

# Avoiding Undesired Behavior while Concurrently Accessing A Data Structure

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## **Abstract**

The key to avoiding inefficiency and inconsistency in concurrently accessed structures is having a well-defined concurrent access algorithm. There are many approaches available to use. We devise a method using spatial and temporal dependency graphs to manage access to arbitrary data structures.

# 1 Introduction

In this paper we would like to describe an algorithmic approach to avoiding undesirable behavior in systems that have multiple processes (threads) accessing a shared data structure. We should first supply a basic definition for a concurrent data structure.

DEF. 1.1 (Concurrent Data Structure) - A *concurrent data structure* is a data structure that is concurrently accessed by multiple processes. The processes are allowed to read and write data as well as modify the structure itself.

There already exist a plethora of approaches to managing access to a shared structure, of which we will make brief mention of only a few techniques e.g. *locks*, *fine-grained locking*, *combining trees*, etc.

For example, here is a basic definition of locking a data structure.

DEF. 1.2 (Locking) - A *lock* is a device that enforces a temporary operation ownership of the concurrent data structure by a process e.g. a process in possession of the write lock will be the only process allowed to write data to the structure. Using a set of locks where each lock applies to only a substructure of the overall data structure is called: *fine-grain locking*.

In most programming languages a lock is called a *mutex* (mutual exclusion).

It is also important to specify what exactly we mean by *undesirable behavior*.

DEF. 1.3 (Undesired Behavior) - The primary potential behaviors we will be focused on avoiding in this paper are: redundancy, data races, access blocking, and a lack of any consistency guarantee.

Essentially we are trying to avoid problems with inefficiency and inconsistency. Namely, we would like to avoid overwriting values that have already been written. And we would also like to avoid problems that are usually seen as a lack of linearization e.g. a value being overwritten with an out-of-date value.

Of course, every access management implementation will require a degree of tradeoff. For example, are we allowed to read a value from our concurrent

data structure at any time or must we always guarantee that all currently-in-progress writes have been completed? We will not focus on tradeoff choices in this paper. How a developer may choose to utilize the algorithm in this paper will depend on the developers personal choice of system requirements. But we do note that the algorithm will be rather flexible in varying the degree of consistency for concurrently accessing a structure.

One of the usual goals of concurrently accessing a single data structure is: computation efficiency i.e. speedup. Sometimes it is also used to avoid having multiple copies of the same structure and being forced to use a consensus algorithm to determine which one has the “true state” of the structure (or a sub-structure) at a given moment in time.

These goals/reasons for concurrent data structure design will not be the focus of this paper. Instead, we will focus on devising an (astoundingly rather simple) algorithm that will be able to ‘monitor’ and maintain the state of an arbitrary concurrent data structure for us to a degree of consistency that we would like it to have.

## 2 Dependency DAGs

We begin our discussion around the crux of avoiding undesirable behavior: *Ordering* (in the literature: *linearization*).

In our definition of a CDS (1.1), we discussed reading and writing data to a structure as well as changing the structure of the CDS itself. We will label all of these processes as: *access types*. More specifically: these are procedural types. Everytime we try to execute an access type we will call this an: *access procedure*.

We do not want to limit ourselves to some predefined set of operations such as “reads, writes, appends, removals, etc.”. These do represent a sort of canonical basis for all possible access types, but we want to be flexible enough to allow for any and all possible methods of accessing a CDS.

Thus, we need to find a way to ensure the linearization, or correct ordering, of access procedures.

For example, when and how will we guarantee that one access procedure completes before another one is started? The how is simple: we can sequentially order our access procedures i.e. apply a total ordering to all access procedures across our system.

But that can be accomplished by using only a single process without the necessity for concurrent processes. Thus we need to address the *when* of ordering access procedures using multiple concurrent processes.

Not all access procedures will need to be totally-ordered i.e. a complete (mathematical) linearization of our access procedures is not always a necessity. It is this *lack of necessity of a total ordering* that allows us to have the possibility of concurrency in the first place.

The degree to which our system can behave non-linearly is exactly the minimal degree to which it can be composed of concurrent processes. (Note: by "system" we are referring to a set of processes plus our CDS).

So, when is ordering a necessity? The only time two access procedures need an order is if one access procedure is *dependent* on the other. We do not specify the reason for the dependency, but if a dependency exists (at all) then it is easy to see that an ordering is necessary.

Since the necessity for an ordering is not always required, we see that a complete linearization of our system is not always a necessity. Rather, the access procedures which carry a dependency on other access procedures create a *partial ordering* for our system.

More specifically: all of our dependencies allows us to have a (disjoint) *dependency graph* for our access procedures.

All good, right?! Sort of. Sadly, this does not resolve all of our problems. We have not discussed exactly how we will order access procedures in terms of processes.

## 2.1 Spatial Dependencies

First, let's diverge quickly back into a discussion of our CDS. Let's try to formalize it:

DEF. 2.1 (Concurrent Data Structure (2)) - A *concurrent data structure* is a graph  $\mathcal{G} = \{\mathbf{N}, \mathbf{E}\}$  composed of  $|\mathbf{N}|$  nodes and  $|\mathbf{E}|$  edges, that is used to index data of type  $\mathcal{T}$ , and is allowed to be accessed by some set of processes  $\mathcal{P}_i$  via some set of access types  $\mathcal{A}_i$ .

This helps us to remember that a data structure is a spatial object. It carries a certain topology and is invariant through time unless modified. Thus, it is completely possible that while access procedures may not carry a dependency: nodes of our CDS just might! The set of all nodular-dependencies will be called the: *set of spatial dependencies*. These dependencies may be the dependencies that an access procedure "adopts" in order to consider itself dependent on another access procedure.

For example: if access procedure  $A$  is trying to write to node  $n_1 \in \mathbf{N}$  and access procedure  $B$  is trying to write to node  $n_2 \in \mathbf{N}$ , but  $n_2 < n_1$  (where  $<$  is a dependency arrow), then we would want to perform  $B$  before  $A$ .

This set of spatial dependencies only covers the dependency relationships between certain nodes in our graph. But what if we wanted sub-graphs of our CDS to be dependent or more importantly *independent* of other sub-graphs of our CDS?

Let's define this:

DEF. 2.2 (Unique-Independent) - Any sub-graph  $\mathcal{S} \subseteq \mathcal{G}$  that does not contain any internal spatial dependencies is called an *unique-independent* of our CDS.

Unique-Independents (UIs) can almost be seen as a *virtualization* of our CDS's spatial topology.

Unique-Independents can obviously have external dependencies i.e. be dependent on each other. Thus, the set of UIs of our CDS forms a dependency graph. Although, since UIs do not have to have other UIs as dependencies, we simply qualify this as a: dependencies list.

DEF. 2.3 (Dependency List) - A *dependencies list*

for a CDS is the adjacency list of our disjointed graph of unique-independents.

Don't let the name "unique-independent" fool you. There is no requirement for an independent to be spatially-unique. In other words, a unique-independent can share nodes from the CDS with other UIs. The only thing that makes a unique-independent "unique" is that it is in totality unique as to the nodes it applies too.

So while, a unique-independent can be completely subsumed by another unique-independent spatially, it will never refer to the exact same set of nodes that another unique-independent is referring too. And it is this notion of "uniqueness" that allows it to be an independent.

This may seem like a unique-independent that subsumes UIs with dependencies that are other subsumed UIs conflicts with our definition (2.2) of an unique-independent.

However, what we have to notice is that a unique-independent is evaluated separately from other UIs i.e. a unique-independent whom subsumes other UIs and their dependencies is only allowed to be addressed after all those other UIs have been addressed.

So, while an independent has "no spatial dependencies" it can still subsume UI-dependencies.

## 2.2 Temporal Dependencies

Now that we have a way to virtualize a CDS using UIs, let's tie UIs back in with our previous discussion about ordering access procedures.

We can now use our UI virtualization of our CDS to assign an access procedure to a particular UI. More precisely, we want an access procedure to be an access type + UI.

$$A_p := A_t \oplus I$$

Since our dependency list of UIs based off this virtualization represents all possible spatial dependencies in our CDS it can be used to help us apply an ordering to access procedures. However, a spatial de-

pendency is not the only way access procedures can be ordered i.e. be dependent on each other. The other way access procedures can have is an ordering: is *per UI*.

In other words, we can still order all access procedures that have been assigned to the same UI. For example, will read access procedures always take precedence over write access procedures for a particular UI? What if we wanted to be more specific (fine-grained) than that and give *certain* access procedures precedence over *certain* write access procedures?

It would be impossible to suggest that access procedures that apply to a specific UI could always be totally-ordered. Thus, we arrive at the same situation we were in before with trying to linearize our system. Thankfully, we have the answer: a dependency graph (list). Except, this time our dependencies list are access procedures assigned to the same UI.

Whereas we had an UIs dependency list that represented a virtualization of the spatial dependencies, we now have a procedures dependency list that virtualizes the temporal dependencies of our CDS (per UI). Every UI will have it's own temporal dependencies list and every node in this disjoint dependencies graph will be a specific access procedure.

## 2.3 Processes

We still have to come back around to combining our ordering of dependencies with the processes in our system.

A Thread is about atomicity: a thread can be assigned to each node, and is assigned to a nodes child if the node only has one child (i.e. a linearized set of nodes would all be on the same thread – and could be considered combined atomically).

Boundary Nodes on our UI dependency graph are useful for determining what access types are allowed for a UI.

EXAMPLE 2.1 (2-Regular Tree): We consider boundary nodes of a UI dependency graph for a 2-Regular Tree CDS.

In Example 2.1, we see that modifying the structure of our tree is dependent on what we want to preserve. Thus, we do not allow UIs with dependencies to have the ability to use access types that modify our CDS structure. But, we could if we wanted too. Thus, each UI could be assigned a list of *immutables*. More specifically, a list of nodes in the CDS that are *invariant* to certain access types.

Note: immutability is only a kind of invariance. A low-resolution invariance which blanket-denies all modification access types.

### 3 Algorithm

How are we going to assign unique-independent modifications to a thread? In other words, how will we ensure that a thread is only allowed to make modifications to a single unique-independent?

We will also address the atomicity of operations and sequence of operations as defined *internally* to a thread.

### 4 Formal Verification

### 5 Memory

Can we utilize this new model to find a better method for Memory Management of Concurrent Data Structures (in runtimes that are not using a built-in GC)?

### 6 Conclusion

### References

- [1] Michel Goossens, Frank Mittelbach, and Alexander Samarin. *The L<sup>A</sup>T<sub>E</sub>X Companion*. Addison-Wesley, Reading, Massachusetts, 1993.