A LINEAR-TIME RECOGNITION ALGORITHM
FOR INTERVAL DAGS

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1. Introduction

In [PY], Papadimitriou and Yannakakis solve the unit-execution-time scheduling problem [C, pp. 51-3] for a family of partial orders called interval orders. Only one other family (the forest orders [H]) is known to have an efficient solution.

The development in [PY] assumes the interval order is given in transitively closed form. This note extends ideas that are implicit in [PY] to remove this assumption. The main tool is a linear-time algorithm to recognize an interval dag, i.e., a dag whose transitive closure is an interval order. This is given in Section 2. Section 3 indicates how the recognition algorithm applies to the scheduling problem.

Before proceeding we establish some notation and give a convenient definition of interval dag. For a dag (directed acyclic graph), n represents the number of vertices and m the number of edges; the vertices are numbered 1, ..., n. For a vertex i, the set of vertices adjacent from i is A(i) = {j | there is an edge from i to j}; the successor set of i is S(i) = {j | there is a path of one or more edges from i to j}.

An interval dag satisfies the following nesting property:

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Definition. A dag is an interval dag iff for any two vertices i, j, either
$S(i) \subseteq S(j)$ or $S(j) \subseteq S(i)$.

So the distinct successor sets $S(j)$ can be labelled as $\phi = T_0 \not\subseteq T_1 \not\subseteq \ldots \not\subseteq T_{\ell-1} \not\subseteq T_{\ell}$.

Figure 1 shows an interval dag. The transitive-closed interval dags are
exactly the interval orders; this can be seen by examining the proofs of [PY].

2. The Recognition Algorithm

The algorithm processes vertices one-by-one, checking the nesting
property is always satisfied. To do this, the vertices are numbered in
topological order [K], so if $(i,j)$ is an edge, $i < j$ (Each vertex is
identified with its number.). Vertices are processed in decreasing order.

Suppose the nesting property has been verified for all vertices
$j > i$. So the distinct successor sets $S(j)$, $j > i$, can be labelled as
$T_0 \not\subseteq \ldots \not\subseteq T_{k-1} \not\subseteq T_k$, where for convenience, $T_k$ does not denote a successor
set but rather $T_k = \{1, \ldots, n\}$. Let $T_q$ be the smallest set containing $A(i)$.
The nesting property implies $T_{q-1} \not\subseteq S(i) \subseteq T_q$. So if $T_{q-1} \not\subseteq S(i)$ is false,
the dag is not interval. Otherwise the dag seen so far is interval. If
$S(i) = T_q$, the next vertex $i-1$ can be processed. If $S(i)$ lies properly
between $T_{q-1}$ and $T_q$, $S(i)$ can be made a new $T$- set and then vertex $i-1$
can be processed.

To implement this approach efficiently, the following data structure
is used (see Figure 2). A set $T_j$ is represented by a node $t$; it has a field
$\text{COUNT}(t) = |T_j|$.
The nodes $T_k, T_{k-1}, \ldots, T_0$ are linked, in this order, to form a linear list
$\text{L}$. A vertex $i$ has entries in two arrays:
$\text{SUCC}(i)$ points to the node for set $S(i)$;
$\text{IN}(i)$ points to the node for the smallest set containing $i$. 
Note the nesting property allows us to use COUNT fields to compare sets. Now we present the algorithm in pseudo-Algol.

begin comment This algorithm halts indicating whether or not the given dag is interval. If it is, a node \( t \) in \( L \) represents the successor set \( \{i | \text{IN}(i) \text{ is } t \} \) or is after \( t \) in \( L \), \( L \) gives the nesting order of successor sets, and vertex \( i \) has successor set \( \text{SUCC}(i) \).

initialization:

1. number the vertices in topological order;
2. let \( L = T_1, T_0 \), where \( T_1 = \{1, \ldots, n\} \), \( T_0 = \emptyset \); let \( \text{IN}(i) \) point to \( T_1 \) and \( \text{SUCC}(i) \) point to \( T_0 \), for \( 1 \leq i \leq n \);

processing:

3. for \( i \) \( \rightarrow \) \( 1 \) by \( -1 \) do
4. if \( A(i) \neq \emptyset \) then begin
5. comment find \( T_q \), the smallest successor set containing \( A(i) \), and \( T_p \), the largest successor set of some \( j \in A(i) \);

   let \( q \) point to the node that maximizes \( \text{COUNT}(\text{IN}(j)) \) for \( j \in A(i) \);
   let \( p \) point to the node that maximizes \( \text{COUNT}(\text{SUCC}(j)) \) for \( j \in A(i) \);

6. comment let \( L_0 = A(i) \cap T_{q-1} - T_p \), \( H_i = A(i) \cap T_q - T_{q-1} \);

   let \( L_0 = \{j | j \in A(i), \text{COUNT}(p) < \text{COUNT}(\text{IN}(j)) < \text{COUNT}(q)\} \);
   let \( H_i = \{j | j \in A(i), \text{IN}(j) = q\} \);

7. comment find \( T_{q-1} \) and check \( T_{q-1} \subseteq S(i) \);

   let \( q' \) point to the node following \( q \) in \( L \);
   if \( \text{COUNT}(q') > \text{COUNT}(p) + |L_0| \) then halt (\( G \) is not interval);

8. comment check if \( S(i) = T_q \);

   if \( \text{COUNT}(q) = \text{COUNT}(q') + |H_i| \) then \( \text{SUCC}(i) = q \)
   else begin comment create a new successor set for \( S(i) \);

9. let \( t \) point to a new node between \( q \) and \( q' \), with

   \( \text{COUNT}(t) = \text{COUNT}(q') + |H_i| \), \( \text{SUCC}(i) = t \), and

   \( \text{IN}(j) = t \) for \( j \in H_i \);

end end

halt (\( G \) is interval)

end.
Theorem: An interval dag can be recognized in time $O(n+m)$.

Proof: Correctness of the algorithm follows from the comments and the preceding discussion. The linear time bound is obvious.

In an actual implementation, the algorithm would be modified for greater speed. The topological numbering could be eliminated by exploring the graph depth-first, processing successors before predecessors. In line 6 it is more economical to compute only $|LU|$ and $|HI|$; only in line 9 might it be necessary to reexamine $A(i)$ to find $HI$.

3. Application to Scheduling

To implement the scheduling algorithm of Papadimitriou and Yannakakis, it is necessary to form a "priority list" of the vertices $i$ in decreasing order of $|S(i)|$. This is done by traversing $L$, listing all vertices $i$ with $SUCC(i) = t$ when node $t$ is visited. It is easy to implement this in time $O(n+m)$.

The complete scheduling algorithm runs in almost-linear time, $O(n\alpha(n)+m)$.* Here $\alpha(n)$ is the inverse of Ackermann's function and is $\leq 3$ for practical applications [T]. The factor $\alpha(n)$ results from the time to convert the priority list to a schedule [S]. There seems to be no simple way to take advantage of the special structure of interval dags to do the conversion faster.

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*This is slightly worse than the linear bound claimed in [PY].
References


Figure 1. Example graph
Figure 2. Data structure after vertex 3 is processed.