Ginseng User's Guide

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1 Overview

Ginseng transforms C programs into updateable C programs that can be updated on the fly in a safe manner. The compiler handles two tasks. First, it compiles programs to be dynamically updateable. In particular, programs are compiled so that when dynamically patched with replacement functions, existing code will be able to call the new versions. In addition, when a type is updated, existing values of that type must be transformed to have the new type's representation, in order to be compatible with the new code. Code is compiled to notice when a typed value is out of date, and to then apply the necessary transformation function. Second, the compiler uses a suite of analyses to ensure that updates are always type-safe, even when changes are made to function prototypes or type definitions. The basic idea is to examine the program to discover assumptions made about the types of updateable entities (i.e., functions or data) in the continuation of each program point. These assumptions become constraints on the timing of updates. For a detailed description of the compiler see [5]. **Ginseng** is based on the CIL framework [6], and uses Banshee [1] for constraint solving.

Section 2 lays out the installation procedure for our compiler. Since **Ginseng** works on single-source programs, applications consisting of multiple source files have to first be merged into a single source file. The merging procedure is explained in Section 3. Section 4 describes modifications that have to be made to C programs before handing them over to **Ginseng**. Section 6 covers the safety analysis step of the compiler, along with warning/error messages, how to interpret and how to fix them. Section 9 describes the dynamic patch generator. Section 10 presents a simple yet realistic example of using **Ginseng** to perform on-the-fly software evolution for a linked list.

2 Installation

First, extract the distribution

```
$ tar xzvf ginseng.tar.gz
```

You will need `ocaml 3.08` or later in order to build **Ginseng**. **Ginseng** seems to work with `gcc 3.3`, `gcc 3.4` and `gcc 4.0`, but has been most thoroughly tested with `gcc 3.4`, hence this is the prefered `gcc` version.

It should build out of the box on Linux and Mac. On *BSD, replace `make` with `gmake`. Now you can do the proper build

```
$ cd ginseng/cil

$ ./configure; make
```

3 Merging programs

Ginseng performs *whole-program* analysis and transformation. That is, the program to be analyzed and compiled has to consist of one source file. In most cases applications consist of multiple source files that are compiled indepedently and linked together, so we first need to "merge" all source files into one.

3.1 Prerequisites

Ginseng performs a semantics preserving, source-to-source transformation of C programs, turning them into updateable C programs. Therefore, before compiling with **Ginseng**, we must be sure the original, unmodified application

performs as expected. The application must compile using the normal C compiler (usually `gcc`), so the first step in constructing updateable programs is to build the application (usually `make`) and make sure it passes the compiler and linker alright. Ideally, the application comes with regression tests, so make sure it passes the tests as well.

3.2 Merging using CIL

We use the CIL merger `http://manju.cs.berkeley.edu/cil/merger.html` for merging all source files into one single file. Since **Ginseng** is built on top of CIL, the CIL merger is already included in your distribution. The CIL merger can be used as indicated in the guide at the URL above, but we had limited success with that approach. Instead, we use these two simple steps: (1) Invoke

```
$ make CC=<path to DSU compiler>/cil/bin/cilly --trueobj --save-temps --merge
```

on the application; CIL will write preprocessed files into files with the `.o_saved.c` extension. (2) Invoke CIL in merge mode

```
$ CILLY_DONT_COMPILE_AFTER_MERGE=1 <path_to>cil/bin/cilly --merge --keepmerged -o App.o `find
.  -name saved.c`
```

The resulting combined one-source is in `App.o_comb.c`, and it is this file that you will feed to **Ginseng**. The resulting object file is in `App.o_comb.o`; it is used for checking the correctness of merging, see Section 3.3. Note: for projects using `automake`

```
$ make CC='<path_to>/cil/bin/cilly --trueobj --merge --save-temps' CCLD='echo'
```

seems to do a good job at generating the preprocessed `.o_saved.c` files.

If there is an inconsistency between declaration and definition, the CIL merger will fail. For example, if `file1.c` contains a declaration

```
extern int foo;
```

and `file2.c` defines `foo` as

```
long foo;
```

the merger will fail with an error like

```
file2.c:1: Error: Incompatible declaration for foo.
 Previous was at file1.c:1 (different integer types int  and long )}
```

Such inconsistencies must be solved manually; in this case by changing `file1.c` to have a proper declaration for `foo` i.e.,

```
extern long foo;
```

3.3 Checking the merged source

The CIL merger is supposed to produce a single source file equivalent to the original source bundle, but there are no formal guarantees for this. Therefore, before feeding the merged source to **Ginseng**, link the `.o_comb.o` file the same way it would be original sources would be linked, and run the regression tests as indicated in 3.1. This should be fairly trivial, and it normally entails linking the `App.o_comb.o` and running the application test suite on the resulting executable.

4 Preparing sources

After merging, the resulting source file is almost ready to be passed to **Ginseng**. There are a few things the user has to inform **Ginseng** about: where the update points are, which loops ought to be extracted, which functions act like `malloc`. These "notes to the compiler" take the form of `#pragma` directives that the user annotates the source code with, and **Ginseng** in turn will pick them up.

4.1 Specifying update points

We define a *quiescent point* in the program as one at which there are no partially-completed transactions, and all global state is consistent. Dynamic updates are best applied at such quiescent points, and preferably those that are stable throughout a system's lifetime. If the application is structured around an event processing loop, the end of the loop defines a stable quiescent point: there are no pending function calls, little or no data on the stack, and the global state is consistent. Once the user has identified quiescent points in the program flow, an update point can be specified by inserting a call to the update function at that point:

```
...
__DSU_update();
...
```

Establishing an update point in the (infinite) event loop is described in Section 4.2.1.

4.2 Code extraction

Ginseng cannot replace code on the stack, but can replace functions (using function indirection). Thus, to replace code on the stack, we have to "extract" that piece of code in a separate function.

This usually comes in handy when an update cannot be applied at a particular point because the patch changes types or functions which are on the stack at that point. The user can request code extraction as indicated in Figure 1; first, delimit the code to be extracted using curly braces, add a label name in front of the scope (e.g., `FOO`), and finally, at the beginning of the file, add a `#pragma __DSU_extract("XT_FOO")` to direct **Ginseng** that the `FOO` block should be extracted.

Original program	**Program prepared for code extraction**

`...`
`f();`
`g();`
`...`
	`#pragma __DSU_extract("XT_FOO")`
	
	`...`
	`  FOO: {`
	`    f();`
	`    g();`
	`  }`
	`...`

Figure 1: Code extraction.

4.2.1 Loop extraction

Ginseng supports a similar mechanism for extracting loop bodies. This is useful when the application is structured around an infinite event loop. The user can request loop extraction as indicated in Figure 2: first, label the loop to be extracted (in this case, `L`), then add a `#pragma __DSU_loop("L")` at the top of the file to inform **Ginseng** about extracting this loop.

Original program	**Program prepared for loop extraction**

`...`
`  while (1) {`
`    ...`
`  }`
`...`
	`  #pragma __DSU_loop("L")`
	`  ...`
	`    L:while (1) {`
	`      ...`
	`    }`
	`  ...`

Figure 2: Loop extraction.

To specify an update point at the end of the loop, use `#pragma __DSU_loopupd("L")` instead. **Ginseng** will automatically insert a `__DSU_update()` in the extracted loop.

4.3 `Malloc` lookalikes

The safety analysis part of **Ginseng** has to treat `malloc` and other memory allocation functions specially, since these functions are used to construct abstract type values (see Section 4 of [5]). **Ginseng** recognizes `malloc` and `alloca` by default, but sometimes the applications use custom memory allocators, hence the names of allocation functions has to be communicated to the compiler using `#pragma __DSU_malloc("function_name")`. For instance, OpenSSH uses a custom function for memory allocation (`xmalloc`), so the user would have to notify **Ginseng** as follows:

```
#pragma __DSU_malloc("xmalloc")
```

4.4 Overriding the analysis

Since the safety analysis in **Ginseng** is conservative, it might deem types non-updatable, even though the programmer knows the types are used in a safe manner. Classical examples are conversions to and from `void *`. The programmer can choose to override the analysis and "force" types updateable by using the directive:

```
#pragma  __DSU_FORCE_UPDATABLE("type_name")
```

Conversely, a

```
#pragma  __DSU_FORCE_NONUPDATABLE("type_name")
```

directive is provided for effectively forcing a type non-updateable; this is useful when the programmer knows the type representation is unlikely to change in future versions, or when type representations are fixed (e.g., hardware-mapped structures). See Section 6 for details.

5 Compiler flags

Flag	Values	Description
Operating modes		
`--doupdate`		Mandatory option for enabling **Ginseng**
`--dosemdiff`		Compiler operates in *AST diff* mode, described at large in [2]; takes two `.c` input files and prints out the AST differences
`--dopatchgeneration`		Compiler operates in patch generation mode; takes two `.c` input files and, depending on the value of `--type-transformers`, generates auto-patches or type transformer files
`--patchmode`		Compiler operates in patch compilation mode; takes a `.patch.c` input files and generates a `.patch.cil.c`
`--testmode`		Compiler operates in test mode. Seldom used.
`--printversiondata`		Dump the contents of the `.vd` file specified in `--versiondata-in`
Ginseng options		
`--update-points`		Controls speculative update points insertion
	`full`	insert speculative update points after all statements
	`returnonly`	insert speculative update points only before `return` keywords
	`none`	no speculative update points are inserted
`--effect-printing`		Controls inferred effect printing
	`full`	print effects (as source code comments) at each program point. Note that for large programs this might take a long time and the generated output (i.e., annotated program) can be quite large.
	`functions`	print effects around function signatures only
	`differential`	instead of printing full effects, print only the differences from the previous statement; useful for large programs where effect sets can be quite large

	types none	effects are not printed
--annotate-fun	<function-name>	Print effect annotations according to the --update-points flag, but for the specified function only.
--gvar-types		Auto-generate unique named types for each global variable
--no-static-conabs		Prevent con/abs functions from being static inline
--versiondata-in		Read the version data from this file. Mandatory in patch compilation mode or when --printversiondata is specified
--versiondata-out		Write the version data to this file. Mandatory in normal and patch compilation modes

Analysis options		
--assembly		Treatment of abstract types used in inline assembly
	warn	do nothing, just issue a warning
	ignore	do nothing, issue no warning
	kill-shallow	kill top level types involved only
	kill-deep	kill top level types and their children
	die	fail-stop; die at that particular program point
--from-void		Treatment of void * values that are cast down to abstract type pointers
	warn	do nothing, just issue a warning
	ignore	do nothing, issue no warning
	kill-shallow	kill top level types involved only
	kill-deep	kill top level types and their children
	die	fail-stop; die at that particular program point
--no-suspect-alias		Don't perform suspect alias analysis
--no-update-restrict		Omit functions, global variables, or functions from being part of restrictions on update points. By default, they are not omitted. *Note: turning on any of these options will enable more permissive update points, but is unsound.*
	f	omit functions
	g	omit global variables
	t	omit types
--no-points-to		Disable the points-to analysis. *Note: turning off the points-to computation makes the analysis more scalable, but is unsound.*
--no-vc		Disable the version consistency analysis. *Note: turning version consistency off makes the analysis more scalable, but is unsound (i.e., might lead to a version inconsistency if the program is annotated with transactions (see Section 7)).*

`--no-tx-isolation`		By default, outer transaction restrictions are not propagated into inner transactions (i.e, isolation is the default policy). This flag disables isolation, allowing outer transactions effects to be propagated into inner transactions (see Section 7).
Patch generation options		

`--type-transformers`	
	`yes`
	`no`
	`exclusive`
		Controls generation of type transformers (applicable in patch mode only)
		type transformers are generated along with the auto-generated patch
		omit type transformer generation
		emit only type transformers

`--no-patchsplit`		Prevent splitting the auto-generated patch file into one-function-files (aka *splinter* files)
`--patchdirectory-out`		Directory where the patch file (or splinter files, see `--no-patchsplit` above) will be generated
Debugging options		
`--enable-debug`		Turn on printing of debug messages for the specified module. See `updatedebug.ml::bugType` for a list of modules
`--stop-loops`		Stop after extracting loops (for debugging loop extraction)

6 Analysis

Ginseng performs a safety analysis to detect types used in a representation-dependent way that hampers future changes in a type's representation. For example, uses of `sizeof` or unsafe type casts that are legal in the current program version might become illegal in future versions, once the type representation has changed. A type used in an illegal fashion is deemed *non-updateable*; **Ginseng** will not use the type wrapping scheme for such a type, and its representation cannot change in future versions.
The programmer might have to guide **Ginseng**'s safety analysis in certain cases. Since the analysis is monomorphic, it will not detect universal or existential uses of types, rendering certain types non-updateable, although they are used in a type-safe, representation-independent fashion. On the other hand, the analysis might deem a type updateable, but the programmer needs to have a fixed, non-wrapped representation for the type in question.
To override the analysis and *force* a type (non)updateable, **Ginseng** provides two `pragma` primitives — `#pragma __DSU_FORCE_NONUPDATABLE` and `#pragma __DSU_FORCE_UPDATABLE`; their use is detailed in Section 4.4.
Whenever **Ginseng** encounters an "illegal" type use, it prints out an error message in the format

```
(<source file>:<line>) setTypeNonUpdatable(<type name>) (<illegal use>)
```

This points the programmer to the offending source code line; there are cases when changes to the source code eliminate the offending use (e.g. instantiating an existential). When such changes are not effective, the last resort is forcing types (non)updateable.
For example, in updating `sshd` we had to use a `#pragma __DSU_FORCE_UPDATABLE("struct_Channel")` to tell **Ginseng** that an existential use of `struct Channel` is update-safe. Conversely, when updating `vsftpd` we used a `#pragma __DSU_FORCE_NONUPDATABLE("struct_vsf_sysutil_ipv4port")` to prevent **Ginseng** from wrapping `struct vsf_sysutil_ipv4port`.
C lacks support for universal or existential polymorphism, so programmers have to resort to using `void *` for polymorphism. **Ginseng** checks all upcasts to `void *` and downcasts from `void *` to ensure no type "laundering" occurs (see Section 4.3 of [5]). **Ginseng** tracks all upcasts from an abstract type pointer `T *` into `void *` by annotating the `void *` and tracking its subsequent flow. If a `void *` flows to an abstract type pointer `S *`, with `T` $\neq$

S, both S and T are set non-updateable, to avoid representation inconsistencies. Whenever a downcast to `S *` from a `void *` with annotation `T *, U *, V *, etc.` is encountered, the **Ginseng** message has the format:

```
(<source file>:<line>) printVoidConstraints <S> <= <T U V> subset:[true|false]
```

Unless both the left and the right hand side of the subset constraint are identical, singleton sets, all types in the lhs and rhs sets are set non-updateable. Pointers to base types are indicated using the format `__base_type_x`.

7 Version Consistency

Ginseng can enforce a safety property called *transactional version consistency* if the user provides transaction annotations in the original program. A *transaction* is a user-designated block of code whose execution can only be attributed to one program version (see [4] for details). To designate a code block as a transaction, the user simply adds curly braces around the code block and adds a `__DSU_TX_<name>` label to the block, as shown in Figure 3. No `#pragma` is necessary. The property **Ginseng** enforces is that if an update is performed inside or outside the transaction, the functions, types and global variables used in the transaction come *from the same program version*. In the Figure 3 example, it is guaranteed that `f()`, `g()`, and `struct S` are from the same program version (all old, all new, or old/new if they didn't change) while `__DSU_TX_1` executes.

Original program	**Program annotated with transactions**

`struct S { int i; };`
`...`
`struct S s;`
`...`
`f();`
`s.i = 0;`
`g();`
`...`
	`struct S { int i; };`
	`...`
	`struct S s;`
	`...`
	`  __DSU_TX_1: {`
	`  f();`
	`  s.i = 0;`
	`  g();`
	`  }`
	`...`

Figure 3: Transactions.

8 Multi-threading

8.1 Check-ins

Ginseng supports both synchronous and asynchronous updates([3]). Synchronous updates take place at an user-specified update point (via `__DSU_update()`). Asynchronous updates take place at an arbitrary (though safe) point inside a scoped check-in block. This is particularly important for multi-threaded programs, since requiring all threads to reach an update point at the same time is not practical. To designate a check-in block, the user simply adds curly braces around the code block and adds a `__DSU_CHECKIN_<name>` label to the block, as shown in Figure 4. No `#pragma` is necessary. Scoped check-ins "snapshot" a safe approximation of thread's current restriction plus the effects of executing the block; the result of this is that the effects of the block will appear in both the prior and future restrictions for the entire execution of the block. While, in our example, this prevents `f`, g, and `s` from changing, the advantage is that multi-threaded programs can perform updates without the need for blocking synchronization—as long as all threads have check-in effects that do not conflict with the update, the update can be performed right away.

9 Dynamic patches

Dynamic patches are generated mostly automatically by **Ginseng**, but (depending on the nature of changes between versions), the programmer might still have to write *type transformers* and *state transformers*. Source code for patches consists of two files: a `.patch.custom.c` file containing state and type transformers, which can be tailored by the programmer, and a `.patch.gen.c` containing definitions of new (or changed) types and functions. **Ginseng** generates both these files automatically, but the programmer is only supposed to alter the former.

Original program

```
struct S { int i; };
...
struct S s;
...
f();
s.i = 0;
g();
...
```

Program annotated with check-ins

```
struct S { int i; };
...
struct S s;
...
  __DSU_CHECKIN_1: {

    // s, f and g appear in both prior and future effects

    f();
    s.i = 0;
    g();

    // s, f and g appear in the prior effetcs here
  }
...
```

Figure 4: Check-ins.

9.1 Type Transformers

When type representations change, *type transformers* will convert values from the old representation to the new one. Ginseng compiler automatically generates type transformer skeletons containing "best guess" conversion functions between representations, but the programmer still has to intervene in order to verify the auto-generated conversions and add initialization code where needed. For instance, if a `struct` type has changed, the stub consists of code to copy the preserved fields over from the old to the new definition, and the programmer will have to initialize newly added fields. Type transformers have the following signature:

void DSU_tt_type(type_old *xin, type_new *xout, wrapped_type *xnew)

The arguments are pointers to the concrete type representations (`xin` and `xout`) and to the wrapped representation (`xnew`); most of the time, `xin` and `xout` are sufficient for writing the conversion function, but when converting linked structures e.g., trees or lists, `xnew` is needed as well. In most cases `type` is a `struct`, and the effort consists of initializing newly added fields.
As an example, in Figure 5 we show the Ginseng-generated type transformer for struct Authct in the update from Sshd version 3.7.1p2 to version 3.8p1. The new version adds a field force_pwchange (line 13). Ginseng generates code to copy the existing fields, but the programmer has to write the correct initializer for the newly-introduced field. Depending on when or how the new code uses the newly added fields, writing the type transformer can range from trivial (assigning a default value) to impossible (Section **??**).
If no type has changed, the auto-generated `.patch.custom.c` will be empty, meaning there are no type transformers to be filled out. Note however that state transformers (described in the next section) might still be necessary.

9.2 State Transformers

A state transformer is an optional function supplied by the programmer and invoked by the runtime system run at update time (Section **??**). The purpose of state transformers is two-fold: 1) to convert global state and establish the invariants the new program version expects, and 2) to run initialization code the new program depends on, but is not part of the old program's initialization code.
Since a state transformer function is optional, it is not included by default in the `.patch.custom.c`; the programmer has to add it using the following skeleton:

void DSU_state_xform() { ... }

As an example, in Figure 6 we show the state transformer we had to write for the update from Zebra version 0.93b to version 0.94. We see that the old version keeps routing tables in four different global variables (rib_table_ipv4, static_table_ipv4 , rib_table_ipv6, and static_table_ipv6), whereas the new version uses a routing table array, vrf. The state transformer makes the array elements point the associated routing table.

```
// OLD program, sshd 3.7.1p2
struct Authct_old {
  int              failures;
  char            *user;
  char            *service;
  struct passwd   *pw;
  char            *style;
};

// NEW program, sshd 3.8p1
struct Authct_new {
  int              failures;
  int              force_pwchange;
  char            *user;
  char            *service;
  struct passwd   *pw;
  char            *style;
};
```

(a) Source code

```
void tt_Authct(struct Authct_old *xin,
               struct Authct_new *xout) {
  xout->failures = xin->failures;
  xout->force_pwchange = ??;
  xout->user = xin->user;
  xout->service = xin->service;
  xout->pw = xin->pw;
  xout->style = xin->style;
}
```

(c) Type Transformer

Figure 5: Type transformer example.

```
// OLD program, zebra 0.93b
struct route_table *rib_table_ipv4;
struct route_table *static_table_ipv4;

struct route_table *rib_table_ipv6;
struct route_table *static_table_ipv6;

// NEW program, zebra 0.94
struct route_table *vrf[4];
```

(a) Source code

```
void DSU_state_xform() {
  vrf[0] = rib_table_ipv4;
  vrf[1] = rib_table_ipv6;
  vrf[2] = static_table_ipv4;
  vrf[3] = static_table_ipv6;
}
```

(b) State Transformer

Figure 6: State transformer example.

Just like in the type transformer case, state transformer complexity can range from trivial (if at all needed) to impossible (e.g., if at boot time hardware is initialized differently by the old and the new program). The most complicated cases we have encountered were refactorings of global structures where global state had to be transferred between the old and new storage model.

10 Example

The *linkedlist* example (`ginseng/cil/test/update/linkedlist`) demonstrates dynamic updating with **Ginseng**. To build and run it:

```
$ cd ginseng/cil/test/update/linkedlist; make; ./linkedlist.exe
```

The easisest way to start your own dynamic updating project is to use the *linkedlist* skeleton (`Makefile` and 0/1 directories). Replace `linkedlist-[012].c` with the successive versions of the application to be updated, and adjust the `PROG` variable in the `Makefile` accordingly.

Ginseng supports updating types, functions, global variables, and long-running loops, and the *linkedlist* example illustrates all these.

In `linkedlist-0.c`, a singly-linked list type (`Tlist`) contains elements of type `T`. `main()` runs a loop whose body will be updated twice. `interactive_update()` prints the list and invokes the dynamic updating function

`__DSU_update()`; `interactive_update()` will also be updated twice.
In `linkedlist-1.c`, the element type `T` has grown to two fields, `x` and `y`. The transformers for updating *linkedlist*$_0$ to *linkedlist*$_1$ are in `0/linkedlist.patch.custom.c`. The `tt_T` type transformer converts values of type `T` from the old (0, $\texttt{T}_{old}$) into the new (1,$\texttt{T}_{new}$) representation. Global state is transformed in the function `__DSU_state_xform()`. Note that `printT()`, `interactive_update()` and the body of `MAINLOOP` are automatically updated, requiring no user intervention.
In `linkedlist-2.c`, the singly-linked list (`Tlist`) is augmented, making it a doubly-linked list. The transformers for updating *linkedlist*$_1$ to *linkedlist*$_2$ are in `1/linkedlist.patch.custom.c`. The `tt_Tlist` type transformer converts values of type `Tlist` from the old (1, $\texttt{Tlist}_{old}$) into the new (2, $\texttt{Tlist}_{new}$) representation. Global state is transformed in the function `__DSU_state_xform()`. Note that the new functions `lastT` and revIterT are automatically rendered accessible to the updated program. As expected, `consT`, `interactive_update()` and the body of `MAINLOOP` are automatically updated.

References

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[4] Iulian Neamtiu, Michael Hicks, Jeffrey S. Foster, and Polyvios Pratikakis. Contextual effects for version-consistent dynamic software updating and safe concurrent programming. In *Proceedings of the ACM Conference on Principles of Programming Languages (POPL)*, pages 37–50, January 2008.

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[6] G. C. Necula, S. McPeak, S. P. Rahul, and W. Weimer. CIL: Intermediate language and tools for analysis and transformation of C programs. *Lecture Notes in Computer Science*, 2304:213–228, 2002. `http://manju.cs.berkeley.edu/cil/`.