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A Means for Incorporating Time-Dependent Phenomena in Existing Vulnerability Analysis Methods

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ARL-TR-738

April 1995

NOTICES

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE April 1995	3. REPORT TYPE AND DATES COVERED Final, July 1993–December 1993

4. TITLE AND SUBTITLE A Means for Incorporating Time-Dependent Phenomena in Existing Vulnerability Analysis Methods	5. FUNDING NUMBERS PR: 1L162618AH80
6. AUTHOR(S) Phillip J. Hanes	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-SL-BA Aberdeen Proving Ground, MD 21005-5068	8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-738
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING / MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

There are many phenomena addressed by the vulnerability analysis community which are, in truth, time dependent. However, due to computational constraints, whether actual or historical, most such phenomena are treated in a manner that ignores or, at best, crudely approximates this time dependency. This report describes a method which could allow such dependencies to be added to existing vulnerability analysis software in a more physically realistic manner. It also describes a possible implementation of these ideas within a vulnerability analysis code.

14. SUBJECT TERMS event queues, vulnerability, time-dependent phenomena	15. NUMBER OF PAGES 19
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

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1. The Need for Time Dependency

There are numerous time dependent phenomena which must be addressed in the process of performing a vulnerability analysis on a given system. Many of these involve events that occur after the initial impact of the threat (e.g., leakage from fuel or hydraulic lines). Such post-impact events have been incorporated into some existing vulnerability methodologies.

There is, however, a class of time dependent effects which does not seem to have been incorporated into any vulnerability methodology in a physically realistic way. These effects take place in the microseconds immediately following a threat impact or detonation. They happen so quickly that they are usually treated simultaneously with the threat impact.

These phenomena include such things as buckling plates, aerosolization of fuel, punching holes in components, electric arcing, and so on. Since the sequence of most analyses is driven primarily by the geometry of the target, these effects are difficult to consider using current software. Therefore, the usual approach is to ignore such effects if they occur outside the normal flow of the geometry. For example, when determining whether a fire has started, most programs look for sparks along the ray trace which perforates a fuel cell but ignore sparks or incendiaries along nearby ray traces. Similarly, holes produced by one fragment are virtually always ignored when considering fragments coming later in time. Such short cuts may be expedient, but they ignore important information which could affect the results of the analysis.

It should be possible to incorporate such effects so that physical considerations (geometry, perforation, etc.) are driven by the order in which events occur. Doing so would allow a more physically realistic examination of synergistic effects.

2. Current Ray Tracing Paradigm (Geometry Driven)

Many vulnerability analyses performed today use ray tracing as their primary means of geometry interrogation. There are more sophisticated methods under development which could augment the use of rays, but most of these are not yet available. Furthermore, it is not likely that they will completely replace rays for vulnerability requirements, since many phenomena travel in straight lines when interacting with a target.

Therefore, since rays are used extensively and will probably continue to be highly useful in the foreseeable future, it seems necessary to continue improvements to software which depends on this capability. This reportdescribes the current use of rays for vulnerability analyses and then develops a method for time dependent ordering in the context of this description.

To the extent possible, implementation details for any particular ray tracing package or vulnerability analysis software are avoided in order to develop a more generic description of the capabilities envisioned. An application of these ideas to the Modular UNIX-based Vulnerability Estimation Suite (MUVES) [1] follows at the end of this report.

For those unfamiliar with ray tracing, a ray trace is a linear path through a geometric model (often called a "target description" in vulnerability analyses). Inside the computer, the geometric information for a ray trace is stored as a series of hit points, segment lengths, normal vectors, curvatures, and perhaps other values, depending on the data required by the analysis. The primary data structures contained in a ray trace might be visualized as shown in Figure 1, where each box represents a component hit by a ray trace through a target and the lines indicate the sequence in which they were hit.

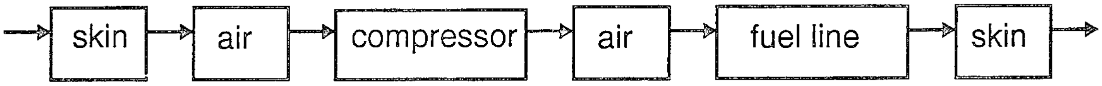

Figure 1. Ray Trace representation

In a vulnerability analysis, some energetic phenomenon (called a *threat*), whose propagation mechanics are governed by a set of equations (called *penetration equations* for armor-piercing munitions or fragments), travels along this path, interacting with the components encountered on the path, losing energy, and usually causing damage to the components. The process of computing the degradation and damage can be called *analyzing* a ray trace.

These ray trace segments are usually analyzed sequentially; that is, one ray trace is analyzed from beginning to end (or until the threat no longer has the capability

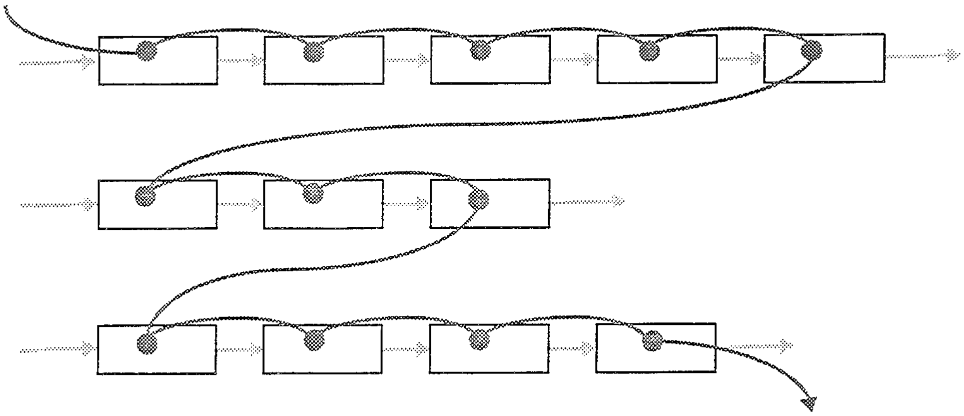

Figure 2. Normal sequence of ray trace analysis for three rays

to damage the target), and then the next ray trace is analyzed. This sequence is repeated until the entire collection of ray traces is fully analyzed. Using the previous representation of a ray trace, the sequence of analysis might be illustrated as shown in Figure 2.

Some modern vulnerability software supports ray tracing on demand rather than computing the collection of all possible rays before any analysis begins. While this is a significant improvement in both efficiency and realism, allowing the ray selection to be determined by computations during the course of the analysis, it does not necessarily introduce a time ordered approach to analyzing the ray traces.

3. Time Ordered Ray Sequencing (Event Driven)

In order to use these rays in some time dependent fashion, it is necessary to change the order in which they are processed. Conceptually, this is a fairly simple task; threat/component interactions are analyzed in the order in which they would happen in a real event. However, cleanly incorporating such a sequence in a program requires some finesse as well as a clear understanding of both the computer science issues and the vulnerability issues involved.

Figure 3 shows a possible sequence for a time ordered analysis of the same set of three ray traces introduced in Figure 2. In this figure, the dark line shows the time ordered sequence of analysis, and the circles represent *events* where the threat traveling along the ray trace impacts the component represented by the box containing the circle. Each event occurs at a particular time, *T*, some examples of which are shown in Figure 3. In this fashion, the software switches from one threat to the other while determining the effects of all the threats initiated during the analysis.

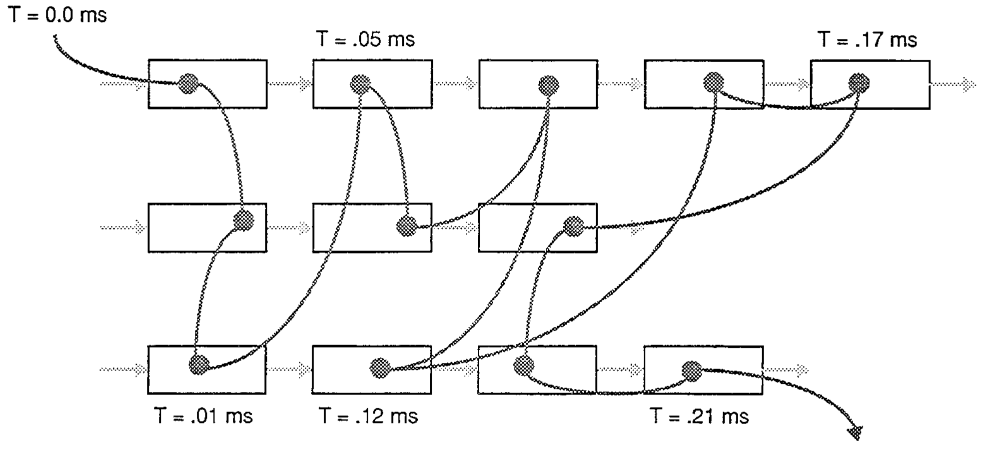

Figure 3: Time ordered sequence of ray trace analysis

Comparing Figure 3 with Figure 2 gives some insight concerning why this has not generally been implemented in vulnerability software. The sequence of events is confusing even for a small number of threats; for a large number of ray traces (a minimum of several hundred for a typical fragmenting threat), the complexity would scale up quickly. The software, in addition to keeping track of where it is in the collection of ray traces, must also keep track of *every* threat propagating along every ray trace at any given moment, since *a priori* there is no certainty which interaction will be performed next. This requirement alone was prohibitive for many years, since computer memory was not large enough to hold the required volume of information. Our goal is to perform these evaluations while keeping the complexity to a manageable level.

In order to implement this concept in a vulnerability code, it is necessary to introduce an abstraction called an *event queue.* An event queue is a list of events which are sorted in the order in which they occur. Thus, the first event is the first item encountered when traversing the list. When a new event is placed on the queue, it is inserted in its time dependent order--that is, after prior events but before later events. The interval between the events is not relevant, only the order in which they occur. As events are processed, they are removed from the queue, and new events may be placed on the queue as a result of other events. Thus, the event queue is a dynamic list which, at any time during the analysis, contains the set of events that are known to be pending.

Therefore, by thinking of the impact of a fragment on a component as an event, the spaghetti in Figure 3 can be sorted into a linear list of known events, much like the original simple concept mentioned at the beginning of this section. This type of event queue is shown in Figure 4 with a hypothetical operation on the first event. Note that this generates another event, which is then inserted onto the queue.

To implement these ideas in a vulnerability code, there are a number things which must be done in succession.

1. Trace all rays required to represent the effects of a given threat (e.g. a high-explosive munition). Note, this may include rays representing more than one damage mechanism (e.g. fragments and blast wave).
2. For each ray trace, compute the time of the *first* component impact (only) along that ray trace and insert the threat parameters and ray trace segment onto the event queue.
3. Pop the first threat/component interaction from the event queue and analyze the effects of that interaction.
4. As each event is analyzed, determine the time of the next impact *for that threat* (which will usually be along the same ray trace) and insert it onto the event queue. If the threat has run out of energy, discard the remainder of the ray trace. If the threat spawns one or more subsequent threats, perform steps 1 and 2 for the new threats.

5. Proceed to the next event on the queue and analyze it as in step 4. Repeat until there are no more events on the queue.

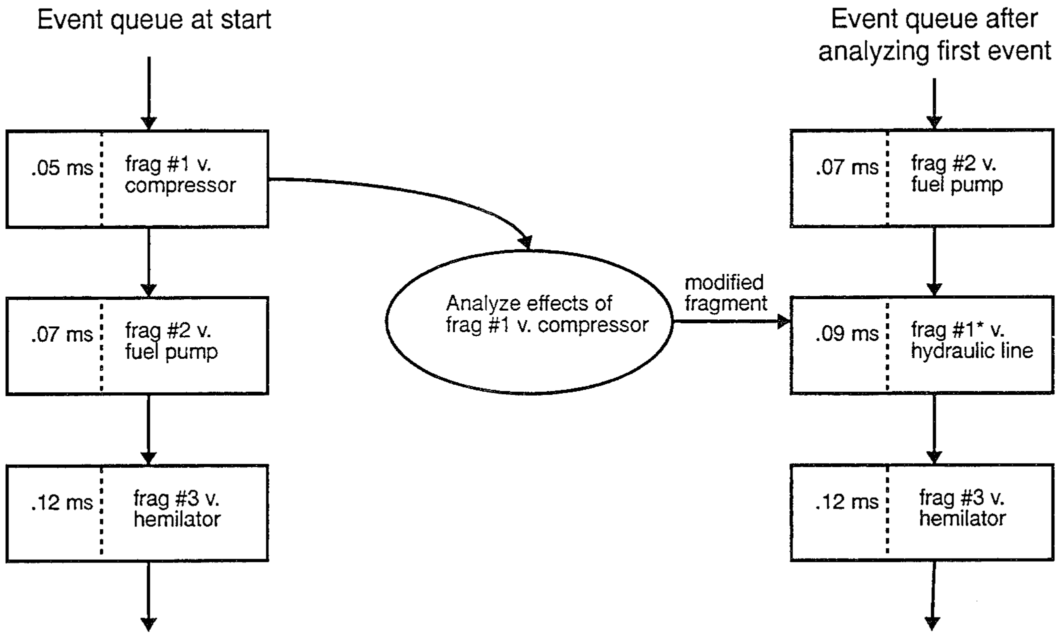

Figure 4. Event queue and results of analyzing the first event

By using data structures which contain both the component information and the threat information for a single event, the management headaches described earlier can be minimized, and the coordination of threat effects becomes virtually automatic.

It should be noted, however, that memory requirements will not be reduced by this method. A fairly large main memory will be required to perform these computations for anything other than trivial targets. Nevertheless, the resulting increase in physical realism should be worth the effort.

4. A Sample Application (MUVES)

In order to show how these ideas might be implemented in vulnerability software, this section develops minispecifications for a hypothetical burst module that might appear in the MUVES environment. The following example could be implemented using functions from the MUVES library and from the time sequence package defined in Appendix A.

This module assumes that some munition, perhaps a high explosive round, has burst. The decision regarding whether the round bursts is assumed to have been made elsewhere.

Burst module specification :

```
establish time of burst
determine number of fragments
for each fragment required to simulate burst
    determine parameters of fragment (must include direction vector)
    ray trace path of fragment
    determine time of first impact (from velocity and distance to component)
    attach threat parameters to component ray trace segment
    insert component onto event queue
while there are events in the event queue
    pop next event from the event queue
    determine appropriate module for threat/component interaction
    invoke interaction module
return (analysis is complete)
```

This is relatively straightforward; the principal requirement is the ability to determine the speed and direction of each fragment. Given the speed and direction, it is possible to determine the time of its impact and insert the interaction event onto the queue.

The next problem is to examine the interaction of a fragment with a component.

Fragment Interaction module specification :

```
perform perforation calculations
determine damage to component (if any) and store for later evaluation
if the fragment perforates
    determine parameters of degraded fragment
    * could deflect fragment at this point, if appropriate *
    assess immediate effects of perforation (holes, etc.)
    determine time of next impact
    attach threat parameters to component ray trace segment
    insert component onto event queue
else
    * could ricochet fragment at this point, if appropriate *

if the fragment spawns another threat (break up, for instance)
    determine parameters of new threat(s) (including direction vector)
    ray trace path of new threat(s)
    determine time of first impact
    attach threat parameters to component ray trace segment
    insert component onto event queue
return (burst module will select next event for analysis)
```

Although this paper uses a fragmenting effect to illustrate the use of a time sequence capability, this method could easily be extended to other threat phenomena, such as a blast wave. The principal requirement is the development of interaction modules to perform computations for each type of threat of interest. Note that the effects of all phenomena would be interleaved through the use of the event queue. This is closer to the real phenomenology and is thus a highly desirable feature of this methodology.

5. Conclusion

It seems possible to add time dependent phenomena to an existing vulnerability analysis code without radically changing its structure.

If the original software has been developed in a modular fashion, this capability could be added by implementing event queue modules and some trivial functions to determine time to impact for various threats. The remainder of the necessary operations should already exist, since they are all needed for current vulnerability analysis software.

Adding such a capability could significantly increase the capability of existing software to analyze the synergistic effects of threats on military systems.

6. References

[1] Phillip J. Hanes, Scott L. Henry, Gary S. Moss, Karen R. Murray, and Wendy A. Winner. “Modular UNIX-based Vulnerability Estimation Suite (MUVES) Analyst's Guide.” U.S. Army Ballistic Research Laboratory, BRL-MR-3954, Aberdeen Proving Ground, MD, December 1991.

Appendix: Time Sequence Interface Definition

What follows is an interface definition for a software library that provides the event queue capability described earlier in this document. This interface definition is written in the style used within the MUVES library.

<Ts.h> -- MUVES "Ts" (time sequence) package definitions

The "Ts" package allocates multiple time sequence queues (event queues) to be handled within MUVES. Generic pointers are inserted into an event queue in time dependent order. The content of the pointers is to be determined by the calling function; Ts neither uses nor examines these pointers. Its sole purpose is to return them to the caller in time sequence order.

typedef TsHandle

The TsHandle is a reference to a time sequence queue. This handle is required when inserting new items onto the queue and when requesting items from the queue. This allows calling functions to maintain distinct queues simultaneously. These may then be used for different purposes if necessary.

TsHandle TsInitQueue()

TsInitQueue() initializes the internal structures for a time sequence and returns a handle to that queue.

bool TsRemQueue(TsHandle queue)

TsRemQueue() clears the memory associated with a given event queue. It should be called whenever the calling function is finished with the event queue. Only empty queues will be accepted by TsRemQueue(); if there is anything in the queue, TsRemQueue() returns false; otherwise the memory is cleared and TsRemQueue() returns true.

void TsInsertEvent(TsHandle queue, double time, pointer data)

TsInsertEvent() inserts a generic data pointer into the time sequence referred to by "queue". The value "time" is used to determine the correct place in the sequence for insertion. Values are inserted in ascending order. The value "data" is a generic data pointer which may refer to any piece of data required by the calling function. The Ts package makes no assumptions about the contents of the pointer nor attempts to de-reference that pointer.

pointer TsGetNextEvent(TsHandle queue)

TsGetNextEvent() determines the next event (lowest time value) in the time sequence referred to by "queue" and returns the pointer associated with that time. The queue entry for that pointer is removed.

void TsRemEvent(TsHandle queue, pointer data)

TsRemEvent() removes an event from the time sequence referred to by “queue”. The value “data” is a generic data pointer which matches one of the data pointers already inserted onto the queue. If it does not match any existing data pointer, TsRemEvent() silently ignores the request.

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