Characterising, Explaining, and Exploiting the Approximate Nature of Static Analysis through Animation

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Abstract

This paper addresses the question: "How can animated visualisation be used to express interesting properties of static analysis?" The particular focus is upon static dependence analysis, but the approach adopted in the paper is applicable to other forms of static analysis. The challenge is twofold. First, there is the inherent difficultly of using animation, which is inherently dynamic, as a representation of static analysis, which is not. The paper shows one way in which this apparent contradiction can be overcome. Second, there is the harder challenge of ensuring that the animations so-produced correspond to features of genuine interest in the source code that are hard to visualize without animation.

To address these two challenges the paper shows how properties of static dependence analysis can be formulated in a manner suitable for animated visualisation. These formulations of dependence have been implemented and the results used to provide dependence visualisations of the structure of a set of C programs. All animations described in the paper are also viewable on-line.

1 Introduction

This paper addresses the question

> "How can animated visualisation be used to express interesting properties of static analysis?"

This question presents two related technical challenges and one obvious presentational challenge: how to depict the results of an implementation of source code analysis that employs animation in a paper. To address the presentational challenge the paper presents stills from the animations described, but all animations are also available on a complementary web page located at

`www.cs.loyola.edu/~binkley/scam06.html`

In addition, as an 'experimental curiosity', an example of one of the animations is available on the upper right hand corner of the paper as a flick-book animation. For optimal performance, this flick-book animation should be viewed on a single-sided version of the paper, though it renders adequately on the double-sided version of the paper in the proceedings. Flicking through the page corners from front to back reveals the animation that is used in the example discussed in Section 4.2. In the electronic form, repeated clicking on 'next page' also should give an impression of the animation.

The two related technical challenges that the paper addresses are to animate the static and to do so in a meaningful, non-trivial, manner. That is, to exploit the potential of animation, it is necessary to find aspects of static analysis that change over time; seeking the dynamic within the static. Furthermore, while it might be possible to resolve this apparent paradox by animating some *superficial* aspect of the static analysis, this would be of little practical use. Rather, it is necessary to construct the analysis, and the animation that brings it to life, in such a way that interesting features of the animation correspond to interesting and important properties of the source code. Furthermore, to be worthwhile, these important properties should be properties that could not be easily visualized without animation.

The essence of the thesis that lies at the heart of this paper is that the inherent approximate nature of static analysis can be used as the basis for a meaningful animated characterisation of the analysis. That is, static analysis typically employs a doctrine of safe approximation; in order to construct results that approximate answers to essentially undecidable questions, static analysis algorithms return answers that denote a safe approximation to the real (but generally undecidable answer).

For example, in pointer analysis, the set of identifiers to which a pointer variable may point cannot be precisely determined using static analysis [22, 32]. Therefore, pointer analyses [41, 43] return a safe approximation that contains the true points-to set, but may contain 'false positives'. Dependence analysis [19, 23, 24] employs a similar safe approximation strategy. It determines, not the true dependence relation between elements of a program, but rather, a weaker relation that is provably certain to contain the true relation. A similar doctrine of 'safe approximation' is adopted to other static analysis problems, for example constant propagation [10], calling context analysis [11, 28], and the construction of flow and call graphs [2, 21].

The increasing levels of approximation available to analysis approaches (usually at the cost of increased computational resource) form a suitable set of time series results, for which animation can be surprisingly illuminating. As the paper will show, such an 'animation of approximation' can yield more than mere insight into the effects of differing levels of approximation; it also imbues the analysis with an additional dimension of representation. This additional dimension can be used to reveal complex semantic structures in the source code. These structures are dynamic by nature and so it would be hard to visualize them without animation.

The necessarily approximate nature of static analysis, has recently led to approximation receiving such a warm embrace that some authors have even gone a step further: considering unsafe approximations [18, 27]. Such unsafe approximations may, despite their lack of safety, reveal important and useful properties of interest. Both work on safe approximation in static analysis, and more recent work on unsafe approximation, provide a wellspring of potential applications from which the animation of approximation approach may draw.

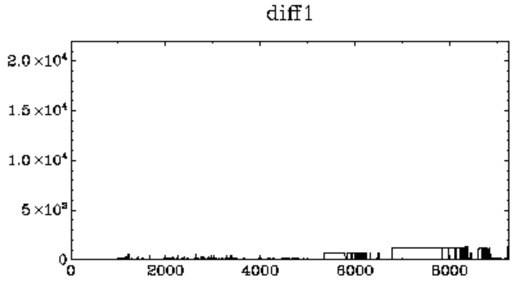
As a case study in the application of the animation of approximation approach, the paper considers the well-studied problems of slice-based dependence analysis [13, 23, 42]. Specifically, the case study considers the problem of visualizing the effects of different levels of call depth on static dependence analysis. The results show the way in which the level of dependence grows with increasing call depth. This reveals interesting dependence structures in the program such as the movement of dependence clusters as well as their formation.

The primary contributions of the paper are as follows:

1. The paper shows that the necessarily safe–but–approximate nature of static analysis can be visualized using animations that show increasing levels of precision of analysis

2. The paper presents the essential characteristics of such a visualisation, illustrating with a case study that formulates a problem in static dependence analysis as a sequence of approximations of monotonically increasing precision.

3. The paper reports results from the implementation of this formulation of dependence and its associated animation, presenting the application of the approach to 13 C programs, ranging from 1,744 to 13,188 LOC. The paper shows how interesting properties of the animations are related to interesting properties of the programs being animated.



The rest of this paper is organized as follows: Section 2 presents a general framework for animated visualisation of static analysis, while Section 3 illustrates the framework with the formulation of a specific animated visualisation of Call-Depth Dependence Analysis, implemented using program slicing. Section 4 presents results of an implementation of Call-Depth Dependence Analysis applied to a set of C programs. Section 5 presents related work and Section 6 concludes with directions for future work.

2 Animated Visualisation of Static Analysis

This section sets out a framework for animation of static analysis in more detail. It defines the terminology used to describe an instance of the application of the animation approach and defines the properties that such an instance may exhibit. These properties are characterised as those that are desirable in order to ensure that animation is both possible and meaningful and those that support certain forms of animation. First, some terminology is introduced that capture the foundations upon which the animation approach is built.

1. **Parameterization**
   There will be a parameter set, denoted π, which defines the behaviour of the static analysis with respect to the approximation. These parameters form the description that characterises the nature of the approximation.

2. **Approximation level**
   The result of an analysis for a particular instantiation of parameter values is not constrained: it may be, for example, a single numeric value, a set of values, or some form of data structure. For each possible instantiation of parameter values of π the static analysis will yield a potentially different result. The set of parameter value instantiations used in the animation will be termed the 'approximation levels'.

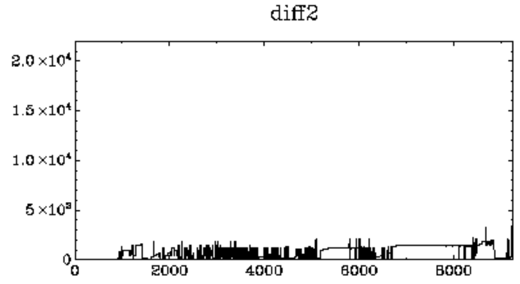
3. **Animation as a sequence of stills**
Animations are comprised of a sequence of ‘still images’ (stills) that are displayed over a series of time steps to create the illusion of continuous motion. In the approach to animation introduced in this paper, each still will correspond to the results of the analysis for a single approximation level. This makes it relatively easy to form a relationship between analysis results and their corresponding animation.

4. **Approximation System**
The term ‘approximation system’ will be used to denote the combination of parameter set π, static analysis formulation, approximation level set, and animation. The goal of the animation is to provide a moving depiction of properties of the static analysis of a subject program with respect to the approximation levels defined by choice of parameters in π.

There are a number of properties that should be enjoyed by an approximation system, in order for the animation to be meaningful. These ‘desirable properties’ ensure that it will be easy to associate each approximation level with a suitable still of the animation. They also aim to establish a framework in which it is likely that the visual properties of the animation correspond to well-defined and interesting semantic structures, implicitly denoted by the sequence of approximation levels. The desirable properties of an approximation system are

1. **Multiplicity**
Multiplicity is the most basic requirement of an approximation system. An approximation system is Multiplicit if it contains more than one approximation level. Of course, for most animations, ‘more than one’ is unlikely to be construed to mean merely two different approximation levels; animations tend to rely upon a larger multiplicity. However, there may be situations in which an oscillating animation, showing merely two approximation levels may have value and so the definition of multiplicity is so-constructed as to allow this.

2. **Visualizability**
An approximation system is Vizualizable if the analysis result of each approximation level is denotable by some value, derived from the outcome of the analysis, that can be visualized in some static graphic form. The nature of the value is left unspecified by the Visualizability constraint: the value need not be numeric, nor need it be scalar, but it has admit static visualisation as a still. Without this property is will be impossible to translate the outcome of a particular analysis to some aspect of a still in an animation, so animation in the form introduced by this paper would be impossible.



3. **Relatedness**
An approximation system is related if there exists a well-defined relationship between the interpretations placed upon the different approximation levels. This property is important to allow some meaning to be placed on the animation. The animation uses the passage of time to indicate a relationship between the different choices of approximation level. Therefore, it should be possible to establish a connection between the passage of time and the approximation level.

4. **Ordinality**
An approximation system is ordinal if the set of approximation levels can be ordered by a total ordering relation. This means that the results obtained from different approximation levels can be animated with animation order corresponding to approximation level. Ordinality subsumes Relatedness, since an ordering is, by definition, a relation. Clearly it would be most attractive to have an ordinal approximation system, since this naturally maps onto a sequence of stills in the animation. However, there may be useful animations that merely respect the (weaker) Relatedness property.

As well as these desirable properties, there are also other properties that an approximation system may possess and that naturally suggest particular forms of animation approach. As research in this area progresses, it is likely that more such properties will be defined. The list below is an initial attempt to establish a starting point for research into the construction of a more complete list of properties.

1. **Monotonicity**
An approximation system is monotonic if the values that result from the analysis at different approximation levels are either monotonically increasing or decreasing in the ordering imposed by the Property 4 defined above. Monotonicity is desirable for ease of comprehension. Monotonic approximation results can be depicted in an animation that progressively moves across the screen (from left to right, for example). This can often add to the expressiveness of the animation. Monotonicity subsumes Ordinality and therefore Relatedness.

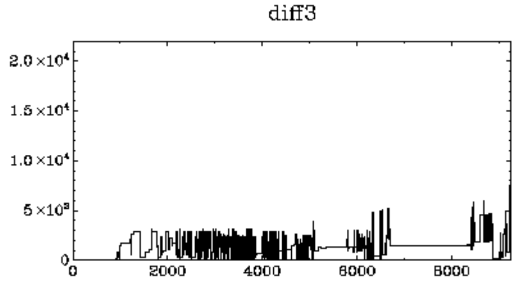
2. **Discreteness**
   An approximation system is discrete if the set of possible values that can result from the analysis for each approximation level are finitely enumerable. This property is useful because the stills in an animation are naturally pixelized. While it will be possible to visualize continuous approximation systems by digitization, it is more likely that discrete approximation systems will map seamlessly onto the stills of the animation.

3. **Sharpness**
   An approximation system is sharp if, for all stills, S and associated approximation levels L, there exists a one-to-one (bijective) mapping between the pixel values in S and the individual components of the value produced by the analysis for L. Clearly, Sharpness subsumes Discreteness since each still contains a finitely enumerable set of pixels. In a Discrete approximation system every dot in every still of the animation *means* something concrete and well-defined in analysis of the program.

3 Animation of Call-Depth Slicing

This section uses *Call depth k-truncated slicing*, a form of approximate static interprocedural dependence analysis, to illustrate the animation approach for static analysis advocated in this paper. A k-truncated slice applies a variant of k-limiting in the construction of an interprocedural slices. Informally, a k-truncated slice, for some chosen value of k, considers only up to k levels of call depth for called or calling procedures. This leads to a series of approximation levels based on choices of the parameter k. Note that this technique is different than k-limited context slicing [28], which is calling-context sensitive up to depth k and then becomes context-insensitive for larger call depths (and thus imprecise but safe). A k-truncated slice is always context-sensitive but does not include anything beyond call-depth k (thus, it is precise but can be considered unsafe until the limiting value of k is reached).

In terms of the framework for animation introduced in the previous section, k-truncating produces an approximation system where the parameter set π is simply the choice of k. The approximation levels therefore correspond to choices of limiting values k, which determine the depth of procedure calls. Each still of the animation is visualized using an Monotone Slice-size Graph (MSG) [9]. A MSG is a graph of slice size, plotted for monotonically increasing size. That is, slices are sorted according to increasing (non-truncated) slice size and the sizes are plotted on the vertical axis against slice number in sorted order on the horizontal axis.



The rest of this section formalizes k-truncated slicing, the MSG used in the animation, and finally considers which of the properties from Section 2 the animation has. It is well known that precise interprocedural slicing requires more than simple transitive closure of a program's dependence relations, because such closure fails to account for *calling context*: when slicing into Procedure Q from a call in Procedure P, a precise slice only "returns" to P and not all callers of Q [23, 42]. Precise interprocedural slices can be computed using a two pass algorithm over the System Dependence Graph (SDG) [23]. For the slice taken with respect to SDG vertex v, the vertices (statements) identified as "in the slice" by this algorithm can be formalized as those having an *interprocedurally realizable path* to v [35].

To define k-truncated slices, a simplified version of these paths is sufficient. This definition makes use of transitive dependence edges in the SDG referred to as *summary edges* [23], which represent transitive dependence paths in the SDG from parameter initial values to parameter final values. In greater detail, a summary edge connects the SDG vertex representing an actual parameter's initial value to the vertex representing a (possibly different) actual parameter's result value if there exists a path in the called procedure connecting the vertices of the corresponding formal parameters. This path may include summary edges. Summary edges allow algorithms to identify realizable paths though a procedure without "descending" into it.

Informally, a path is realizable if when traversing the path from call-site c, the analysis only returns to call-site c after processing the called procedure. Such paths can be described using context-free language reachability as introduced by Reps [35]. This approach views the SDG as a finite automaton where each edge is labeled by one of three symbols. The string induced by a realizable path must be accepted by a regular language. Edges in the SDG are labeled according to their source and target vertices:

- "Call edges" from a call vertex to the entry vertex of the called procedure are labeled "(".

- "Parameter-in edges" from the vertex representing an actual parameter's initial vertex to the vertex representing the corresponding formal are also labeled with "(".

- "Parameter-out edges" from the vertex representing the final value of a formal parameter to the corresponding actual at each call-site are labeled with ")".
- All other edges (including summary edges) are labeled with ϵ.

Every SDG path induces a word over $\{(,)\}$ obtained by concatenating the labels of the edges on the path. A path is an intraprocedural path if it induces the empty word ϵ. Such paths have their start and end vertex in the same procedure. Interprocedural realizable paths are built from two parts formalized as follows:

Definition 1 (Realizable Path)
A path is an interprocedurally *right-balanced* path if it is a word of the context-free language defined by $R \rightarrow R(\mid \epsilon$. A path is an interprocedurally *left-balanced* path if it is a word of the context-free language defined by $L \rightarrow)L \mid \epsilon$. Combined, an *interprocedurally realizable path* starts as a left-balanced path and ends as a right-balanced path: $I \rightarrow LR$

This definition is simpler that the original [35] because it assumes the existence of summary edges in the SDG (summary edges themselves can be defined and computed using the more complex definition of realizable paths).

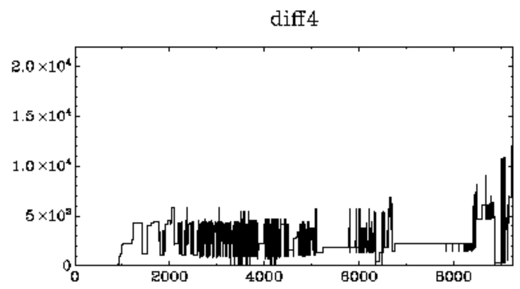
Definition 2 (Slice in an SDG)
The (*backward*) *slice* $S(v)$ of an SDG $G = (V, E)$, taken with respect to vertex $v \in V$, consists of all vertices on which v (transitively) depends via an interprocedural realizable path.

The set of vertices having an interprocedural realizable path to Vertex v can be efficiently computed using the two pass algorithm of Horwitz et al., which first slices from v *ascending* into calling procedures (*i.e.*, traverse paths along R), and then from all visited vertices *descending* (*i.e.*, along L) into called procedures [23, 36]. Summary edges are used by the algorithm to "pass-through" calls in a context sensitive manner.

Finally, a k-truncated interprocedural slice restricts the interprocedurally realizable paths to no more than k calls up or down.

Definition 3 (k-truncated Slice)
Let w_p be the induced word for interprocedurally realizable path p, $up(w_p)$ the number of "(" in w_p and $down(w_p)$ the number of ")" in w_p. The *k-truncated slice* $S_k(v)$ of SDG $G = (V, E)$ taken with respect to vertex $v \in V$ consists of all vertices on which v (transitively) depends via an interprocedural realizable path p where $up(w_p) \leq k$ and $down(w_p) \leq k$.

The Horwitz et al., algorithm essentially traverses dependence edges in an un-order fashion. A modification of



this algorithm, which provides an efficient method to compute k-truncated slices, is presented in Figure 1. During the first pass, the traversal of parameter-out edges (dependences from a call-site to the called procedure) is delayed to the second pass (as in the original algorithm). In order to process the SDG level by level, the traversal of parameter-in and call edges (dependences from call-sites in calling procedures to the current procedure) is delayed to the next iteration within the first pass. Because only k iterations are done, the slice will not ascend along more than k levels of call depth. The second pass starts with the traversal of the edges that have been delayed in the first pass. The traversal of parameter-out edges encountered is delayed to the next iteration within the second pass. Parameter-in and call edges are not traversed in the second pass (as in the original algorithm).

Finally, this section introduces the visualization experimented with in the next section, which is based on the Monotone Slice-size Graphs (MSGs) computed using k-truncated slices. A k-truncated MSG is a graph of truncated slice sizes which are sorted according to increasing non-truncated slice size. In order to show that the k-truncated approximation system is monotonic, the ordering relation on k truncated MSGs must be defined. For each value of k, the k-truncating approximation produces a set of slice sizes (one for each slice point). In each still of the animation, these are ordered according to the order defined by the final still (the non approximate MSG). To break ties in the ordering, the penultimate still is used. Ties in the penultimate still are resolved by the previous still and so on. The only remaining ties are those that exist through all stills of the animation. Therefore each MSG is composed of a sequence of v values $s_1, \ldots, s_v$, where v is the number of program points for which slices are constructed. The ordering relation on two such sequences S_1 and S_2 is defined as

$$S_1 \leq S_2 \text{ iff } \forall i.1 \leq i \leq n.S_1(i) \leq S_2(i).$$

That is, the arithmetic inequality $\leq$ is simply distributed through the sequence. A sequence of slice sizes, S_1 is below another, S_2 in the ordering if all the elements of S_1 are below the corresponding element of S_2.

In the case of k-truncated slices, it is easy to show that the size of a slice for a chosen program point cannot de-

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Input: $G = (V, E)$ the given SDG
        $v \in V$ the given slicing criterion
        $k$ the given limit
Output: $S \subseteq V$ the slice for the criterion $v$
$W^{\text{up}} = \{v\}, W^{\text{down}} = \emptyset, S = \{v\}$
first pass, ascending slice
$k_1 = 0$
while $W^{\text{up}} \neq \emptyset$ and $k_1 \leq k$ do
  $k_1 = k_1 + 1$
  $W = W^{\text{up}}$
  $W^{\text{up}} = \emptyset$
  while $W \neq \emptyset$ work-list is not empty do
    $W = W/\{v\}$ remove one element from the work-list
    $S = S \cup \{v\}$
    foreach $u \rightarrow v \in E$ do
      if $u \notin S$ then
        if $u \rightarrow v$ is a parameter-out edge ($u \overset{\text{po}}{\rightarrow} v$) then
          delay further traversal until second pass
          $W^{\text{down}} = W^{\text{down}} \cup \{u\}$
        elsif $u \rightarrow v$ is a parameter-in
            or call edge ($u \overset{\text{pi,cl}}{\rightarrow} v$) then
          traversal will continue in the next iteration
          $W^{\text{up}} = W^{\text{up}} \cup \{u\}$
        else
          $W = W \cup \{u\}$
second pass, descending slice
$k_2 = 0$
while $W^{\text{down}} \neq \emptyset$ and $k_2 \leq k$ do
  $k_2 = k_2 + 1$
  $W = W^{\text{down}}$
  $W^{\text{down}} = \emptyset$
  while $W \neq \emptyset$ work-list is not empty do
    $W = W/\{v\}$ remove one element from the work-list
    $S = S \cup \{v\}$
    foreach $u \rightarrow v \in E$ do
      if $u \notin S$ then
        if $u \rightarrow v$ is a parameter-out edge ($u \overset{\text{po}}{\rightarrow} v$) then
          traversal will continue in the next iteration
          $W^{\text{down}} = W^{\text{down}} \cup \{u\}$
        elsif $u \rightharpoonup v$ is not a parameter-in
            or call edge ($u \overset{\text{pi,cl}}{\rightarrow} v$) then
          $W = W \cup \{u\}$
return $S$ the set of all visited vertices
```

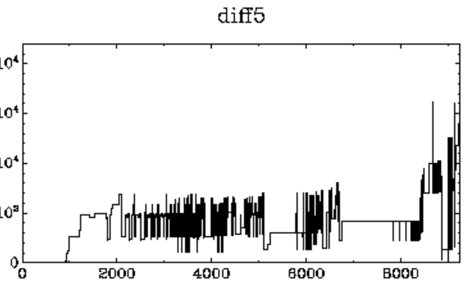
Figure 1. k-truncated Slicing

crease as the value of k increases and so the slice sequences produced by increasing values of k is monotonic.

The k-truncating approximation, enjoys many (but not all) of the properties outlined in the previous section. Specifically, it is

1. **Multiplicit**, providing that $k > 0$, which it is for all programs except (degenerate) programs with no calls.

2. **Vizualizable**, because the MSG is a visualization.



3. **Monotonic** as described above (and therefore ordinal and related).

4. **Discrete**, because the value for a given approximation level, determined by parameter k, is a set of slice sizes, each of which is an integer. A sequence of integers is a discrete quality.

However the k-truncating approximation system is not sharp, in general, since there will be more slices in a typical program than pixels on a screen. However, for small programs where there are fewer program points than pixels on the viewing screen, the k-truncating approach is also sharp, meaning that every pixel in every animation, corresponds to a real value in the static analysis (in this case an approximate slice of the program). However, for larger programs, several slices will become merged into a single pixel.

4 Results from Experiments with k-Truncated Slicing

This section applies the example k-truncating animation to a suite of example C programs and shows how these animations can be used to reveal interesting properties of the static analysis of the programs. For each program P, the slice $S_k(v)$ was computed for each $k < 14$ starting from all vertices v in the SDG that correspond to source code (similar to other studies [12, 9, 28]). For all the programs studied, when $k \geq 14$, $S_k(v) = S_{k+1}(v)$.

4.1 Programs Studied

The programs studied are a suite used in previous evaluations of dependence analysis [28, 29, 31]. The programs stem from two different sources: ctags and diff are GNU programs. The rest are from the benchmark database of the PROLANGS Analysis Framework (PAF) [38]. The details of the analyzed programs are shown in Table 1 where the 'LOC' column shows lines-of-code (measured via wc -l), the 'proc.' column the number of procedures and the 'vertices' and 'edges' columns show the number of vertices and edges in the SDG. The last column shows the number of slices computed for each k.

	LOC	proc.	vertices	edges	slices
agrep	3,968	90	11,922	35,713	5,617
ansitape	1,744	76	6,733	18,083	1,713
assembler	3,178	685	13,393	97,908	3,575
bison	8,313	161	25,485	84,794	7,489
cdecl	3,879	53	5,992	17,322	2,644
compiler	2,402	49	15,195	45,631	3,005
ctags	2,933	101	10,042	24,854	2,604
diff	13,188	181	46,990	471,395	9,259
flex	7,640	121	38,508	235,687	5,789
football	2,261	73	8,850	30,474	4,149
gnugo	3,305	38	3,875	10,657	2,317
rolo	5,717	170	37,839	264,922	5,401
simulator	4,476	283	9,143	22,138	4,871
average	4,846	160	17,997	105,582	4,495

Table 1. Details of the test programs

4.2 Animation Results

Of course, it is hard to show animations in a paper (all animations can be found on the web page). However, because the MSG animation is monotonic, an impression for the animation can be obtained using a grey scale approximation. In essence, older stills appear in lighter grey in the approximation. (As if they were shown in order, but were slow to fade from the viewing window.) This approximation would not work for a non-monotonic animation as the new images would overlap the older in ways that would make the view useless. For six of the programs shown in Table 1, the grey scale animation approximations are shown in Figure 2.

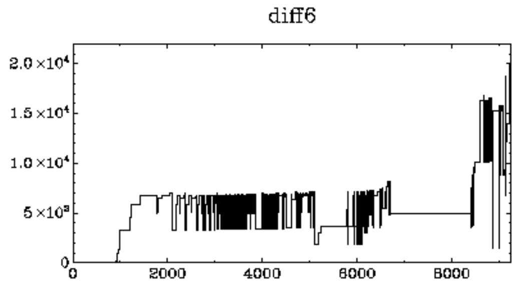
To give an attempt at a 'moving image impression' of the animation in this paper, the animation of the program diff (Line 8 of Table 1) can be seen as a *"flick-book"* animation on the upper right corners of this paper.

4.3 Some Interesting Animation Features

This section briefly illustrates the way in which the animation of static analysis can shed light on properties of the static analysis that can be seen in animations much more clearly than in static visualization form. As an example consider the animation of the program diff, which is shown in 'flick-book' animation throughout the paper. This animation reveals the movement of a plateau on the right side of the animation. The plateau exists in every still and it rises upward as k increases.

The plateau runs from approximately slice number 7000 through to slice number 8200. Closer examination reveled that this plateau is actually made of several almost identical plateaus. Visual queues exist for this in the middle of the animation (stills diff4 and diff5) in the vertical lines that drop down from the plateau before 'catching up'.

Each of these separate plateaus comes from a function whose slices include the same statements. The largest is



from the function regex_compile, which compiles regular expression patterns. Just under two thirds of the slices are taken with respect to statements from regex_compile. Any set of statements from a single procedure, such as the ones from regex_compile, that have the same slices when k is zero, will, by construction, have the same size slice as k increases. Thus, in the animation there is a flat plateau that "rises" during the animation.

In this way, it can be seen that the movement of the plateau corresponds to the presence of a large intraprocedural connected component. This is not just a dependence cluster (which can be viewed by static visualization [9]) it is a dependence cluster that is formed by one large knot of code within a single procedure. This corresponds to the way in which the plateau tends to 'rise as one' as it moves through the animation. By contrast, other dependence clusters form gradually as the animation proceeds.

The animation also reveals the formation of a long plateau, running from slices 1000 to 4000 as animation proceeds. Because the animation is not sharp, it is not possible to visually see that this plateau is in fact a plateau from 1000 to 2000 and then a very gradual rise over the next 2000 slices (slice 4000 is less than 1% larger than slice 2000). Although different, these slices share over 99% of the same code, and thus this loss of sharpness has potential advantages.

Focusing in on the first 1000 slices of the plateau, the animation shows the merging of a collection of sub-plateaus. Looking at the source code, these slices come from 38 functions, four of which account for just under two-thirds of the slices. The call sub-graph for these functions contains one self recursive and one pair of mutually recursive functions. Thus as k increases, sub-plateaus should merge together. The animation shows this formation and thus suggests the overall structure of the code. The four plateaus have fully formed in diff5 and begin merging in the later stills (*e.g.*, in diff6 the latter two have merged).

The animation reveals how large dependence clusters depend on intra- and interprocedural dependence clusters. It clarifies that the connection between the various parts of a program can only be observed based on the interprocedural behavior along multiple levels of call depth.

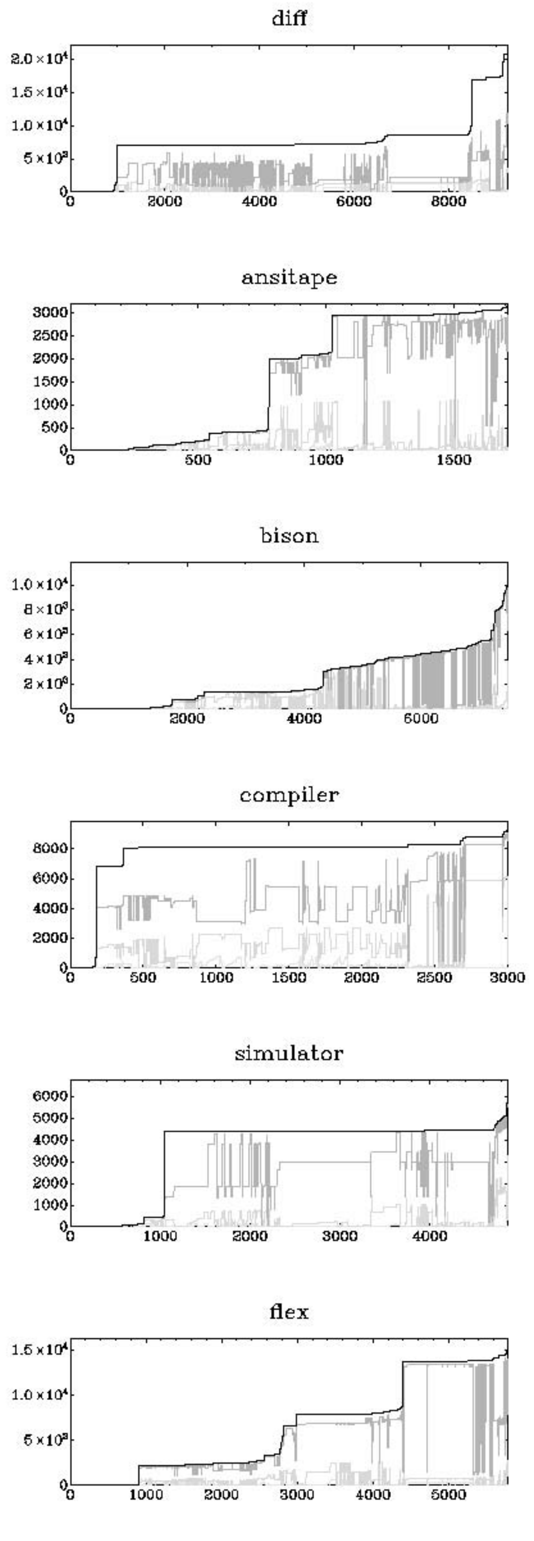
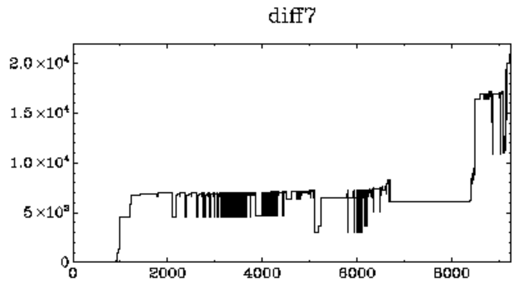


Figure 2. Gray scale approximations for six MSG animations.



5 Related Work

Software Visualization [39, 16] has a long history. However most visualizations are static (*e.g.*, Ball and Eick [7] describe different approaches to visualize static and dynamic software structures). This can also be referred to as *program visualization*. The value of dynamic visualization (*i.e.*, animation) is mostly seen in algorithm visualization or *algorithm animation*, who's goal is to explain the mechanisms that underpin the algorithms concerned. For example, Brown's work describes a toolbox to support programmers in the construction of hand crafted animations [14]. Animations are also often used in (visual) debugging, where the state of the debugged program is animated to visualize the change from statement to statement. A recent example is DDD [44]. To the authors' knowledge, animations have rarely been used to visualize the *results* of static program analysis – in contrast to their more common use in, for example, algorithm animation which would visualize the algorithms' execution. Such approaches often visualize and animate graphs (*e.g.*, the GEVOL system that visualizes the graphical evolution of software, which also uses a flip-book animation [15]).

Unlike the work reported in the present paper, the overwhelming majority of previous work on visualisation has concerned isolated still images, not animation. However, there has been previous work on virtual reality environments [26, 25]. In such work, the virtual environment is animatory. Unlike the work presented in the present paper, however, this previous work is immersive (following the principle of immersion in virtual reality). The animation users, is immersed in a virtual world in which objects serve as metaphors for source code constructions. Therefore, the animation exists as a result of the need for movement of the viewers' point of reference; it does not represent change properties of the source code.

There has also been previous work on properties of visualisations (for example [34]), with similar goals as that set out in Section 2 of the present paper. However, this previous work has tended to focus almost exclusively on non-animatory visualization, and no previous work has concerned properties of animations of static source code analysis.

Binkley and Harman used slicing to visualize dependence clusters [9]. They introduced the MSG, used in the animations reported upon here; the MSG of Binkley and Harman corresponds to the final still in each of the animations described in the present paper.

The present paper used dependence visualisation and slicing as a focus for the case study in animation of static dependence. Current approaches to slicing technology visualize results directly in the source code. Some approaches use navigational aids or restricted forms of slicing to improve the visualization [3, 17, 40]. Visualizations of slices can be distinguished in graphical and textual visualizations. The SeeSlice slicing tool [6] visualize slices not through source code but with an abstraction representing characters as single pixels.

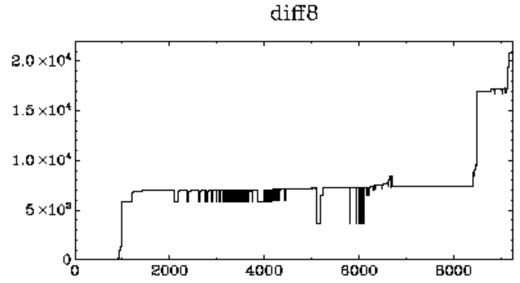
Other approaches to visualisation of dependence visualize the underlying dependence graph [8, 4, 20, 37, 30], however, most authors report that such visualizations become unmanageably large as the size of the systems visualized increases. One advantage of the animation approach introduced in the present paper is the way in which scalability is achieved naturally and only at the expense of property of sharpness.

The animation used in the case study in the present paper was based on the concept of calling context. The effects on calling context on slicing has been previously studied (but without animation). Some studies examine the tradeoff between precision and speed for context-sensitives vs. -insensitive slicing [5, 1, 33, 28, 11]. Krinke [31] has studied the effects of restricting the calling context to a specific call stack.

6 Conclusion and Future Work

This paper has introduced an approach to the animation of static source code analysis that exploits the unavoidable approximate nature of static analysis. The approximate nature of static analysis is used to resolve the apparent contradiction at the heart of any attempt to animate (which is inherently dynamic) static analysis (which is inherently static).

The paper introduced a framework for defining approaches to animation of static analysis, based upon stills that correspond to levels of approximation available to the analysis. The paper also presented a case study in the application of this framework to dependence analysis. Results were reported from the implementation of this approach and its application to 13 C programs. The results indicate that the animation is not only interesting but also that it illuminates several properties of the dependence structure of the programs that would be hard to visualize without animation. Future work will consider the application the animation framework to other forms of static analysis, such as pointer analysis and context sensitivity.



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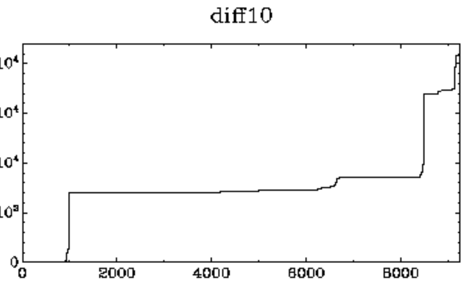

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