CMath* (6.115).

96. (a) When $n = 1$, $g_\sigma(z) = 1$. If we know all the generating functions for n , we can use the case analysis of exercise 88 to compute the contribution of each $g_\sigma(z)$ to the generating functions for $n+1$. Let σj and $\sigma j'$ be the sequences that result from augmentation in Cases j and j' . In Case 1’ the result depends on h , the number of sources hit in W_1 ; we shall denote that sequence by $\sigma 1' h$. Let $n'_j = n_j + \dots + n_r$.

With that notation, $g_\sigma = g_\sigma(z)$ contributes $z^{s_j}(1+z)^{n'_j-s_j}g_\sigma$ to $g_{\sigma j}$, for $1 \leq j \leq r$; $\binom{s_1}{h}z^h(1+z)^{n'_1-s_1}g_\sigma$ to $g_{\sigma 1' h}$, for $0 < h < s_1$; $((1+z)^{n'_1-s_1} - (1+z)^{n'_2})g_\sigma$ to $g_{\sigma 1' 0}$; $((1+z)^{n'_j} - z^{s_j}(1+z)^{n'_j-s_j} - (1+z)^{n'_{j+1}})g_\sigma$ to $g_{\sigma j'}$ for $1 < j \leq r$; and g_σ to $g_{\sigma(r+1)}$.

For example, the generating functions for $n = 2$ are $g_{1111} = z$, $g_{12} = 0$, $g_{22} = 1$, if we write $(s_1, n_1; \dots; s_r, n_r)$ without punctuation. Let $\sigma = (2, 3; 2, 3)$; it turns out that $g_{2323} = 9z^6 + 45z^7 + 90z^8 + 90z^9 + 45z^{10} + 9z^{11}$. This g_σ contributes $z^2(1+z)^4g_\sigma$ to $g_{\sigma 1} = g_{112323}$ and $z^2(1+z)g_\sigma$ to $g_{\sigma 2} = g_{3423}$; $2z(1+z)^4g_\sigma$ to $g_{\sigma 1' 1} = g_{2423}$; $((1+z)^4 - (1+z)^3)g_\sigma$ to $g_{\sigma 1' 0} = g_{3423}$ and $((1+z)^3 - z^2(1+z) - 1)g_\sigma$ to $g_{\sigma 2'} = g_{37}$; g_σ to $g_{\sigma 3} = g_{37}$. Notice that, in general, we have $\sigma 1' 0 = \sigma 2$, and $\sigma j' = \sigma(j+1)$ for $1 < j \leq r$.

(The generating function g_σ will be zero if and only if $s_j = 1$ and $n_j > 1$ for some j ; hence the number of nonzero cases is not F_{2n} but $(1, 2, 5, 12, 28, \dots)$ for $n = (1, 2, 3, 4, 5, \dots)$, a sequence whose growth rate is approximately 2.32472^n instead of 2.61803^n .)

(b) The sum $\sum_{s=1}^n g_{(s_n)}(1)$ is $(1, 1, 4, 31, 474, 14357, 865024, 103931595, \dots, 303505765229448690912596327628571427)$ for $1 \leq n \leq 16$; see OEIS A350608.

(c) Let $g_n^{(r)}$ be the sum of g_σ for all σ with r weak components and $n_1 + \dots + n_r = n$; for example, $g_4^{(2)} = 8z^3 + 7z^4$, and $g_n^{(n)} = z^{n-1}(1+z)^{(n-1)(n-2)/2}$. Then the probability of r weak components when each arc is independently present with probability p is $(1-p)^{n(n-1)/2}g_n^{(r)}(p/(1-p))$. In particular, when $1 \leq r \leq n = 16$ we get the following

Tarjan
lazy deletion
WHIT
HIT
SRC
source
Historical note
Tarjan
Pacault
SRANK
no consecutive 1s
consecutive 1s
Morse code
11-free binary strings
OEIS

approximate results: (i) (.007, .017, .034, .057, .082, .106, .123, .130, .124, .108, .085, .060, .037, .019, .008, .002); (ii) (.228, .154, .167, .140, .108, .078, .052, ..., .00003); (iii) (.808, .095, .057, .023, .010, .004, .002, ..., 10^{-7}); (iv) (.99999990, 10^{-7} , 10^{-8} , 10^{-9} , 10^{-10} , 10^{-11} , $2 \cdot 10^{-12}$, ..., $9 \cdot 10^{-19}$). [See OEIS A350609.]

98. Suppose D is a weakly connected subgraph of K_n . For $1 \leq k < n$, there are vertices (u_k, v_k) with $u_k \leq k < v_k$ with $u_k \not\Rightarrow v_k$, by Lemma W. Let's choose them so that $v_k - u_k$ is minimum. Then $(u_k, v_k) \neq (u_{k'}, v_{k'})$ when $k < k'$; otherwise we'd have $u_k \leq k < k' < v_k$ and $u_k \Rightarrow k+1 \Rightarrow v_k$, a contradiction. Hence we've found at least $n-1$ arcs $u_k \rightarrow v_k$ that are *not* in D , and D has at most $\binom{n}{2} - (n-1) = \binom{n-1}{2}$ arcs.

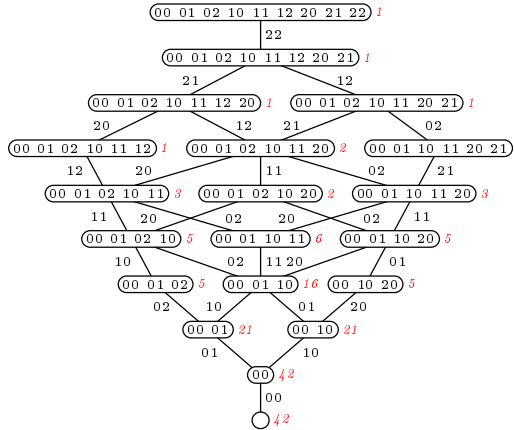
Given $a_2 \dots a_{n-1}$, let $b_1 = c_n = 0$ and $b_j = 1 + b_{j-1}$ if $a_j = -$, otherwise $b_j = 0$; $c_j = 1 + c_{j+1}$ if $a_j = +$, otherwise $c_j = 0$. The corresponding digraph D omits the arcs from $j - b_j$ to $j + 1 + c_{j+1}$, for $1 \leq j < n$.

For example, the digraph that corresponds to $--++0+-00-$ omits $1 \rightarrow 2$, $1 \rightarrow 3$, $1 \rightarrow 6$, $4 \rightarrow 6$, $5 \rightarrow 6$, $6 \rightarrow 8$, $7 \rightarrow 8$, $7 \rightarrow 9$, $9 \rightarrow 10$, $10 \rightarrow 11$, $10 \rightarrow 12$. And in this digraph we have $1 \not\Rightarrow 2$, $1 \not\Rightarrow 3$, $1 \not\Rightarrow 6$, $4 \not\Rightarrow 6$, ..., $10 \not\Rightarrow 12$.

100. (a) Given $x_1 x_2 \dots x_n$, each set $I_k = \{x_1, \dots, x_k\}$ is an order ideal. For if $y \in I_k$ and $x \preceq y$ but $x \notin I_k$, we'd have $y = x_j$ for some $j \leq k$ but $x = x_i$ for some $i > k$. Conversely, every such path $I_0 \subset I_1 \subset \dots \subset I_n$ defines a topological sort $x_1 x_2 \dots x_n$ where $x_k = I_k \setminus I_{k-1}$: If $x_i \preceq x_j$ we have $x_i \in I_j$, hence $i \leq j$.

(b) Each order ideal corresponds naturally to the elements above a path from $(0, 0)$ to (n, m) that makes m upward steps $(x, y) \mapsto (x, y+1)$ and n rightward steps $(x, y) \mapsto (x+1, y)$.

(c) The edges of this diagram are labeled with the element being newly added, so that we can "read off" the topological sort that corresponds to each path from bottom to top. (The small numbers in italics to the right of each order ideal are examples of the "counts" in the following exercise.)



101. Let the given digraph D have vertices $\{v_0, \dots, v_{n-1}\}$. The following algorithm works depth-first in the lattice, not in D , starting at the bottom with the empty ideal. (Thus "deeper" actually means "higher in the lattice," having more elements.) Each order ideal I is represented by the binary number $\sum \{2^k \mid v_k \in I\}$, with its count stored in $\mathcal{C}[I]$; of course a hash table could be used if there's no room for an array of size 2^n .

Let I_l denote the ideal of size l with which we're currently working. The key data structures are **IN**, an array that contains in-degrees, together with **S**, a stack that contains all s for which $v_s \notin I_l$ and $\text{IN}[s] = 0$. Backtracking is controlled by three arrays: **HT** $[l]$ is one less than the stack size when the current node at level l was entered; **MV** $[l] = s$ if $I_{l+1} \setminus I_l = \{v_s\}$; and **POS** $[l] = x$ if **MV** $[l]$ was previously **S** $[x]$. For each ideal I not at the top, the algorithm outputs **LIST** (I) , a list of the elements s for which $I' = I + 2^s$ is immediately above I in the lattice.

L1. [Initialize.] Set $\mathcal{C}[i] \leftarrow 0$ for $0 \leq i < 2^n - 1$, and $\mathcal{C}[2^n - 1] \leftarrow 1$. Starting with $\text{IN}[k] \leftarrow 0$ for $0 \leq k < n$, examine all arcs of D and set $\text{IN}[k] \leftarrow \text{IN}[k] + 1$

whenever $v_j \rightarrow v_k$. Set $p \leftarrow 0$; then, for $0 \leq k < n$, set $S[p] \leftarrow k$ and $p \leftarrow p + 1$ if $IN[k] = 0$. Set $l \leftarrow 0$ and $I \leftarrow 0$.

- L2.** [Enter level l .] (At this point p , which is the number of sources in the current digraph $D \setminus I$, will always be positive, because D is acyclic.) Set $p \leftarrow p - 1$, $LIST(I) \leftarrow (S[0], \dots, S[p])$, $HT[l] \leftarrow p$, $x \leftarrow p$, and $s \leftarrow S[x]$.
- L3.** [Try source s .] Set $I' \leftarrow I + 2^s$. If $C[I'] > 0$, set $C[I] \leftarrow C[I] + C[I']$ and go to L6.
- L4.** [Delete v_s .] For each arc $v_s \rightarrow v_j$, set $IN[j] \leftarrow IN[j] - 1$, and if this makes $IN[j] = 0$ also set $S[p] \leftarrow j$ and $p \leftarrow p + 1$.
- L5.** [Increase l .] (If stack S was $s_0 s_1 \dots s_h$ when level l was entered, it now contains $s_0 \dots s_{x-1} s_{x+1} \dots s_h s_x^+$, where s_x^+ is a list of vertices that became sources when vertex v_{s_x} left D .) Set $MV[l] \leftarrow s$, $POS[l] \leftarrow x$, $I \leftarrow I'$, $l \leftarrow l + 1$, and go to L2.
- L6.** [Try another source.] If $x > 0$, set $x \leftarrow x - 1$, $t \leftarrow S[x]$, $S[x] \leftarrow s$, $s \leftarrow t$, and return to L3.
- L7.** [Backtrack.] (Now $C[I']$ has the correct final value for all ideals $I' \supseteq I$.) Terminate if $l = 0$. Otherwise set $l \leftarrow l - 1$, $p \leftarrow HT[l]$, $k \leftarrow p - 1$. While $k > 0$, set $S[k] \leftarrow S[k - 1]$ and $k \leftarrow k - 1$. Then set $S[0] \leftarrow s$, $s \leftarrow MV[l]$, $x \leftarrow POS[l]$, $t \leftarrow C[I]$, $I \leftarrow I - 2^s$, and $C[I] \leftarrow C[I] + t$. For each arc $v_s \rightarrow v_j$, set $IN[j] \leftarrow IN[j] + 1$. Go back to L6. ■

[See K. De Loof, H. De Meyer, and B. De Baets, *Fundamenta Informaticæ* **71** (2006), 309–321, a paper that also inspired the next two exercises.]

102. Begin with $I \leftarrow 0$ and $k \leftarrow 1$. While $k \leq n$, set x_k to the j th element s_j of $LIST(I)$ with probability $C[I + 2^{s_j}] / C[I]$, and set $I \leftarrow I + 2^{x_k}$, $k \leftarrow k + 1$.

For example, the lattice for $P_3 \square P_3$ appears in answer 100 with C values appended to each ideal. We set $x_1 \leftarrow 00$ with probability $\frac{42}{12}$; then $x_2 \leftarrow 01$ with probability $\frac{21}{12}$; and if $x_2 = 01$ we set $x_3 \leftarrow 02$ with probability $\frac{5}{21}$. (In general, the C values for $P_m \vec{\square} P_n$ are given by the hook length formula for Young tableaux, Theorem 5.1.4H.)

103. Given y , every path from bottom to top of the lattice runs through a unique edge from an ideal I that doesn't contain y to an ideal I' that does, namely an edge labeled ' y ' in answer 100(c). And a path goes through it with x preceding y if and only if $x \in I$.

The algorithm of exercise 101 can be turned upside down, so that it computes $D[I]$, the number of paths between I and the *bottom*, instead of $C[I]$. (Sources become sinks, and we start with $I \leftarrow 2^n - 1$, $D[0] \leftarrow 1$, etc., but the basic logic is the same.) And when we know both C 's and D 's for every ideal, the number of paths that go through an edge from I to I' is $D[I] \cdot C[I']$.

Thus, starting with $T(x, y) = 0$ for all x and y , we simply run through all edges in the lattice, increasing $T(x, y)$ by $D[I] \cdot C[I']$ whenever $x \in I$ and $I' \setminus I = \{y\}$.

104. Glue the top element of W_k to the bottom element of W_{k+1} , for $1 \leq k < t$.

999. ...

De Loof
De Meyer
De Baets
directed $m \times n$ grid
hook length formula
Young tableaux
sinks

INDEX AND GLOSSARY

Hippocrates
D'ISRAELI

*I, for my part, venerate the inventor of indexes;
and I know not to whom to yield the preference,
either to Hippocrates, who was the first great anatomiser of the human body,
or to that unknown labourer in literature,
who first laid open the nerves and arteries of a book.*
— ISAAC D'ISRAELI, *Miscellanies* (1796)

When an index entry refers to a page containing a relevant exercise, see also the *answer* to that exercise for further information. An answer page is not indexed here unless it refers to a topic not included in the statement of the exercise.

$\iff$: If and only if.

Barry, David McAlister (= Dave), iii.

FGbook: Selected Papers on Fun & Games,
a book by D. E. Knuth.

Hauptman, Don, iv.

*LIPICs: Leibniz International Proceedings
in Informatics* (2008–).

Nothing else is indexed yet (sorry).

Preliminary notes for indexing appear in the
upper right corner of most pages.

If I've mentioned somebody's name and
forgotten to make such an index note,
it's an error (worth \$2.56).