

Extending C with bounds safety

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Summary

System programmers need a system programming language that detects or prevents common programming errors involving pointers. This will improve the reliability and security of system software and the productivity of system programmers. This technical report describes Checked C, an extended version of C that provides a way to write C code that is guaranteed to be bounds-checked.

Checked C adds new pointer types and array types that are bounds-checked, yet layout-compatible with existing pointer and array types. In keeping with the low-level nature of C, programmers control the placement of bounds information in data structures and the flow of bounds information through programs. Static checking enforces the integrity of the bounds information and allows the eliding of some dynamic checking. Dynamic checking enforces the integrity of memory accesses at runtime when static checking cannot. Checked C is backwards-compatible: existing C programs work “as is”. Programmers incrementally opt-in to bounds checking, while maintaining binary compatibility.

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Chapter 1

Introduction

The C programming language [87, 50] allows programmers to use pointers directly. A pointer is an address of a location in memory. Programs may do arithmetic on pointers, dereference them to read memory, or assign through them to modify memory. The ability to use pointers directly makes C well-suited for low-level system programming that is “close to the hardware” and allows programmers to write efficient programs. C also unifies pointer types and array types. They can usually be used interchangeably and array subscripting is a synonym for equivalent pointer operations.

Pointers and the unification of arrays and pointers are one of the strengths of the C programming language, allowing programmers to write concise, efficient programs. At the same time, they are a source of reliability and security problems in modern software. This is because pointers and array indices are not bounds checked in C and related languages such as C++. Bounds checking checks that a pointer or array index is in bounds before it is used to read or write memory. A pointer to an array object is in bounds if it points to an element of the array object. An array index is in bounds if the index is greater than or equal to zero and less than the size of the array.

Between 2010 and 2015, buffer overflows accounted for between 10-16% of publicly reported security vulnerabilities in the U.S. National Vulnerability Database each year [72]. The vulnerabilities have affected software implemented in C and C++ that is widely used, including the Windows and Linux operating systems, the Internet Explorer, Chrome, and Safari web browsers, the Apache web server, the OpenSSL security library, scripting language implementations for Bash, Ruby, and PHP, and media playback software such as QuickTime.

Because pointers and array indices are not bounds checked in C, a programming error involving them may corrupt memory locations used by the program. The memory locations may hold data that is important to the computations being done by the program or data that is essential to the control-flow of the program, such as return address locations and function pointers. Memory corruption can lead to a program producing incorrect results or, in the hands of a malicious adversary, the complete malfunctioning of the program and the takeover of a running process by the adversary.

This technical report describes Checked C, an extension to C that provides bounds checking for pointers and arrays. There are two obstacles to adding bounds checking to C. First, it is not clear where to put the bounds information at runtime. Second, it is not clear how to make the bounds checking efficient for programs where performance matters. The solution of changing the representation of all C pointer types and arrays to carry bounds information is not sufficient in practice. C may be used at the base of systems where hardware or standards dictate data layout

and data layout cannot be changed. C programs must also interoperate with existing operating systems and software that require specific data layouts.

1.1 Overview

Checked C addresses the bounds checking problem for C by:

- Introducing different pointer types to capture the different ways in which pointers are used. The unchecked C pointer type `*` is kept and three new *checked* pointer types are added: one for pointers that are never used in pointer arithmetic and do not need bounds checking (`ptr`), one for *array pointer types* that are involved in pointer arithmetic and need bounds checking (`array_ptr`), and an extension to `array_ptr` for null-terminated arrays (`nt_array_ptr`).
- For array pointer types (`array_ptr`), in keeping with the low-level nature of C, bounds checking is placed under programmer control. This differs from languages like Java, where bounds checking is completely automatic. A programmer declares *bounds*, where the bounds for an `array_ptr` variable are given by non-modifying C expressions. These are a subset of C expressions that do not modify variables or memory. They include local variables, parameters, constant expressions, casts, and operators such as addition, subtraction, and address-of (`&`) operators. Static checking ensures that programs declare and maintain bounds information properly. The bounds are used at runtime to enforce
- Introducing different array types to distinguish between arrays whose accesses are bounds-checked and existing C arrays whose accesses are not bounds-checked. A programmer places the modifier `checked` before the declaration of the bound(s) of the array: `int x checked[5][5]` declares a 2-dimensional array for which all accesses will be bounds-checked. Arrays with null terminators as their last element can be declared using `nt_checked` instead of `checked`.
- For structure types with `array_ptr`-typed members, a programmer declares *member bounds* for those members. A member bounds declares the bounds for a member in terms of members of the structure type. Member bounds can be suspended temporarily for specific variables and objects. Static checking ensures that updates to members maintain the member bounds.
- Introducing bounds-safe interfaces to address the problem of interoperation between checked code and unchecked code. A bounds-safe interface describes the checked interface to unchecked code by declaring bounds for unchecked pointers in function signatures and data structures. It describes a boundary that is “checked” or “unchecked” depending on what kind of code is using it. The interface is trusted in checked code (code that uses only checked pointer types). Proper usage is enforced via checking at compile time and runtime. For code that uses only unchecked pointer types, the interface is descriptive and not enforced by language checking. This provides a way to upgrade existing code to provide a checked interface without breaking existing users of the code.
- Introducing checked program scopes, where bounds checking is the default behavior. In a checked program scope, definitions of variables and functions can use checked pointer types and cannot use unchecked pointer types. Declarations involving unchecked pointer types must provide bounds-safe interfaces. Checked program scopes avoid problems with subtle misuse of bounds-safe interfaces.

- Reasoning about the correctness of programs with declared bounds sometimes requires reasoning about simple aspects of program behavior. To support this, lightweight invariants are added to Checked C. A lightweight invariant declares a relation between a variable and a simple expression using a relational operator. An example would be the statement `x < y + 5`. Lightweight invariants can be declared at variable declarations, at assignment statements, for parameters, and for return values. Checked C is extended with rules for checking these lightweight invariants. Just as type checking rules are defined by the programming language, so are rules for checking lightweight invariants. The checking of the correctness of programmer-declared bounds is integrated with the checking of invariants.
- For the cases where static checking reaches its limits, a programmer can introduce dynamic checks that are runtime errors if they fail. Dynamic checks use the syntax `dynamic_check e`, where `e` is an integer-valued expression. A check is similar to an assert, except that it is never removed from the program (unless a compiler proves it is redundant). It cannot be removed because the integrity of the program depends upon it.

For an existing C program to be correct, there has to be an understanding on the part of the programmer as to why pointers and array indices stay in range. The goals of the design are to let the programmer write this knowledge down, to formalize existing practices, such as array pointer parameters being paired with length parameters, and to check this information.

To simplify bounds and reasoning about bounds for `array_ptr` types, pointer arithmetic overflow for `array_ptr` types is considered a runtime error. Pointer arithmetic involving a null pointer for `array_ptr` types is also a runtime error.

Efficiency is addressed by extending the static checking so that it can guarantee that specific bounds checks will always succeed at runtime for `array_ptr`. The static checking supports the scenario of simple control-flow enclosing the bounds check guaranteeing that the bounds check will succeed. For example, a for-loop may iterate only over values within the declared bounds of an `array_ptr` variable.

A problem with incorporating static checking into a programming language is that static checking needs to be something that compilers can do quickly and deterministically. Static checking can become very expensive to do, depending on the language of invariants and the inference that compilers are expected to do. For example, Presburger arithmetic is integer arithmetic restricted only to addition and less than or equal operations. It is NP-complete to determine whether a formula in the first-order logic for quantifier-free Presburger arithmetic is satisfiable (true or false). Even statically checking properties of simple fragments of real programs can be computationally intractable.

This problem is addressed in two ways. First, the language rules that are used to check the validity of bounds are limited intentionally. The rules can check the validity of bounds that are needed in practice. However, there are bounds that are true that cannot be proved using the rules. In the terminology of program logics, the rules are incomplete. As an example, the rules about distributivity limit the size of expressions that they produce. In practice, this means that simple disjunctive bounds can be checked, but complex disjunctive bounds cannot be checked.

Second, the inference that compilers do for checking program invariants is limited. Compilers act as *checkers* for invariants. They check that declared invariants follow from other declared invariants, the program control-flow, intervening assignments, and simple axioms about invariants, such as transitivity of relational operators. Compilers do not try to devise invariants or prove the correctness

of invariants; they apply simple local reasoning to check them. The programmer has to call out the relevant facts. If a programmer declares an invariant `x == y` but neglects to declare the invariant `y == z`, a checker may not be able to reason several statements later that `x == z`, even though it may be true at that point in the program. This is taking advantage of the fact that checking a proof is usually much easier than creating the proof.

Establishing the bounds-safety of pointer operations is just the first step in establishing type safety for C programs. There are other ways which C programs may fail. C programs may incorrectly deallocate memory that is still in use, do incorrect type-unsafe pointer casts, or have concurrency races that tear data structures. Addressing these problems is beyond the scope of this technical report. For now, it is assumed that programs are correct in these other aspects.

This design is being done in an iterative fashion. To validate the design, we mocked up modifying a subset of the OpenSSL code base [25] to be bounds-safe. We created C++ templates for the new pointer types and modified OpenSSL to compile as valid C++ code. We hand-edited about 11,000 lines of the code to use checked pointer types with full bounds annotations. We used macros to encapsulate the bounds annotations so that they could be elided from the code and OpenSSL compiled and tested using the new types. We also modified the generic stack type in OpenSSL to use the `ptr` type, which required cross-cutting changes across the code base (in all, about 160 files were changed) as well dealing with complicated macros.

We learned the following from this experience. First, it was important to have a compact, succinct syntax for declaring bounds. Second, in most cases, declaring bounds at declarations was sufficient for tracking the bounds of variables. Large blocks of code remained unchanged, which matches the observations of the Cyclone project [51], an earlier research effort to create a type-safe version of C. Third, the expressions allowed in declaring bounds needed to be rich. Fourth, pointer casts were used fairly extensively, but often times it was obvious that the casts were correct with respect to bounds. The existing bounds could be modified easily to be appropriate for the new referent type of the pointer. Fifth, it was clear that there needed to be a graceful way of interoperating with existing libraries that could not be changed. Finally, signed integer overflow was a pervasive possibility, which raised questions about the meaning of bounds declarations that used signed integers.

We revised the design to address these issues. In particular, we paid close attention to tracking bounds through pointer casts. We also made sure that the constraints on signed integer expressions used in bounds expressions were understood and could be written down in the language of simple invariants.

The design is a work-in-progress. Some material will be missing or incomplete because the language design has not yet been done. Readers should be aware that all parts of the document are subject to change. We are interested in feedback and suggestions about ways to improve the design.

1.2 Principles for extensions

Here are the principles that are followed to extend C to support bounds checking:

1. Preserve the efficiency and control of C. C is designed to be low-level and work with the same types that computer processors work with. This allows programmers to control what programs do precisely at the machine level. This efficiency and control are reasons why C is valued as a

system programming language. Extensions will be “pay-as-you-go” and continue to provide precise control to programmers at the machine level. Hidden costs will be avoided.

2. Be Minimal. This means adding the minimal set of extensions needed to accomplish the goals. It is easier to learn extensions if there are as few of them as possible. It also stays true to the design goals of C.
3. Aim for clarity and succinctness. Clarity means that code is easy to understand and extensions are straightforward to understand. Succinctness means the programmers have less to read or type. Programmers value clarity and succinctness because it makes them more productive. Sometimes clarity and succinctness are in tension and sometimes they are not. When they are in conflict, clarity will be prioritized above succinctness, primarily because source code is usually read many more times than it is written.
4. Enable incremental use. Real systems are large and complicated, with hundreds of thousands and millions of lines of code. The teams that work on those systems will adopt checked pointer operations over time, not all at once, so incremental use of checked pointer operations will be supported. Teams will prefer incremental conversion paths because of practical matters such as reducing risk, fixing existing bugs identified by introducing bounds checking, maintaining system stability, and understanding performance effects. Even though incremental use will be supported, it is not the end goal. We believe that benefits of using checked pointer operations will be modest until almost an entire system is converted. At that point, we expect a qualitative increase in system reliability and programmer productivity.

Two specific design principles are adopted based on these principles:

1. Do not change the meaning of existing C code. Methods that do not use extensions will continue to compile, link, and run “as is”. If the meaning of existing C code is changed, it will violate the principles of clarity and enabling incremental adoption.
2. Adopt existing notations from C++ when it meets our needs, instead of inventing new notations. Many systems are hybrid C/C++ systems, so this approach fits with the principle of clarity. It also enables incremental adoption. One of the design goals of C++ has been that C is a subset of C++. It is a design goal to allow Checked C to be a subset of C++ too.

1.3 Notation

This specification includes many code examples. Code will be shown in a teletype font (like `this`). Operators and symbolic characters will be shown in black (like `->`). Keywords will be shown in blue and program variables will be shown in light blue (like `for (int i = 0; i<10; i++)`). At times, we will define properties or make mathematical statements that range over sets of values or program elements, such as mathematical integers, variables, or expressions. We will use meta-variables in *italics* that range over these values or program elements. We might say something like “for all expressions e_1 and e_2 .” These meta-variables differ from program variables, which are elements of specific C programs.

1.4 Organization of this document

The target audience for this document includes programmers interested in learning about Checked C, compiler writers, and language designers. These groups have different and conflicting needs. Programmers will find that some sections have too much detail, while language designers will likely find that some sections do not have enough detail. Language designers may be less interested in compiler implementation details. We first describe the organization of the document and then provide a roadmap for the different audiences.

Chapter 2 describes the new pointer types and the new array types, including syntax, semantics, and error conditions. It also covers other extensions to C semantics. One extension is the introduction of checked program scopes to prevent inadvertent use of unchecked types. Another extension is a refinement of C's notion of undefined behavior. We wish to maintain bounds safety even in the face of integer overflow, which is a widespread possibility in C programs. This requires a more nuanced requirement on the result of overflow than “the result is undefined.”

Chapters 2 through 7 present the extensions to C for declaring bounds for `array_ptr` values stored in variables and structures and checking the consistency of those declared bounds. The extensions are organized by C language feature, moving from simple language features to more complicated language features. This allows a reader to understand concepts one at time.

Chapter 3 describes how programmers declare the bounds for `array_ptr` variables and the meaning of bounds declarations. Bounds can be declared at variable declarations. They can also be declared for automatic (local) variables at assignments. If the only bounds declaration for a variable is at the declaration of the variable, the bounds declaration is an invariant bounds declaration. An invariant bounds declaration must be true for the lifetime of the variable. If there are bounds declarations for the variable at assignments or other declarations, all bounds declarations for the variable are dataflow-sensitive. Dataflow-sensitive bounds declarations extend via dataflow to uses of the variable.

Invariant bounds declarations must usually be valid after every statement and declaration in the scope of a variable. Sometime multiple statements are needed to update the set of a variables used in an invariant bounds declaration. To support this, expression statements and declarations can be *bundled*, in which case bounds declarations must be valid only at the end of the bundle. Within the bundled block, the variables may be inconsistent with respect to bounds declarations that use them. The variable can be updated so that consistency is re-established at the end of the bundled block.

Chapter 4 describes rules that the compiler uses to check the validity of bounds declarations. It covers inferring bounds for expressions. Because expression may have assignments embedded within them, it also covers inferring effects of an expression on the bounds of variables. This inferred information is then used to validate that declarations and statements correctly declare bounds and maintain the bounds information.

Chapter 5 covers interoperation between checked and unchecked code. It covers conversions between checked and unchecked pointers, as well as conversions between the new kinds of checked pointers. It pins down the notion of checked code and unchecked code. Finally, it covers bounds-safe interfaces in depth.

Chapter 6 extends these ideas from variables to data structures by introducing member bounds, which are type-level invariants about members of structure types. For now, it assumes that the programmer has done concurrency control around shared data properly and ignores the fact that

data structures may be modified in racy ways such that invariants are violated. The chapter also describes the rules that the compiler uses to check programs with member bounds.

Chapter 7 describes how to extend reasoning about bounds to pointers to data that has `array_ptr`-typed values within it. This includes pointers to structures with members that have `array_ptr` types and pointers directly to `array_ptr`s. Pointers to structures can be used easily by ensuring that modifications to members preserve type-level bounds invariants. This follows the lead of the Deputy system [19]. Complexity arises for pointers to `array_ptr`s where the `array_ptr`s have bounds that depend on other variables or members. The other variables or members need to be abstracted by pointers as well to ensure that invariants for bounds are not violated. Assignments via pointer indirections need to be coordinated to maintain the invariant. This gives rise to constraints on the pointers and the variables or members whose addresses have been taken.

Chapter 8 extends the checking of bounds to incorporate simple reasoning about bounds and program behavior. It includes a set of rules for deducing facts that are true about a program at a specific point in the program (for example, given an assignment `x = y`; the fact that `x == y` is true after the assignment). Facts can also be deduced from program control-flow. There are additional rules for reasoning about whether one fact is true given a set of other facts (for example, given `x == y` and the statement `z = y`; `z == x` is true after that statement). These rules and facts can be used to deduce the correctness of bounds declarations that differ from those inferred directly by the checking described in Chapters 4 and 7. For example, a programmer may wish to narrow the memory that is accessible via an `array_ptr` variable by declaring bounds that are a subrange of the bounds inferred by the checking. A programmer may wish to update the bounds for an `array_ptr` variable after an assignment `x = y`, substituting `x` for `y`.

The same static checking that is used for bounds can be used to reason about the ranges of variables at specific points in a program. From there, it is a short step to deducing at compile-time that bounds are always satisfied at a particular memory access in a program. For example, a fact can be that the range of an integer variable `i` is always between 0 and 10. This can be used to deduce that an array access in a crucial inner loop is always in bounds.

Chapter 9 describes related work that addresses the lack of bounds checking in C. Because of the serious practical consequences for computer security and software reliability, there has been extensive work in the area. We are heavily influenced by the Deputy system [115, 19]. Chapter 10 summarizes open issues that remain to be addressed by the design. Chapter 11 discusses design alternatives that were considered and not chosen. It explains why those alternatives were not chosen.

Here are the suggested roadmaps for the different groups of readers. For programmers interested in learning about Checked C, we suggest reading Chapter 2 except Sections 2.10 and 2.12, Chapter 3 except Section 3.10, Section 4.2 of Chapter 4, Chapter 5 except for Section 5.3.7, Chapter 6 except for Sections 6.3.2 and 6.6, and Chapter 8 through the first section. Sections 3.9, 3.7, and 5.4 are advanced topics that can be read after the other recommended chapters and sections.

We suggest language designers and compiler writers read most of the document. Language designers can skip Sections 3.10.4, 4.5.1, and 4.5.2. Compiler writers can skip the discussions in Section 2.11 and Chapters 9 and 11.

1.5 Acknowledgements

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Chapter 2

Extensions to existing C concepts

This chapter describes extensions to existing C concepts. It covers new kinds of pointer types and array types, their meaning, and the operations on them. It introduces two new program scopes: `checked` and `unchecked` blocks. It covers a generalization of assertions to dynamic checks that are never removed (unless a compiler proves them redundant) because bounds safety depends upon them. Finally, it describes changes to undefined behavior needed for bounds safety.

2.1 New keywords

Some of the extensions use new keywords. Introducing new keywords for C can cause conflicts with identifier names in existing C programs. Fortunately, C provides a backward-compatible way to introduce new keywords. Identifiers that begin with an underscore followed by a capital letter are reserved for system use, as are identifiers that begin with two underscores [50, Section 7.1.3]. The following new keywords are introduced:

```
_Array_ptr  _Checked  _Dynamic_check  _Nt_array_ptr  _Nt_checked  _Ptr  
_Where  _Unchecked
```

It is desirable to have all-lowercase versions of the identifiers for readability and ease of typing. The C preprocessor is used to provide these. A standard header file `stdcheckedc.h` is provided that has macros that map the lowercase versions of keywords to the actual keywords. Programs that do not have identifiers that conflict with the lowercase versions of the keywords can include it. Note that to allow header files to be included by programmers in any order, the implementations of standard header files need to be modified to not use identifiers that conflict with these keywords. The all-lowercase versions of the keywords are:

```
array_ptr  checked  dynamic_check  nt_array_ptr  nt_checked  ptr  
where  unchecked
```

The pattern of using an identifier reserved for system use coupled with a header file was used before to introduce the boolean type. The keyword name is `_Bool`. The standard header file `stdbool.h` has a macro that maps `bool` to `_Bool`.

Throughout this document, we use the shorter and easier-to-read lowercase versions of the keywords. It is assumed that `checkedc.h` is included before examples.

2.2 New kinds of pointer types

Three new checked pointer types are added to C. Each pointer type can be used in place of ‘*’:

1. `ptr<T>`: this points to a value of type T . Pointer arithmetic is not allowed on these kinds of pointers. The expectation is that many pointers are not involved in pointer arithmetic and can be given this type. When values of this pointer type are used to read or write memory, they must be non-null. The non-nullness is checked at runtime if necessary. The name `ptr` is chosen for these kinds of pointers because these are expected to be the most common type of pointer. `ptr` is a short succinct name.
2. `array_ptr<T>`: this is a pointer to an element of an array of type T values. A variable of type `array_ptr` that is used to access memory must have an associated declaration of the valid bounds for the variable. When values of this pointer type are used to read or write memory, they must be non-null and in bounds. The non-nullness and bounds are checked at runtime if necessary. Pointer arithmetic can be done on these pointer types. The resulting pointers do not need to be in bounds.
3. `nt_array_ptr<T>`: this is a variant of `array_ptr<T>` for null-terminated arrays. It is described in Section 2.4

Unchecked C pointer types that use ‘*’ and are unchecked in their ranges continue to exist. Pointer arithmetic is not forbidden on unchecked pointer types because it would break existing C code. C compilers will have an error or warning mode that flags unexpected uses of ‘*’.

The same syntax as C++ template instantiations is used for building instances of these types because this syntax is well-known and understood. The new pointer types are added to the syntax for *type specifiers* [50, Section 6.7.2]. The parameters to these type constructors must be types, which are described syntactically by *type names* [50, Section 6.7.7]. If Checked C is extended to C++, in the C++ extension these new types will be template types that have special meaning.

Checked pointers provide checking that memory accesses are in bounds. They do not provide checking that memory for objects is being managed properly. For example, they can still be used to access memory for objects after the objects have been deallocated.

Here are examples of declarations using pointer types. These declare variables that are all pointers to integers:

```
int *p;
ptr<int> q;
array_ptr<int> s;
```

The new checked pointer types can have `const` and `volatile` modifiers, just like unchecked pointer types. They can be applied to the type of the object to which the pointers points or to the pointer itself. Here are examples of pointers to constant integers:

```
const int *p;
ptr<const int> q;
array_ptr<const int> r;
```

A pointer to a constant integer cannot be used to modify the value of the integer.

Here are examples of constant pointers to modifiable integers:


```
int x;
int *const p = &x;
const ptr<int> q = &x;
const array_ptr<int> r = &x;
```

In this case, the pointers cannot be modified after they are defined, but the integer that they point to can be modified. The checked pointer declarations have simpler syntax than the unchecked pointer declaration, where `const` must be placed after the `*`. The checked pointer declarations are all analogous to `const double y = 5.0;` declaring a variable `y` that is `const`. In the declaration of `y`, `double` specifies a type. The `const` keyword is placed before it to declare that the variable in the declaration is `const`. In the examples, `ptr<int>` and `array_ptr<int>` all specify types too.

The checked pointer types follow the same rules that apply to modifiers for unchecked pointer types. For example, a variable that is a pointer to a `const` value can be assigned a pointer to a non-`const` value. The reverse is not allowed.

Array pointers (`array_ptr`) of function types are not allowed. Functions have no size associated with them, so bounds checking pointers to them does not make sense. Programmers should use `ptr` instead:

```
typedef array_ptr<int (int x, int y)> callback_fn; // illegal
typedef ptr<int (int x, int y)> callback_ptr;      // legal
typedef array_ptr<callback_ptr> callback_arr;     // legal
```

2.3 New kinds of array types

A new checked array type is added to C. Just as there are checked pointer types, there are checked array types. They are declared by placing the modifier `checked` before the declaration of the bound of the array¹:

```
int a checked[10];
```

All array references to checked array types are bounds checked. C has the rule that an “array of *T*” is converted implicitly to a “pointer to *T*” in a number of situations. This rule is extended to convert a “checked array of *T*” to an “`array_ptr` to *T*”.

In C, array types may be complete or incomplete. A complete array type specifies the bound of each dimension of the array using constant expressions. An incomplete array type does not specify the bound of the first dimension of the array. Examples of complete array types are `int[10]` and `int[10][10]`. Examples of incomplete array types are `int[]` and `int[][10]`.

If a checked array type is incomplete, there must be an associated declaration of the valid bounds for the first dimension of the array. For a complete array type, the bounds declared by the type are used to bounds check array references. For example, given a declaration `int a[10]` and a use `a[i]`, the bounds check is that `i >= 0` and `i < 10`.

Array references to multi-dimensional arrays must be uniformly bounds checked or not bounds checked. If any dimension is bounds checked, all dimensions must be checked. A programmer

¹We can just as easily adopt the syntax that the checked annotation is postfix and propagates from the inner most array to the outermost array. We have chosen the prefix syntax because the notation can be read easily from left to right “this is a checked array of 10x10 elements”.

can simply declare that the outer dimension of an array is checked. The checked property will be propagated to the inner dimensions:

```
int b checked[10][10];
```

In C, multidimensional arrays are arrays of arrays, where the nested array types have known dimensions at compile-time. A 2-dimensional array is an array of array of T, a 3-dimensional array is an array of array of array of T. The checked property is propagated from the outer array to the nested array types.

2.3.1 An example

It is easy to convert a function that operates only on complete array types to one where array accesses are bounds checked: just add the `checked` keyword to the declarations of the variables with complete array types. Consider a method that adds 2x2 integer arrays `a` and `b` so that `a = a + b`:

```
void add(int a checked[2][2], int b checked[2][2])
{
    for (int i = 0; i < 2; i++) {
        for (int j = 0; j < 2; j++) {
            a[i][j] += b[i][j];
        }
    }
}
```

2.3.2 Propagation of checked property to nested array types

The checked property of an array type is propagated to a nested array type as follows. A declaration of a variable has the form $T D$, where T is a type and D is a declarator. The declarator can be as simple as an identifier `x`:

```
int x;
```

It can be a more complex form that declares an identifier and modifies T to produce a new type for the identifier. An example is `x[5]`:

```
int x[5];
```

Given a declaration $T D$, if D is an array declarator, it will have the form $D1 [constant-expression_{opt}]$ where $D1$ is another declarator. The type of the identifier in the declaration $T D1$ will be determined first. The type can be some constructed type of the form *type-modifier* of T , where *type-modifier* is a sequence of array, checked array, or pointer type modifiers. If the first element in the *type-modifier* sequence is an array or pointer, the type of the identifier will be *type-modifier* “array of T ”. If the first element in the *type-modifier* sequence is a checked array, the type of the identifier will be *type-modifier* “checked array of T ”.

For example, in parsing the declaration of `b`, $D1$ will be `int b checked[10]`. The type of `b` in $D1$ is “checked array of int”. The type of `b` in `int b checked[10][10]` will be “checked array of checked array of int”.

2.3.3 Propagation and type definitions

A `typedef` declaration defines a name for a type. This name can be used to declare multi-dimensional arrays:

```
typedef int arr_ty[10];
arr_ty x[10];
```

The checked property is propagated only to array declarators that are nested directly within other array declarators. It is not propagated to the bodies of type definitions. It is an error if an array type and a nested array type from the use of a type name have different checked properties.

Here are examples of correct and incorrect declarations:

```
typedef int t1 checked[10];
t1 x checked[10]; // correct: checked properties match

typedef int t2[10];
t2 x checked[10]; // error: mismatched checked properties
```

2.4 New types for null-terminated arrays

C programmers are familiar with the concept of a null-terminated array. This is a sequence of elements in memory that ends with a null terminator value. We add a new type `nt_array_ptr<T>` to represent pointers to these kinds of arrays. We divide these arrays into two parts: a prefix with bounds and a sequence of additional elements that ends with a null terminator. The initial elements of the sequence can be read, provided that preceding elements are not the null terminator. The bounds can be *widened* based on the number of elements read.

A programmer may declare bounds for an `nt_array_ptr` variable. If bounds are declared, they are used to check that accesses to memory are in range at runtime.

If no bounds are declared, the bounds are inferred. At variable declarations, the declared bounds are for arrays with a prefix of 0 elements. At variable uses, the bounds are determined using a program analysis that widens bounds based on control-flow. The bounds are then used to check memory accesses. A problem with using an analysis to determine bounds is that the bounds are not written down in the program. This may lead to unexpected failures if the bounds are narrower than expected and it may make it difficult to understand failures. To avoid these problems, we require that memory accesses using inferred bounds be provably in-range at compile time. At a minimum, the proof system should support local reasoning about widened bounds involving pointer variables with constant offsets. This is enough to handle simple cases such as:

```
nt_array_ptr<char> p = ...
if (*p == 'a')
  if (*(p + 1) == 'b')
    if (*(p + 2) == 'c')
```

The element type T of an `nt_array_ptr<T>` must be an integral or pointer type. `nt_array_ptr<T>` extends `array_ptr<T>`: the prefix with bounds is treated the same as if an `array_ptr<T>` pointed to it. An `nt_array_ptr<T>` value can be converted to an `array_ptr<T>` value with the same bounds.

Here is a declaration of a function that takes a null-terminated array of characters and counts its length:

```
int compute_length(nt_array_ptr<char> s);
```

Modifiers can be applied to the reference type of an `nt_array_ptr`, in the same way that they can be applied to the referent type of an `array_ptr`. The function `compute_length` should not modify the contents of a string. Here is a version that uses `const` to declare that:

```
int compute_length(nt_array_ptr<const char> s);
```

Just as there are new checked array types for `array_ptr`s, there are new checked null-terminated array types for `nt_array_ptr`s. These are useful for declaring checked types for string constants. Null-terminated array types are declared using the `nt_checked` keyword before the array dimensions, instead of the `checked` keyword:

```
int arr nt_checked[10];
```

`nt_checked` declares an array whose last element is a null terminator. The size of the array includes the null terminator element. Here is an example of a declaration of a checked null-terminated array type for a string constant:

```
char s nt_checked[6] = "hello";
```

An `nt_checked` array with size d converts to an `nt_array_ptr` with a count of $d - 1$ elements. This is the number of elements in the prefix array. This means that programs can still read an array element containing a null terminator. However, attempting to overwrite the null terminator with a non-null value is a runtime error.

2.4.1 `nt_array_ptr` usually follows the rules for `array_ptr`

Because `nt_array_ptr` extends `array_ptr`, the discussion and rules for `array_ptr` in the rest of the specification usually apply to `nt_array_ptr` too. Most mentions of `array_ptr` can usually be read as “`array_ptr` or `nt_array_ptr`”. We discuss `nt_array_ptr` only when there is a difference between it and `array_ptr`.

2.5 Operations involving pointer types

The following operations involving pointer-typed values are allowed:

- Indirection: the `*` operator can be applied to a value of type T *, `ptr<T>`, or `array_ptr<T>`. It produces a value of type T .
- Array reference: the `[]` operator can be applied to a value of type T * or `array_ptr<T>`. It cannot be applied to a value of type `ptr<T>`. $e1[e2]$ is equivalent to $*(e1 + e2)$.
- Assignment: two pointers of the same type can be assigned.
- Adding or subtracting a pointer type and an integer. This is allowed for T * and `array_ptr<T>` types.

- Pointers to objects of the same type can be compared for equality or inequality. The pointers do not have to be the same kind of pointer. To support reasoning about program behavior, the result of comparing pointers to different objects must be defined. Checked pointers can also be compared for equality or inequality with 0 and `void` pointers, just like unchecked pointers.
- Pointers to objects of the same type can be compared relationally. Relational comparisons are the `<`, `<=`, `>`, `>=` operators. The pointers do not have to be the same kind of pointer. For example, an `T *` can be compared with an `array_ptr<T>`. To support bounds checking and reasoning about program behavior, the result of comparing pointers to different objects must be defined. Section 2.12 describes this requirement in detail.
- Pointers to objects of the same type can be subtracted. The pointers do not have to be the same kind of pointer. The result of subtracting pointers to different objects of the same type must be defined. Section 2.12 describes this requirement in detail.

A value of one pointer type may be converted to a value of another pointer type. For casts to or from checked pointer types where bounds-safety can be checked at compile-time, a cast operator can be used. If bounds safety cannot be checked at compile-time, bounds cast operators must be used. There are two kinds of bounds cast operators: `dynamic_bounds_cast`, which does runtime checks of any conditions required to enforce bounds safety and `assume_bounds_cast`, which does no runtime checking and trusts the programmer. The rules for pointer casting and the bounds cast operators are described in Section 5.1.

2.5.1 Rules for the address-of operator

If an address-of operator (`&`) applied to an lvalue expression of type `T`, the following rules apply:

- If the operator occurs in a checked block, the address-of operator produces a value of type `array_ptr<T>`.
- Otherwise, the address-of operator produces a value of type `T *`.

2.5.2 Rules for conversion of checked array types to pointer types

If the type of an expression is “checked array of `T`”, the type of the expression is altered to be `array_ptr<T>`. If the type of an expression is “checked null-terminated array of `T`”, the type of the expression is altered to be `nt_array_ptr<T>`.

Following existing C language rules, this alteration does not happen if the expression is an operand of an address-of operator, `++`, `--`, `sizeof`, or the left operand of an assignment operator or the `.'` operator. The prohibition against this conversion occurring for operands of the address-of operator gives the results of the operator a more precise type. For `sizeof`, it also results in a more precise answer. The prohibitions against it for `++`, and `--` operands and the left operand of an assignment operator keeps array variables from being modifiable.

2.6 Variable and member initialization

Variables that have checked pointer types and that may be used to access memory must be initialized when they are declared. This includes variables that have `ptr` or `nt_array_ptr` type and variables that have `array_ptr` type and declared bounds. Variables with `array_ptr` type that have no declared bounds do not have to be initialized because they cannot be used to access memory. In addition, variables that have members or elements with checked pointer types and that may be used to access memory must be initialized when they are declared.

Static variables and their members or elements are zero-initialized at program start-up time, if no initializer is declared. Programmers do not need to do anything to initialize them. Zero is a valid value for a checked pointer. Automatic variables are indeterminately initialized when they are created. Programmers must initialize these variables explicitly using C's initializer syntax when they are declared.

Initializing an automatic variable with a checked pointer type is simple: a programmer adds `= 0` or `x = NULL` to the variable declarator. C's initializer syntax allows compact initializers for structure variables and array variables. A list of initialization values is specified using a brace-enclosed list of expressions. The initializer list can be partial list that describes only some of the initialization value. The remaining data will be initialized to default values for types (0 for pointer types). It suffices to have an initializer for the first member of a structure or element of an array. The initializer list `{ 0 }` can be used.

Here are examples of variable declarations with initializers:

```
ptr<int> p = 0; // initializer required.
array_ptr<int> q : count(5) = 0; // has bounds; initializer required.
array_ptr<int> lower, upper; // no bounds; initializer not required.
lower = q;
upper = q + 5;

struct VariableBuffer {
    array_ptr<int> buf : count(len);
    int len;
};

struct Range {
    array_ptr<int> lower;
    array_ptr<int> upper;
};

struct VariableBuffer buf = { 0 }; // initializer for struct required.
struct Range pair; // no bounds on members; initializer
                    not required.
ptr<int> data checked[10] = { 0 }; // initializer for array required.
struct VariableBuffer stack checked[10] = { 0 }; // initializer for array
                    required.
```

For heap-allocated data that contains checked pointers that may be used to access memory, the data must be zero-initialized by the programmer. We recommend that programmers use `calloc` instead of `malloc` for heap-allocating data containing checked pointers.

2.7 Program scopes for checked pointer types

To improve program reliability and to simplify understanding programs, it is desirable to limit code to using only checked pointers. To support this, we introduce checked program scopes. The `checked` keyword can be attached to blocks and function definitions. In checked program scopes, the declared types of variables are allowed to be or use checked pointer types or checked array types; unchecked pointer types and unchecked array types are not allowed. Similarly, for functions, return types and parameter types are allowed to be or use checked pointer types or checked array types.

On the other hand, declarations in checked scopes can use unchecked pointer types and unchecked array types, provided that the declarations provide a bounds-safe interface. These are described in Section 5.3. Variables and functions used in checked scopes are allowed to have or use checked pointer types, checked array types, or unchecked pointer types and unchecked array types with bounds declarations.

A new pragma directive `CHECKED_SCOPE` is introduced to control whether the top-level scope is a checked scope:

```
#pragma CHECKED_SCOPE on-off-switch
```

Where *on-off-switch* is one of `ON OFF DEFAULT`

By default, function definitions are not checked. A block inherits the checking properties of its parent. This preserves the meaning of existing C code.

A checked block is introduced by placing `checked` before a compound block:

```
checked
{
    int a = 5;
    ptr<int> pa = &a;

    int b checked[5][5];
    for (int i = 0; i < 5; i++) {
        for (int j = 0; j < 5; j++) {
            // all references are bounds checked
            b[i][j] = -1;
        }
    }
}
```

It is rarer for a programmer to need to introduce an unchecked scope. It is needed usually to allow the use of unchecked pointers within a checked block. The `unchecked` keyword can be used in all the places where the checked keyword can be used. This example shows the use of an unchecked block:

```
checked
{
    int a = 5;
    unchecked
    {
        int *upa = &a;
        int b[5][5];
        for (int i = 0; i < 5; i++) {
            for (int j = 0; j < 5; j++) {
```

```
        // not bounds checked
        b[i][j] = -1;
    }
}
...
}
```

In a checked function definition, the body of the function is a checked block. A checked function definition is declared by placing the `checked` keyword before the definition. Here are examples of checked and unchecked function definitions:

```
// checked at the function level: no unchecked pointers can appear in
// argument types, the return type, or the body of the function.
checked int f(ptr<int> p)
{
    int a = 5;
    ptr<int> pa = &a;
    ...
}

// unchecked at the function level: checked and unchecked pointer types
// can occur in argument types, the return type, or the body of the
// function.
unchecked int f(int *p, ptr<int> r)
{
    int a = 5;
    int *pa = &a;
    ...
}

// f is unchecked by default
int f(int *p, ptr<int> r)
{
    int a = 5;
    int *pa = &a;
    ...
}
```

When a function call occurs in a checked block, the function being called does not have to be declared as checked. The notion of whether a scope is checked or not checked is lexical and the function definition is a separate lexical scope.

C allows declarations of functions without prototypes², where the types of the arguments to functions are not specified. These functions are dangerous to use because there can be mismatches between argument types and parameter types at function calls. This can corrupt data or the call stack. In checked scopes, the use or declaration of functions without prototypes is not allowed.

As we add different notions of checking to Checked C, we will use the `checked` and `unchecked` keywords for all the different notions of checking. We may introduce additional keywords to control

²These are sometimes referred to as K&R-style function declarations because this is the only way functions were declared in the first edition of the C Programming Language book by Brian Kernigan and Dennis Ritchie. The second edition incorporated changes from the C ANSI Standard and introduced function prototypes.

specific kinds of checking.

2.8 String literals, compound literals, and initializer expressions

C programs can declare string literals and compound literals. Examples of string literals are expressions such as `"hello"` and `L"hello"` (in the latter case, the modifier ‘L’ changes the type of the characters in the string). A compound literal is an expression that declares an array literal or an object literal. It consists of a parenthesized type name followed by list of initializers in braces. A compound literal has static storage if it is at the top level of a file and automatic storage if it occurs within a block. Here are examples of compound literals:

```
int *arr = (int []) { 0, 1, 2};
struct Point {
    int x;
    int y;
};
struct Point *zero_coord = &((struct Point) { 0, 0 });
```

A string literal has an array type with an element type that is one of `char`, `wchar_t`, `char16_t`, or `char32_t`. For Checked C, there is a question about whether the array type should be an unchecked or checked array. The type of a string literal with an element type T depends on whether the literal occurs in a checked scope or an unchecked scope:

- In a checked scope, the type is “null-terminated checked array of T ”.
- In an unchecked scope, the type is “unchecked array of T ”.

This creates an issue in unchecked scopes when a string literal is used where a null-terminated checked pointer type is expected. It makes sense to allow this because string literals have known bounds. However, a string literal would have the type “unchecked array of T ”, which would convert to “unchecked pointer to T ”. There is no conversion from the unchecked pointer type to “unchecked null-terminated pointer to T ”. To allow this, we alter the rule for implicit conversion of array types to pointer types:

- If the type of a string literal or compound literal expression with type “array of T ” has been altered to be “ $T *$ ”, and the expression appears in a context where a checked pointer type is expected, the type of the expression is further altered to be “checked pointer to T ”. The kind of the checked pointer shall match the kind of the expected pointer type. The contexts where this is allowed are the right-hand side of an assignment, an argument to a function call, or in an initializer.
- The string literal or compound literal may be possibly parenthesized.
- The type “checked pointer to T ” must be a valid type. Null-terminated array pointers to non-scalar and non-integer types are not allowed.

This rule is not strictly necessary for compound array literals. The type name in the compound array literal could be modified, of course. We allow this rule anyway to reduce the amount of code changes required to modify code to be checked.

Note that some C compilers use the same memory to represent different occurrences of string literals that have the same characters sequence. The meaning of modifying a string literal is

implementation-dependent. For bounds safety, an implementation should either

- not do this for string literals whose modified pointer types differ in whether they are null-terminated, or
- make string literals read-only.

2.8.1 Examples

```
checked void f(void) {
    // "hello" has type char nt_checked[6]. The type is altered during type
    // checking to nt_array_ptr<char>.
    nt_array_ptr<char> p = "hello";

    // "goodbye" has type char nt_checked[8]. The type is altered during
    // type checking to the pointer type array_ptr.
    array_ptr<char> r = "goodbye";

    // Use compound array literals instead.
    p = (char nt_checked[6]) { 'h', 'e', 'l', 'l', 'o', '\0' };
    r = (char checked[8]) { 'g', 'o', 'o', 'd', 'b', 'y', 'e', '\0' };
}

checked char lookup(int i) {
    // "abcdef" has type char nt_checked[7]. The type is altered during type
    // checking to nt_array_ptr<char>. The subscript operation will be
    // bounds checked.
    return "abcdef"[i];
}

unchecked char unsafe_lookup(int i) {
    // "abcdef" has type char[7]. The type is altered during type checking
    // to char *. The subscript operation will not be bounds checked.
    return "abcdef"[i];
}

// find pattern in str
extern int find(nt_array_ptr<char> pattern, nt_array_ptr<char> str);

int g(void) {
    // "brown" has type char[6]. The type is altered during type checking
    // to the type char *. It is then further altered to have the type
    // nt_array_ptr<char>, matching the argument type for pattern.
    // A similar alteration happens for the second argument string literal.

    int r = find("brown", "the brown fox jumped over the fence");
    return r;
}

// Declare a string with a count.
struct string_with_count {
    nt_array_ptr<char> buf;
    int len;
}
```

```
};
```

```
ptr<struct string_with_count> S =
    &((struct string_with_count) { "hello world", 11 });
```

2.8.2 Initializers

C allows declared variables to be initialized using initializers. An initializer is either an expression or a brace-enclosed list of initialization values. The brace-enclosed list may be a partial list and specify values only for part of an object or array. In that case, the remaining part of the array or object is initialized with default values (0 for integers or pointers).

For Checked C, no modifications are needed to initializers. the value of the initializer is interpreted based on the type of the declared variable and its members. A checked array or pointer is initialized the same way that an unchecked array or pointer is initialized. For null-terminated checked arrays, we require that the last element in the array be initialized to a null terminator.³

A variety of interesting and complex initialized checked data structures can be declared:

```
// Initialize a checked pointer to the null pointer.
ptr<int> p = 0;

// Initialize a checked array.
int arr1 checked[5] = { 0, 1, 2, 3, 4 };
int arr2 checked[3] = { 0, 1, 2 };

// Initialize pointers to checked arrays
array_ptr<int> ap1 = arr1;
array_ptr<int> ap2 = (int checked[4]) { 0, 0, 0, 0 };

// Initialize a multi-dimensional checked array
float unit_transform checked[2][2] = { { 1.0f, 0.0f }, { 0.0f, 1.0f } };

// A ragged 2-dimensional array, where the inner dimension size varies.
struct inner_array {
    int len;
    array_ptr<double> elems; // bounds declaration missing because we
                           // haven't described them yet.
};

typedef struct inner_array ragged_2d_arr[];

ragged_2d_arr data =
    { { 3, (double checked[]) { 1.0, 0.0, 0.0 } },
      { 1, (double checked[]) { 5.0 } },
      { 0, 0 },
      { 2, (double checked[]) { 6.0, 7.0 } }
    };

struct BufferPair {
    int len1;
```

³There does not need to be a full list of initialization values. An initializer with a partial list of initialization values will still meet this requirement. The default for integers and pointers is 0, which is the null terminator for those values.

```

    array_ptr<int> buf1;
    int len2;
    array_ptr<int> buf2;
};

// Initialize all members.
struct BufferPair p1 = { 5, arr1, 3, arr2 };

// Declare a partial initializer.
// len2 and buf2 are initialized to 0.
struct BufferPair p2 = { 0, arr1 };

// Strings and initialized arrays of characters.

nt_array_ptr<char> red = "red";
char green checked[] = "green";
char blue nt_checked[] = "blue";
char purple nt_checked[7] = "purple";

// Checked arrays of checked strings
nt_array_ptr<char> colors checked[] = { "red", "green", "blue",
                                         "purple" };

// Null-terminated arrays of checked strings
nt_array_ptr<char> more_colors nt_checked[] = { "white", "black",
                                                  "grey", 0 };

// A null-terminated array of pointers to null-terminated arrays
// of strings.
nt_array_ptr<nt_array_ptr<char>> sentences nt_checked[4] =
{ (nt_array_ptr<char> nt_checked[]) { "this", "is", "the", "first",
                                         "sentence", 0 },
  (nt_array_ptr<char> nt_checked[]) { "here", "is", "another", 0 },
  (nt_array_ptr<char> nt_checked[]) { "this", "is", "the", "last",
                                         "one", 0 },
  0
};

```

2.9 Relative alignment of `array_ptr` values

`array_ptr<T>` pointers provide pointer arithmetic on arrays. The bounds for these pointers usually describe a range of memory that is exactly the size of some array of T . The pointers point to an element of the array. In other words, the lower bound, the upper bound, and pointer are relatively aligned to the type T . Given a lower bound lb , an upper bound ub , and a pointer p , there should exist some integer $count$ such that $ub = lb + count$. In addition, there is either some integer $index$ such that $p = lb + index$, where addition is C pointer arithmetic, or p is null.

The type to which a pointer and its bounds are relatively aligned is called the relative alignment type. By default, the relative alignment type for a pointer and its bounds is the referent type. However, the relative alignment type can be overridden by specifying it explicitly as part of the bounds. This is described in Section 3.9.1. This can be used for bounds for the results of pointers

casts and for `array_ptr<void>` pointers. The type `void` has no defined size, so the default relative alignment is undefined for `void`.

We considered removing the entire concept of relative alignment from the design to simplify the design. We decided against that because it would increase the cost of bounds checking throughout the program. Section 11.3 explains this choice in more detail.

2.10 Pointer arithmetic error conditions

For existing unchecked C pointers, the definition of pointer arithmetic is described in terms of addresses of elements of an array object. The C Standard [50] states, that given a pointer `p` that points to some element `i` of an array object, `p + j` points to the $(i+j)$ th element of that object. Pointer arithmetic is defined only for pointers to elements of the array object or one past the last element of the array object.

We take an alternative approach to defining the meaning of pointer arithmetic and the error conditions for pointer arithmetic. Pointer arithmetic is allowed to go out-of-bounds and has a well-defined semantics. Section 2.10.1 defines the semantics of the new pointer types directly in terms of byte addresses, instead of with respect to addresses of elements of an array. Pointer arithmetic that overflows or involves a null pointer is defined to produce a runtime error.

The new pointer types allow pointer arithmetic that produces out-of-bounds values. The C definition leaves pointer arithmetic that produces out-of-bounds values undefined because it is not clear what the meaning of should be when the pointers are dereferenced. The new pointer types prevent out-of-bounds pointers from being dereferenced, and solve this problem another way. In addition, in practice C implementations often allow pointer arithmetic to produce out-of-bounds values and C programs end up relying on this implementation-specific behavior. There is no reason to cause existing code that computes out-of-bounds pointers but does not dereference them to break when it is converted to use the new pointer types.

When pointer arithmetic overflows or involves a null pointer, the resulting value of the expression cannot be used and program execution stops. If a system provides for error handling, an error handling mechanism may be invoked to redirect program execution to a new point of execution that does not use the value of the expression.

Defining pointer arithmetic this way simplifies reasoning about the new pointer types. Expected identities such as `p + 1 > p` now hold because, if `p + 1` overflows, the value cannot be used. This allows programmers to narrow the bounds for `array_ptr` values by incrementing the lower bound or decrementing the upper bound, even in situations where the bounds are at the ends of the address space. Later sections describe places where allowing an undefined value to be used would complicate reasoning about programs.

If a compiler cannot prove that a new pointer type value is non-null before a pointer arithmetic operation, it must insert a check. Similarly, if a compiler cannot prove that a pointer arithmetic expression for a new pointer type cannot overflow, it must insert a check. This may slow a typical program down by a slight amount.

2.10.1 Semantics of pointer arithmetic for new pointer types

This section defines the semantics of pointer arithmetic and explains when overflow occurs in pointer arithmetic. It is assumed that memory is addressable at the byte level. The order of bits within a byte is not specified. The order of bytes within built-in types larger than a byte, such as integers and floating-point numbers, is also not specified. Pointers shall be treated as addresses of locations of bytes in memory. The addresses shall be unsigned integers with a defined range of 0 to `UINTPTR_MAX`. The maximum value of a signed integer that can be added to an address shall be given by `INTPTR_MAX` and the minimum value of a signed integer that can be added to an address shall be given by `INTPTR_MIN`.

For the new `array_ptr<T>` pointer types, there are distinct operations for addition and subtraction of pointers by signed and unsigned integers. The operations behave similarly, but have different overflow conditions for scaling because the ranges of signed integers and unsigned integers are different.

- First scaling an integer by `sizeof(T)` is defined. To scale an integer i , i shall be multiplied by `sizeof(T)`, producing an integer j . If i is a signed integer, the scaled result shall be treated as a signed integer. If i is an unsigned integer, the scaled result shall be treated as an unsigned integer. For a signed integer, the minimum and maximum range for j shall be `INTPTR_MIN` and `INTPTR_MAX`. For an unsigned integer, the minimum and maximum range for j shall be 0 and `UINTPTR_MAX`. If j is outside its valid range, the operation doing the scaling operation shall produce a runtime error.
- $p + i$, where p is an `array_ptr<T>` pointer and i is an integer. The integer i shall be scaled by `sizeof(T)`, producing an integer j . The pointer p will be interpreted as an unsigned integer. The mathematical value $p + j$ shall be the result of the operation. If $p + j$ is out of range for a pointer, the operation shall produce a runtime error.
- $i + p$, where p is an `array_ptr<T>` pointer and i is an integer, shall be defined as $p + i$.
- $p - i$, where p is an `array_ptr<T>` pointer and i is an integer. The integer i shall be scaled by `sizeof(T)`, producing an integer j . The pointer p will be interpreted as an unsigned integer. The mathematical value $p - j$ shall be the result of the operation. If $p - j$ is out of range for a pointer, the operation shall produce a runtime error.
- $p - q$, where p and q are `array_ptr<T>` pointers. The two pointers will be interpreted as unsigned integers and the mathematical value $p - q$ shall be computed, producing an integer j . If j is out of range for signed integer that can be added to an address, the operation shall produce a runtime error. If j is a multiple of `sizeof(T)`, the result shall be $j / \text{sizeof}(T)$. If j is not a multiple of `sizeof(T)`, then the value shall be determined as follows:
 - If j is non-negative, $j / \text{sizeof}(T)$ shall round toward 0.
 - If j is negative, it shall be implementation-defined whether $j / \text{sizeof}(T)$ rounds toward 0 or away from 0.

An important implication of these definitions is that they put a maximum limit on the number of elements in an array of type T . It is `UINTPTR_MAX/sizeof(T)`. They also put maximum limits on the number of elements that can be accessed in an array by a signed integer or an unsigned integer. That leads to limits on the size of arrays that can be described by some bounds. A signed integer that must be non-negative can describe an array of `INTPTR_MAX/sizeof(varT)` elements.

2.10.2 Expressing pointer arithmetic as integer arithmetic

During static checking, pointer arithmetic operations will be converted to use integer arithmetic. This is necessary in C because at times programmers do explicit size computations that follow the same rules as pointer arithmetic.

To support this expansion, integer arithmetic operators are extended with the operators `+ovf`, `-ovf`, and `*ovf`. The operators interpret pointers as unsigned integers in some range 0 to `UINTPTR_MAX`. An operator produces a runtime error if the value of its result cannot be represented by the result type:

- `+ovf` takes an unsigned integer `i` and an integer `j` and produces an unsigned integer in the range 0 to `UINTPTR_MAX`. Its result is the mathematical value `i + j`.
- For subtraction, there are two forms:
 - `-ovf` takes an unsigned integer `i` and an integer `j` as an argument and computes `i - j`, producing an unsigned integer in the range 0 to `UINTPTR_MAX`. Its result is the mathematical value `i - j`.
 - `-ovf_diff` takes two unsigned integers `i` and `j` and computes `i - j`, producing a signed integer of type `ptrdiff_t`. Its result is the mathematical value `i - j`.
- `*ovf` takes two integers `i` and `j` (both either signed or unsigned) as arguments. It produces an integer whose type is the same as the input argument types. Its result is the mathematical value `i * j`.

Given an expression `e1` with a pointer type and an expression `e2` with an integer type, the expansion of `e1 + e2` from pointer arithmetic to integer arithmetic depends on the type of `e2`. The number of bytes to added must be the same kind of signed or unsigned integer as `e2`.

- If `e2` is an unsigned integer, `e1 + e2` expands to `e1 +ovf sizeof(T) *ovf e2`.
- If `e2` is a signed integer, the expansion of `e1 + e2` must cast `sizeof(T)` to a signed integer. We introduce a signed integer type `signed_size_t` that is large enough for this cast. `e1 + e2` expands to `e1 +ovf ((signed_size_t) sizeof(T)) +ovf e2`. This cast is necessary because in C, multiplying a signed integer by an unsigned integer implicitly converts the signed integer to be an unsigned integer.

2.10.3 Runtime performance implications

There will be concerns about the effect of overflow checks on the speed of pointer arithmetic using the new pointer types. These concerns are an empirical question to be settled after implementing and using the new pointer types. It is unclear what the actual cost will be. First, there will be sometimes be additional conditions on expressions used in pointer arithmetic that prevent overflow from occurring. Second, compiler optimizations often can remove the checks. Third, programmers can use lightweight invariants to show statically that checks are not necessary.

In our experience working on an operating system written in managed code that required these checks, the slowdown was a few percent, even when *all* arithmetic instructions were checked for overflow too. The cost of checks was low because it is often the case that checks are redundant or can be combined into adjacent machine instructions. For example, in the code `t = *p; p += 1;` the first dereference of `p` implies that `p` is non-null before the increment. Otherwise, in a typical

C environment, the program would fault at `*p`. In the code `if (p < hi){ p += 1; }` the check `p < hi` implies that the increment cannot overflow. The checks are also inexpensive on superscalar processors: they can be placed so that they are statically predicted by processors to never fail.

2.11 Programmer-inserted dynamic checks

A bounds check generates a runtime error if it fails. The ability to generate a runtime error is not limited to the C implementation. A programmer can check a Boolean condition and generate a runtime error using the expression `dynamic_check(e1)`, where `e1` is an integral valued expression. At runtime, `e1` is evaluated. If the result is 0 (false), a runtime error occurs. If the result is non-zero (true), no runtime error occurs. Just as with a bounds check, if a runtime error occurs and a C implementation provides an error-handling facility, the error-handling facility may be invoked. `e1` must be a non-modifying expression that does not modify program state (see Section 3.6.1).

The `dynamic_check` expression is similar to an assertion, but unlike an assertion, it is expected to be used in production or release versions of software. The `dynamic_check` expression is useful for these reasons:

- It provides an escape hatch for limits of static checking. If a programmer knows a condition is true at runtime, yet the static checking cannot prove the fact, the programmer can use `dynamic_check` to show that the condition is true.
- It maintains programmer control: programmers can use unchecked pointers and `dynamic_check` to write the same code that the compiler would generate for checked pointers.
- It gives programmers more control over bounds checks. A programmer can place a pre-condition before a loop that ensures that the loop is free from dynamic bounds checks, without having to restructure the control-flow of the program.

The expression being checked must be non-modifying because `dynamic_check` checks if an invariant holds. An invariant should not modify program state.

The following example illustrates why having an escape hatch from static checking is useful. Suppose a decoder from a compressed representation to an uncompressed representation is being converted to use checked pointers. This example is based on code patterns seen in the Abstract Syntax Notation (ASN1) parsing code of OpenSSL [25].

```
void decode(char *output_buffer, char *input_buffer, size_t input_len)
{
    char *src = input_buffer;
    char *src_bound = src + input_len;
    char *dst = out_buffer;

    while (src < src_bound) {
        switch (*current++) {
            case UNCOMPRESSED_BYTES: {
                // just copy bytes; compression wasn't useful here.
                size_t len = src[0] + src[1]*256;
                src += 2;
                memcpy(dst, src, len);
                src += len;
                dst += len;
            }
        }
    }
}
```



```

        break;
    }
    case COMPRESSED_INT64: {
        ...
        break;
    }
    ...
}

```

The caller knows that the destination buffer will be large enough and that the contents of the source buffer are well-formed. However, these invariants cannot be expressed using lightweight invariants. These are complicated high-level invariants that require the use of techniques for proving functional correctness.

To use checked pointers, the size of the destination buffer must be passed in and there must be a check before the memcpy that the destination buffer and source buffer have enough room. We ignore the details of how the bounds are described for now. The new code for checked pointers is italicized and highlighted in yellow:

```

void decode(array_ptr<char> output_buffer, array_ptr<char> input_buffer,
            size_t input_len, size_t output_len)
{
    array_ptr<char> src = input_buffer;
    array_ptr<char> src_bound = src + input_len;
    array_ptr<char> dst = output_buffer;
    array_ptr<char> dst_bound = out_buffer + output_len;

    while (src < src_bound) {
        switch (*current++) {
            case UNCOMPRESSED_BYTES: {
                size_t len = src[0] + src[1]*256;
                src += 2;
                // need check that dst and src have at least len bytes of space
                memcpy(dst, src, len);
                src += len;
                dst += len;
                break;
            }
            case COMPRESSED_INT64: {
                ...
                break;
            }
            ...
        }
    }
}

```

How should that check be written? One approach is to change the control-flow by inserting if-statements into the program. Something must be done if the check fails, though. One possibility is to just ignore a failure. This is a bad programming practice because now the program might fail silently:

```

void decode(array_ptr<char> output_buffer, array_ptr<char> input_buffer,
            size_t input_len|\textit{, size\_t output\_len}|)

```

```

{
    ...
    case UNCOMPRESSED_BYTES: {
        size_t len = src[0] + src[1]*256;
        src += 2;
        // check that dst and src have at least len bytes of
        // space
        if (dst + len >= dst_bound || src + len >= src_bound) {
            goto failure;
        }
        memcpy(dst, src, len);
        src += len;
        dst += len;
        break;
    }
    ...
failure:
    return;
}

```

This could be fixed by having `decode` return a status code indicating success or failure. That just pushes the problem upward to the caller and leaves a testing problem. The program should never fail, so there is no way to test the path.

```

int decode(array_ptr<char> output_buffer, array_ptr<char> input_buffer,
           size_t input_len, size_t output_len)
{
    ...
failure:
    return 1;
}

```

The problems with requiring functions that validate buffer lengths to return status codes for errors are analyzed by O'Donnell and Sebor[78]. Annex K of the C Standard [50] introduced a new set of standard library functions to replace functions that provide no way to validate their arguments. These functions return status codes to indicate success or failure. A classic example of a function prone to misuse is `strcpy(char *dst, const char *src)`. It copies all bytes in `src` to `dst` until it hits a null byte. If `src` is missing the null byte or `dst` is too small, this causes a buffer overrun. The new function `strcpy_s` takes an additional size parameter for `dst` and has the signature `errno_t strcpy_s(char *dst, size_t dest_len, const char *src)`. O'Donnell and Sebor explain how using these functions is awkward, leading to more complicated and less efficient code.

In contrast, `dynamic_check` allows the checking to be localized and not propagate upward in the call chain. If the programmer is correct, the check never fails. If the programmer is incorrect, the check might fail and invoke error-handling code:

```

void decode(array_ptr<char> output_buffer, array_ptr<char> input_buffer,
           size_t input_len, size_t output_len)
{
    ...
    case UNCOMPRESSED_BYTES: {
        size_t len = src[0] + src[1]*256;
        src += 2;

```

```

        dynamic_check(dst + len < dst_bound && src + len < src_bound);
        memcpy(dst, src, len);
        src += len;
        dst += len;
        break;
    }
    ...
}

```

One can argue that it is a problem to have a dynamic point of failure that leads to error-handling code being invoked. This is the same way systems treat null pointer dereferences, though, which are a possibility throughout C code. The alternative of having a program with undefined behavior is worse.

The following example uses `dynamic_check` to eliminate bounds checks in a loop. It is based on experience hand-optimizing C# and Java programs. This kind of example is typically found during a performance tuning phase of program development. In the example, the `: count(exp)` notation indicates that *exp* is the length of the buffer.

```

void append(array_ptr<char> dst : count(dst_count),
            array_ptr<char> src : count(src_count),
            size_t dst_count, size_t src_count)
{
    for (size_t i = 0; i < src_count; i++) {
        if (src[i] == marker) {
            break;
        }
        dst[i] = src[i];
    }
}

```

The italicized expressions are bounds checked:

```

void append(array_ptr<char> dst: count(dst_count),
            array_ptr<char> src : count(src_count),
            size_t dst_count, size_t src_count)
{
    for (size_t i = 0; i < src_count; i++) {
        if (src[i] == marker) {
            break;
        }
        dst[i] = src[i];
    }
}

```

It is clear that the accesses to `src` are in-bounds based on just information from the for-loop, so a compiler will eliminate those bounds checks. It is not clear that assignments through `dst` are always in bounds, so the check there must remain. It can be eliminated by adding a `dynamic_check`:

```

void append(array_ptr<char> dst: count(dst_count),
            array_ptr<char> src : count(src_count),
            size_t dst_count, size_t src_count)
{
    dynamic_check(src_count <= dst_count);
}

```

```

for (size_t i = 0; i < src_count; i++) {
    if (src[i] == marker) {
        break;
    }
    dst[i] = src[i];
}
}

```

The compiler now knows that `i < src_count <= dst_count`, so it can eliminate the check.

A compiler would not introduce this `dynamic_check` because it would alter the behavior of `append`. The bounds check on `dst` in the original code is done only if a marker is not found in `src` and `src_count > 0`. A compiler could try to deduce a precondition for the loop that prevents the bounds check from failing, but this is not possible because the precondition depends on the contents of `src`. A compiler would have to clone code to maintain the same behavior. This increases code size, so production compilers do not this sort of transformation or do it sparingly. Programmer control produces better results. Here is the code a compiler might generate with cloning.

```

void append(array_ptr<char> dst: count(dest_count),
            array_ptr<char> src : count(src_count),
            size_t dst_count, size_t src_count)
{
    if (src_count <= dst_count) {
        for (size_t i = 0; i < src_count; i++) {
            if (src[i] == marker) {
                break;
            }
            dst[i] = src[i]; // no bounds check needed
        }
    } else {
        for (size_t i = 0; i < src_count; i++) {
            if (src[i] == marker) {
                break;
            }
            dst[i] = src[i]; // bounds check needed
        }
    }
}

```

2.12 Changes to undefined behavior

C has situations where an expression has undefined behavior or the meaning of an expression is undefined:

- Pointer arithmetic for unchecked pointer types only has defined behavior when the resulting pointer points to the same object as the original pointer, or one element past the object.
- Pointer comparison for unchecked pointer types only has defined behavior when comparing pointers to the same object (where one or both pointers may point one element past the same object).

- Pointer subtraction for unchecked pointer types only has defined behavior when subtracting pointers to the same object (where one or both pointers may point one element past the object).
- Arithmetic expression behavior is undefined on signed integer overflow and integer division by 0.
- Expressions may have nested assignments within them. The evaluation order of side-effects in subexpressions is defined only in specific circumstances; otherwise it is undefined. This leads to expressions with undefined meaning. There can be multiple assignments to the same variable that have no defined evaluation order with respect to each other or an assignment and a use of a variable that have no defined evaluation order.
- Initializers may have nested assignments within them. These can have undefined meanings as well for the same reasons as expressions.

Undefined behavior is different from unspecified behavior, where one of a number of choices may be made. Unspecified behavior in C includes:

- The order of evaluation of side-effects in expressions (so long as the expression does not have undefined behavior).
- The order of evaluation of side-effects in initializers.

C also has implementation-defined behavior, which includes:

- The ranges of values for integer, floating-point, and pointer types.
- Data layout, including the sizes of types, padding, and alignment of data.
- Some aspects of pointer conversion.

It is difficult to reason about the correctness of programs that have expressions with undefined behavior. One has to make sure that a program never arrives at a point where behavior is undefined. In practice, this would mean proving that signed integer overflow can never occur, for example. For unspecified behavior, one has to reason about all possible behaviors, such as all possible orders of evaluation. For implementation-defined behavior, one has to reason about the implementation-specific behavior or have reasoning that is independent of the details.

A careful reading of the rules for unchecked pointer comparison implies that it is impossible to detect an out-of-bounds unchecked pointer in C, for example. If an unchecked pointer p is not in the valid range for an object, the pointer comparison is undefined.

To provide for pointer bounds safety, we require that C implementations provide defined behaviors for unchecked pointer arithmetic operations and signed integer overflow:

- Unchecked pointers shall be treated as addresses of locations in memory, just as checked pointers are treated as addresses. The addresses shall be unsigned integers with a defined range of 0 to `UINTPTR_MAX`:
 - Comparison of pointers for all different kinds of pointers shall be defined as the corresponding integer comparison.
 - Subtraction $p - r$ of two pointers p and r of type T where one pointer is a checked pointer and the other is an unchecked pointer shall be done following the rules for

subtraction of checked pointers, treating the unchecked pointer as a checked pointer in those rules.

- To be able to maintain pointer bounds safety, it is important that signed integer overflow produce a defined value. When a signed integer expression produces an out-of-range value, either (1) the operation must convert that value to an in-range integer value or (2) the expression shall produce a runtime error. The conversion must be a function of only the input values of the expression.
- Integer division by 0 shall also produce a runtime error or produce a defined value.

In the case of a runtime error, program execution cannot continue in a way that uses the value of the expression that produced the error.

For programs with expressions and initializers with undefined meanings, those programs must be rejected at translation-time. Section 4.11 describes this in detail.

Of course, there are other ways in which C expressions may have undefined behavior:

1. By reading or writing memory through an out-of-bounds pointer.
2. By storing a value of one type and accessing the value as a different type later, when the value is not valid for the different type. A program might write bit patterns that do not correspond to valid values for a type or write an integer and use it as a pointer later, even though the pointer is not within the range of memory for a valid object.
3. By accessing memory that has been deallocated.
4. By using variables or functions with inconsistent declarations across different translation units. This can cause the type of a variable or a function to be different at the definition and the use. This can be addressed with suitable link-time checking.

The aim is to be able to show partial correctness of programs for the first item (avoiding out-of-bounds pointer accesses). A partial correctness guarantee has the form “assuming X holds, then Y is true”. Informally, one might say “assuming that memory allocation and type casts are correct and that unchecked code never reads or write through out-of-bounds pointers, then checked code never reads or writes through out-of-bounds pointers.” These assumptions can be turned into formal statements about program behavior at runtime. Given those assumptions, we might then prove that at runtime checked code never reads or writes through out-of-bounds pointers.

Chapter 3

Bounds for variables

Variables with `array_ptr` types that are used to access memory must have bounds declared for them. The same requirement holds for variables with incomplete checked array types. The bounds will be used to check memory accesses at runtime involving the pointers stored in the variable or pointers produced by pointer arithmetic that uses those pointers. Runtime checks can be omitted if a compiler proves that they are redundant. In addition, for performance-critical code, checks will be omitted when programmers demonstrate at compile-time that the checks are redundant (see Section 8.2.6 for details).

3.1 Bounds declarations

Bounds are declared using bounds declarations. Bounds declarations have the form:

bounds-decl:

x : *bounds-exp*

bounds-exp:

`count`(*non-modifying-exp*)

`bounds`(*non-modifying-exp*, *non-modifying-exp*)

`bounds`(`unknown`)

`bounds`(`any`)

where x is a variable. Additional forms for handling `void` pointers and casts are described in Sections 3.2.5 and 3.9.

A bounds expression describes the memory that can be accessed using the value of x , provided that x is not null. Bounds expressions include counts, pairs that specify an upper bound and lower bound, `bounds`(`unknown`), and `bounds`(`any`):

- x : `count`($e1$) describes the number of elements that are accessible beginning at x . Only memory that is at or above x and below $x + e1$ can be accessed through x , where $x + e1$ is interpreted using `array_ptr` pointer arithmetic.
- x : `bounds`($e1, e2$) describes the range of memory that can be accessed through x . Only memory that is at or above the location specified by $e1$ and below $e2$ can be accessed through

x .

- $x : \text{bounds}(\text{unknown})$ declares that x has bounds that are unknown at compile-time. It is a compile-time error to attempt to access memory using a variable of type `array_ptr` with unknown bounds.
- $x : \text{bounds}(\text{any})$ is a special form that readers can ignore for now. It is used for null pointers (0 cast to a pointer type) and means that x can have any bounds. Because null pointers cannot be used to access memory, they can have any bounds.

Bounds expression use “non-modifying” expressions. These are a subset of C expressions that do not modify variables or memory. They include local variables, parameters, constant expressions, casts, and operators such as addition, subtraction, and address-of. Section 3.6.1 describes non-modifying expressions in detail.

In a bounds declaration of the form $x : \text{bounds-expr}$, x can have an `array_ptr` or a checked array type. For the form $x : \text{count}(e1)$, the type of x cannot be `array_ptr<void>` and the type of $e1$ must be an integral type. The usual C integer conversions are applied to $e1$.¹ For $x : \text{bounds}(e1, e2)$, $e1$ and $e2$ must be pointers to the same type. Typically x is also a pointer to that type or an array of that type. However, x can be a pointer to or an array of a different type. This is useful for describing the results of casts and bounds for `array_ptr<void>` pointers.

For any variable with a bounds declaration, the variable must be non-null when memory is accessed. There is no requirement that an `array_ptr` variable stay within its bounds. The requirement is that the `array_ptr` variable can only be dereferenced if it is in bounds. This avoids bound checks on pointer arithmetic.

Count expressions have limits on their ranges to prevent signed integer overflow and unsigned integer wraparound from affecting size computations. Section 3.7 explains these limits in detail. The limits depend on the element type of the `array_ptr` and the type of the count expression. For $x : \text{count}(e1)$, where x has type `array_ptr<T>` $e1$ must be greater than or equal to 0. $e1$ must be less than the maximum number of `array_ptr<T>` elements that can be indexed by an integer whose type matches that of $e1$. For `nt_array_ptr`, there is a null terminator at or beyond the upper bound, so $e1$ must be less than the maximum number of `array_ptr<T>` elements minus one.

A bounds declaration $x : \text{count}(e1)$ is an abbreviation for $x : \text{bounds}(x, x + e1)$ with additional conditions that $e1 \geq 0 \ \&\& \ e1 \leq (\text{char} *) \text{ub}$. ub is either `UINTPTR_MAX/sizeof(T)` or `INTPTR_MAX/sizeof(T)`.

The conditions may require programmers to add additional checks at memory allocations to show that $e1$ is in range. However, the conditions have advantages too. They provide scaffolding for proving that expressions based on element counts of `array_ptr` variables do not overflow or wraparound.

The meaning and correctness of bounds are based on the C semantics for pointers and pointer arithmetic. At runtime, any non-null pointer in C has an object associated with it. The association starts when a pointer is created by a memory allocation operation, address-of expression, or conversion of an array variable to a pointer-typed expression. It flows through to pointers that result from pointer arithmetic. At runtime, the bounds for a pointer must be the bounds of the object associated with the pointer or a subrange of those bounds. The correctness of declared bounds

¹If the type of $e1$ is a character, a short integer, a bit field, or an enumeration type, the expression is promoted to an `int` type if that is large enough to hold all values of the type or an `unsigned int` type otherwise.

information at compile-time is ensured by making allocation sites and address-of expressions be creators of bounds information and by propagating bounds with the pointers with which they are associated. Bounds can be narrowed during propagation, but they cannot be widened.

The meaning of a bounds expression can be defined more precisely. At runtime, given an expression e with a bounds expression `bounds(lb, ub)`, let the runtime values of e , lb , and ub be ev , lbv , and ubv , respectively. The value ev will be 0 (null) or have been derived via a sequence of operations from a pointer to some object obj with `bounds(low, high)`. The following statement will be true at runtime: $ev == 0 \vee (low \leq lbv \wedge ubv \leq high)$. In other words, if ev is null, the bounds may or may not be valid. If ev is non-null, the bounds must be valid. This implies that any access to memory where $ev \neq 0 \wedge lbv \leq ev \wedge ev < ubv$ will be within the bounds of obj .

In this chapter, to simplify the description, it is assumed that none of the `array_ptr` variables that have bounds declarations have their addresses taken. It is also assumed that the values of variables whose addresses are taken are not used in bounds declarations. It is acceptable to use the address of an address-taken variable in a bounds declaration. This is provided that the resulting address is not used to access memory in the bounds declaration (that is, indirectly access the value of a variable). For example, given the declaration `int x`, the expression `&x` may appear in a bounds expression. Chapter 7 extends the design to avoid these restrictions. It covers pointers to data with `array_ptr` values, pointers to variables used in bounds, and bounds that use pointers.

3.2 Using bounds declarations

Bounds declarations may be added to declarations and statements using `where` clauses. They also may be placed inline at a declaration by following the declarator with `: bounds-exp`. In that case, the bounds expression applies to the variable that is the subject of the declarator. By making the bounds be part of the program, this preserves the control and efficiency of C. The bounds declarations will be checked statically for correctness using rules described in Chapter 4.

3.2.1 Bounds declarations at variable declarations

Here are some examples of bounds declarations as part of variable declarations. The first function sums the integers stored in memory between `start` and `end`, where the integer stored at `end` is not included.

```
int sum(array_ptr<int> start : bounds(start, end), array_ptr<int> end)
{
    int result = 0;
    array_ptr<int> current : bounds(start, end) = start;
    while (current < end) {
        result += *current++; // *current is bounds-checked. The checking
                             // ensures
                             // that current is within the bounds of (
                             // start, end)
                             // at the memory access.
    }
    return result;
}
```

This can be written using `where` clauses as well, at the inconvenience of typing variable names twice in declarations:

```
int sum(array_ptr<int> start where start : bounds(start, end),
        array_ptr<int> end)
{
    int result = 0;
    array_ptr<int> current where current : bounds(start, end) = start;
    while (current < end) {
        result += *current++;
    }
    return result;
}
```

This function searches for an integer in an array. If it finds the integer, it returns the index in the array where the integer occurs. Otherwise, it returns -1.

```
int find(int key, array_ptr<int> a : count(len), int len)
{
    for (int i = 0; i < len; i++) {
        if (a[i] == key) { // a[i] is bounds checked. The checking
                           // ensures that i is between 0 and len.
            return i;
        }
    }
    return -1;
}
```

If the code was written assuming that it would always find the integer, bounds-checking would detect the buffer overrun in the case the integer was not present:

```
int bad_find(int key, array_ptr<int> a : count(len), int len)
{
    int i = 0;
    while (1) {
        if (a[i] == key) { // The bounds check will fail when i == len
            return i;
        }
        i++;
    }
    return -1;
}
```

This function adds two arrays of 2x2 arrays.

```
int add(int a checked[][2][2] : count(len), int b checked[][2][2] : count(
    len),
        int len)
{
    for (int i = 0; i < len; i++) {
        // All array accesses are bounds checked
        a[i][0][0] += b[i][0][0];
        a[i][0][1] += b[i][0][1];
        a[i][1][0] += b[i][1][0];
        a[i][1][1] += b[i][1][1];
    }
}
```

```
    }
}
```

Externally-scoped variables can have bounds as well:

```
// external-scoped variables that hold a buffer and its length
int buflen = 0;
array_ptr<int> buf : count(buflen) = NULL;

int sum(void)
{
    int result = 0;
    for (int i = 0; i < buflen; i++) {
        result += buf[i]; // bounds checked
    }
    return result;
}
```

This is a declaration of a function that copies bytes provided that the pointers and lengths are aligned:

```
int aligned_memcpy(array<char> dst where dst : count(len) &&
                  aligned(dst, 4),
                  array<char> src where src : count(len) &&
                  aligned(src, 4),
                  int len where len % 4 == 0);
```

The declaration can be shortened using in-line bounds declarations to:

```
int aligned_memcpy(array<char> dst : count(len) where aligned(dst, 4),
                  array<char> src : count(len) where aligned(src, 4),
                  int len where len % 4 == 0);
```

This example is adapted from the OpenSSL library. The signature of a method has been modified to have bounds declaration. The size of input and output buffers must be multiples of 16 because the function operates on 16-byte chunks of data.

```
void AES_cbc_encrypt(array_ptr<const unsigned char> in : count(len),
                    array_ptr<unsigned char> out : count(len),
                    size_t len where len % 16 == 0,
                    ptr<const AES_KEY> key,
                    array_ptr<unsigned char> ivec : count(16),
                    const int enc);
```

3.2.2 Bounds declarations for return values

Bounds may be declared for the value returned by a function. The parameter list can be followed by either : *bounds-exp* or a *where* clause. The special variable *return_value* can be used to refer to the return value. The parameters are considered in scope for the bounds declaration or *where* clause. Any parameters occurring in the return bounds declaration or *where* clause may not be modified by the body of the function.

The following example show the *find* function from Section 3.2.1 modified to return a pointer to the element instead of the index:

```

array_ptr<int> find(int key, array_ptr<int> a : count(len), int len)
: bounds(a, a + len)
{
    for (int i = 0; i < len; i++) {
        if (a[i] == key) { // a[i] is bounds checked. The checking
                           // ensures that i is between 0 and len.
            return &a[i];
        }
    }
    return NULL;
}

```

This also can be written as:

```

array_ptr<int> find(int key, array_ptr<int> a : count(len), int len)
    where return_value : bounds(a, a + len)
{
    ...
}

```

Here is the declaration of a function that allocates memory:

```

array_ptr<char> alloc(size_t size) : count(size);

```

3.2.3 Bounds declarations at statements

Programmers may wish to delay initializing variables or may wish to change the bounds of a variable in the middle of a function. This can be done using bounds declarations attached to expression statements. In C, an expression is converted to a statement by placing a semi-colon after the expression. This creates an expression statement. A `where` clause may be added before the terminating semi-colon of an expression statement.

Any variable that has bounds declared at an expression statement has dataflow-sensitive bounds throughout the body of the function. Only automatic variables can have bounds declared for them at expression statements. It does not make sense to have dataflow-sensitive bounds for externally-scoped variables and variables with static or thread storage. The bounds extend to the next assignment to any variable in the bounds declaration, with some exceptions for pointer incrementing or decrementing. Section 3.10 describes the extent of flow-sensitive bounds in more detail.

Here is a simple example that illustrates bounds declarations at statements. The variable `tmp` first points to an array with 5 elements and then points to an array with 10 elements; the bounds are adjusted accordingly.

```

void f(void)
{
    int x[5];
    int y[10];
    array_ptr<int> tmp;
    tmp = x where tmp : count(5);
    ...
    tmp = y where tmp : count(10);
}

```

In the second example, an `array_ptr` `c` and its length are initialized lazily to either `a` or `b`, depending on another parameter `val`:

```
/* use either a or b depending on val */
int choose(int val, array_ptr<int> a : count(alen), int alen,
           array_ptr<int> b : count(blen), int blen)
{
    array_ptr<int> c;
    int clen;
    if (val) {
        clen = alen;
        c = a where c : count(clen);
    }
    else {
        clen = blen;
        c = b where c : count(clen);
    }
    ...
}
```

Declaring bounds at assignments supports updating of variables that are used in the bounds for an existing `array_ptr` variable. New bounds for the `array_ptr` variable can be declared to reflect the update. Consider the following example:

```
/* sum integers stored between start and end, where end is not included */
int sum(array_ptr<int> start : bounds(start, end), array_ptr<int> end)
{
    ...
    // Adjusting end. Can declare new bounds for start at the assignment
    end = end - 1 where start : bounds(start, end + 1);
}
```

3.2.4 Invariant bounds declarations

Variables that only have bounds declared for them at their definition have bounds that are invariants. Any assignments to the variable *or* variables in the bounds expression must maintain the invariant. The invariant can be suspended temporarily during updates.

Because externally-scoped `array_ptr` variables can have bounds declared for them only at their definitions, by definition their bounds are always invariants.

3.2.5 Byte counts for pointers to void

The definition of count expressions poses a problem for `array_ptr<void>`. `Void` is an incomplete type and has no defined size, which means that count expressions are ill-defined for `array_ptr<void>`. To address this, a variant of count expressions where counts are given in terms of bytes is added:

bounds-exp:

```
...
byte_count(non-modifying-exp)
```

`byte_count` is the identifier `byte_count`. The bounds declaration `x : byte_count(e1)` describes the number of bytes that are accessible beginning at `x`. Only memory that is at or above `x` and below `(array_ptr<char>) x + e1` can be accessed through `x`. The type of `e1` must be an integral type. The usual C integer conversions are applied to `e1`. This bounds declaration is a synonym for `x : bounds((array_ptr<char>)) x, (array_ptr<char>) x + e1) rel_align(char)`

The standard C library functions for `malloc`, `memcmp`, and `memcpy` will be given bounds-safe interfaces to avoid breaking existing code as described in Section 5.3. However, if they were to return checked pointer types, their bounds declarations would be:

```
array_ptr<void> malloc(size_t num) : byte_count(num);

int memcmp(array_ptr<const void> dst : byte_count(num),
           array_ptr<const void> src : byte_count(num), size_t num);

array_ptr<void> memcpy(array_ptr<void> dst : byte_count(num),
                     array_ptr<const void> src : byte_count(num), size_t
                     num) :
    byte_count(num);
```

The return value of `memcpy` is `dst`. The bounds for this return value could be described more precisely by:

```
array_ptr<void> memcpy(array_ptr<void> dst : byte_count(num),
                    array_ptr<void> src : byte_count(num), size_t num)
    :
    bounds((<array_ptr<char>) dst, (array_ptr<char>) dst + num) rel_align(
        char)
```

3.3 Syntax changes

The grammar from the “C Programming Language” [87] is extended to include in-line bounds declarations and `where` clauses for declarations:

```
init-declarator:
    declarator inline-bounds-specifieropt where-clauseopt
    declarator inline-bounds-specifieropt where-clauseopt = initializer where-clauseopt
    ...

parameter-declaration:
    declaration-specifiers declarator inline-bounds-specifieropt where-clauseopt

inline-bounds-specifier:
    : bounds-exp

where-clause:
    where facts

facts:
    fact
```

fact && facts

fact:

variable inline-bounds-specifier

variable relop non-modifying-exp

non-modifying-exp relop variable

where *relop* is one of <, <=, ==, !=, >=, >.

In addition, the grammar is updated to allow where clauses at expression statements:

expression-statement:

expression_{opt} where-clause_{opt};

The names used in bounds expressions (*any*, *bounds*, *count*, and *unknown*) are identifiers. They are not keywords. They can still be used for variable names, avoiding backward-compatibility problems. The grammar for bounds expressions is:

bounds-exp:

identifier(non-modifying-exp)

identifier(non-modifying-exp, non-modifying-exp)

After parsing, the following rules are applied to bounds expressions:

- If the first grammar clause was parsed,
 - If *identifier* is *bounds*, the *non-modifying-exp* must be the identifier *any* or the identifier *unknown*.
 - Otherwise *identifier* must be *count*.
- If the second grammar clause was parsed, *identifier* must be *bounds*.

3.4 Insertion of bounds checks at pointer dereferences

The semantics of C expressions is subtle. The expression **e1* does not dereference memory. It produces an lvalue that can be used to access memory. If the expression occurs on the left-hand side of an assignment, the memory pointed to by the lvalue is updated with the value of the right-hand side of the assignment. For example, given **e1 = e2*, the memory pointed to by the lvalue is updated with the value of *e2*. If the expression occurs within another expression, the lvalue is usually (but not always) used to read memory. In the terminology of the C Standard, an lvalue conversion is inserted that reads memory. For example, given **e1 + 5*, an lvalue conversion is inserted for **e1*. A case where a conversion is not inserted is when the address of an expression is taken: *&*e1*. Subscript expressions behave like pointer dereference expressions. The expression *e1[e2]* produces an lvalue that can be used to access memory.

A bounds check is inserted at a dereference expression or subscript expression of an *array_ptr* or *nt_array_ptr* whose result will be used to directly access memory (the result must be used by the left-hand side of an assignment or an lvalue conversion). We first describe bounds checks

for `array_ptr`. The bounds checks for `nt_array_ptr` are slightly different. We describe them after `array_ptr`.

Given `*e1`, where `e1` is an expression of type `array_ptr`, the compiler determines the bounds for `e1` following the rules in Section 4.2. Special rules are followed in `bundled` blocks to determine the bounds for `e1`. The compiler inserts the bounds check as part of the evaluation of `*e1`. The bounds check is inserted after `e1` is evaluated and before the result of `*e1` is produced. The compiler also inserts a null check.

If `e1` has `bounds(e2, e3)`, the compiler computes `e1` to a temporary `t`. The compiler inserts a runtime check that `e2 <= t && t < e3`. If the runtime check fails, the program will be terminated by the runtime system or in, systems that support it, a runtime exception will be raised. If `e1` has `bounds(count(e2))`, the bounds are expanded to `bounds(t, t + e2)` before inserting a check.

Consider as an example `z = *x`; where `x` has `bounds(x, x + c)`. The compiler will produce code equivalent to:

```
dynamic_check(x != null);
dynamic_check(x <= x && x < x + c);
z = *x;
```

The condition `x <= x` is trivially true. The condition `x < x + c` simplifies to `0 < c`, that is `c > 0`, which is what one would expect.

Now suppose pointer arithmetic is involved and `z = *(x + 5)`. The bounds of `x + 5` will be the same as the bounds of `x`. The expression `x + 5` must point into the same object as `x` for this to be a valid memory access. This means that `x + 5` has `bounds(x, x + c)`. The compiler will produce code equivalent to:

```
dynamic_check(x != null);
t1 = x + 5;
dynamic_check(t1 != null)
dynamic_check(x <= t1 && t1 < x + c);
z = *t1;
```

Array subscripting works as expected. For `e1[e2]`, the compiler inserts bounds checks if the result of `e1[e2]` is used to access memory. The compiler computes the bounds of `e1`. The compiler inserts runtime checks that `e1 + e2` is within this bounds as part of the evaluation of `e1[e2]`. For example, given `x[5]` where `x` has `bounds(x, x + c)`, the compiler inserts runtime checks that `x <= x + 5 < x + c`. The runtime checks simplify to `5 < c`.

For a multi-dimensional array access, only one bounds check is done. The check ensures that the memory access is within the bounds of the entire multi-dimensional array. Given `e1[e2][e3]`, the expression `e1[e2]` is evaluated. However, `e1[e2]` has array type, so no lvalue conversion is inserted. That means that no bounds check is inserted: `e1[e2]` becomes pointer arithmetic. The bounds check is inserted as part of the subscript operation involving `e3`.

This means that bounds are not checked for each individual dimension access. Accessing outside of the bounds for an individual inner dimension is a violation of the C Standard and logically incorrect, but it does not compromise memory safety or type safety.

Bounds checks for `nt_array_ptr` values allow read access to memory at the upper bound. An `nt_array_ptr` points to an array with declared bounds that is followed by a sequence of elements

that is null-terminated. The element at the upper bound is the beginning of the null-terminated sequence. Allowing a read at the upper bound lets a program check the first element of the sequence to see if is non-null (bounds checks for `array_ptr` values only allow access to memory below the upper bound). For memory reads, given `*e1` where `e1` has `bounds(e2, e3)`, the compiler computes `e1` to some temporary `t`. The compiler inserts a runtime check that `e2 <= t && t <= e3`.

For memory writes, assignment of 0 (the null value) using the assignment operator is allowed at the upper bound. This is the first element of the null-terminated sequence and there must be enough space in the sequence for at least a null terminator. Otherwise, the check is the same as for `array_ptr`. For an expression `e1` that has `bounds(e2, e3)`:

- Given an assignment of the form `*e1 = e4`, the value of `e4` is computed to some temporary `v`. The check is `(e2 <= t && t < e3) || (e2 <= t && t == e3 && v == 0)`.

When checking for a write of 0 exactly at the upper bound, we include the first element of the sequence in the allowed memory range. The second lower bound comparison `e2 <= t` prevents an assignment at the upper bound when this expanded range is empty. A compiler can avoid the duplicate comparison by using the check `e2 <= t && (t < e3 || (t == e3 && v == 0))`

- Given an assignment via a compound assignment operator, the check is `e2 <= t && t < e3`.

If the bounds for `e1` are inferred, the checks must be provably true at compile time.

No bounds checks are inserted when the `&` operator is applied to a dereference or subscript expression. The dereference or subscript expression does not produce a result that is used to access memory. This expression `&e1[e2]` works as expected by C programmers. It is equivalent to pointer arithmetic computed using `e1 + e2`. Similarly, `*&e` works as expected. The `&` and the `*` operator cancel so that the value of the entire expression is `e`.

3.4.1 Deferring evaluation of bounds expressions to bounds checks

The previous section covered an important point about the evaluation of bounds expression in passing that is worth emphasizing: the evaluation of a bounds expression that occurs in a bounds declaration is *deferred* until a bounds check uses the bounds expression.

Consider the following code:

```
array_ptr<int> x;
x = malloc ((sizeof(int) * 5)
where x : bounds(x, x + 5);
```

The bounds expression `bounds(x, x + 5)` is not evaluated at the bounds declaration. it is evaluated at any bounds check involving a pointer derived from `x`. The reason for deferring the evaluation of bounds expressions is that it avoids the need for storage to hold the ranges produced by the bounds expressions (in this case, the values of `x` and `x + 5`). Additional storage would be particularly problematic when bounds declarations are extend to structure members. It would cause the size and layout of data structures to change. Deferring evaluation also avoids complications when `x` is `null`. Section 11.6 discusses eager evaluation of bounds expressions at bounds declarations in more detail and explains why this was not chosen.

3.5 Bundling statements and declarations

It is common in C code to use multiple statements to update program state. This can cause problems when variables in a bounds declaration are updated. Invariant bounds declarations must be valid at the end of every statement. When updates involve multiple statements, a bounds declaration may be valid only after all the updates are done. In Checked C, statements and declarations can be grouped into bundled blocks. Bounds declarations are checked only at the end of bundled blocks.

Consider the following example where a function is added to the earlier `sum` example that allows a buffer to be reallocated:

```
// external-scoped variables that hold a buffer and its length
int buflen = 0;
array_ptr<int> buf : count(buflen) = NULL;

int sum(void)
{
    int result = 0;
    for (int i = 0; i < buflen; i++) {
        result += buf[i]; // bounds checked
    }
    return result;
}

/* buggy resize function */
void resize(int len)
{
    array_ptr<int> tmp : count(len) = malloc(sizeof(int) * len);
    copy(tmp, buf, buflen);
    buflen = len; // fails at compile-time because the bounds are not
                  // true.
    buf = tmp;
}
```

Without bundling, the update to `buflen` will fail compile-time checking because the bounds declaration is not true after the assignment.

The updates to `buflen` and `buf` can be grouped together, so the checker considers them to be one action:

```
/* correct resize function */
void resize(int len)
{
    array_ptr<int> tmp : count(len) = malloc(sizeof(int) * len);
    copy(tmp, buf, buflen);
    bundle {
        buflen = len;
        buf = tmp;
    }
}
```

The C syntax for is extended with:

statement:

bundled-statement

bundled-statement:

`bundled { bundled-item-listopt }`

bundled-item-list:

bundled-item

bundled-item-list bundled-item

bundled-item:

declaration

expression-statement

There is some subtlety with bundled blocks and function calls. The bounds declarations for any static variables must be valid before any function call in a bundle. This is because the called function may make use of the static variables. It will assume that the bounds declaration holds when it uses the static variables. In general, programmers may deal with this requirement by using the idiom of storing function call results in temporary variables and updating static variables *en masse* after the required function calls have been made.

Bundled blocks expose an interesting difference between regular C and Checked C programs. In regular C,

```
expr1, expr2;
```

is always the same as:

```
expr1;  
expr2;
```

In Checked C, however, bounds declarations are checked for validity only at the ends of statements. Thus bounds could be valid after `expr1`, `expr`, but not valid after `expr1` alone. In the `resize` example, the following succeeds with a bundle block:

```
void resize(int len)  
{  
    array_ptr<int> tmp = malloc(sizeof(int) * len);  
    copy(tmp, buf, buflen);  
    buflen = len, buf = tmp; // succeeds, surprisingly  
}
```

Bundled blocks are still necessary because new declarations cannot be introduced within a comma operator. They also provide easier-to-read syntax for complex updates to variables.

3.6 Additional requirements for bounds declarations

3.6.1 Operations allowed in non-modifying expressions

As mentioned earlier, non-modifying expressions are a subset of C expressions that do not modify variables or memory. The subexpressions of a non-modifying expression must themselves be non-modifying expressions. Non-modifying expressions include the following kinds of expressions:

- Local variables and parameter variables
- Constant expressions
- Cast expressions
- Address-of expressions
- Unary plus/minus expressions
- One's complement expressions
- Logical negation expressions
- Sizeof expressions
- Multiplicative expressions (*, /, %)
- Additive expressions (+, -)
- Shift expressions (>>, <<)
- Relational and equality expressions (<, >, <=, >=, ==, !=)
- Bitwise expressions: and (&), or (|), exclusive-or (^)
- Logical AND (&&) and logical OR (||) expressions
- Conditional expressions

They also include expressions that access members of types or memory:

- Member references (to members of structures or unions) (the . operator)
- Indirect member dereferences (->)
- Pointer dereferences

The static checking of the validity of bounds declarations restricts the usage of non-modifying expressions that read memory when memory is being modified.

Non-modifying expressions do not include:

- Assignment expressions (for the reason that evaluating them repeatedly at bounds checks would produce unexpected results)
- Pre-increment/decrement and post-increment/decrement expressions (these are forms of assignments)
- Volatile variables
- Function calls (because these may contain assignments that modify variables or memory)
- Comma expressions at the top level (because this introduces syntactic ambiguity). Because non-modifying expressions do not allow side effects, all comma expressions can be simplified to the expression on the right of the comma.

It is suggested that programmers use simple non-modifying expressions because the expressions may be fully re-evaluated at every bounds check involving the bounds expression. More complicated bounds expressions are allowed because programmers might find them useful.

3.6.2 Storage class-related requirements

Local variables with static storage class or thread storage class can have only bounds declarations with bounds expressions that use variables with the same storage class as the local variable or variables that are declared `const`. The memory for static variables and thread variables persists across exit and reentry from functions and blocks. It follows that the bounds information must persist also.

Local variables with automatic storage class can have bounds declarations with bounds expressions

that use variables with automatic, static, or thread storage class. However, the extent of local variable bounds declarations that use variables with external linkage ends at function calls, unless the variables with external linkage are declared `const`. This is because the function calls may modify the variables with external linkage.

3.6.3 Lexical hiding of variables

A nested lexical scope can hide a variable used in a bounds declaration within the extent of the bounds declaration. This will limit the ability to update the *other* variables used in the bounds declaration. There will be no way to update the hidden variable to make the bounds declaration be valid. Here is a simple example:

```
/* function that will fail checking */
void bad(int i)
{
    array_ptr<int> x : count(i) = malloc((sizeof(int) * i);
    {
        int x = 5;           // hide x
        i = INT_MAX;         // illegal: the bounds declaration for
                             // array_ptr<int> x would no longer be valid;
    }
}
```

When compilers insert bounds checks, they need to use the appropriately-scoped variables, even if some of the variables are hidden.

3.6.4 Variables at external scope

If there are multiple declarations of a variable with external scope in a translation unit, the bounds declaration and/or `where` clauses for the variable must be identical at all the declarations. This prevents the specification of different bounds for global variables in the same compilation unit. Any variables with external scope that have bounds declarations and/or `where` clauses must have the same bounds declaration and where clauses in all translation units.

All places in a program that may write to a variable with external scope also must have the same view of the bounds declarations involving that variable. This allows static checking to ensure that bounds declarations remain valid.

To see what can go wrong without this requirement, consider the following example:

```
extern int size;

void update_size(int i)
{
    num = i;
}

extern array_ptr<int> ap : count(size);

void go(void)
{
```

```

    update_size(INT_MAX);
    ap[100] = 0xbad;
}

// define size and ap
int size = 10;
int arr[10];
array_ptr<int> ap = arr : count(size);

```

The checking of bounds declarations does not know at `update_size` that `ap` needs to have at least `i` elements when `size` is updated, allowing a programmer to accidentally invalidate bounds declarations.

A simple rule enforces this restriction. Given the initial declaration in a translation unit of a variable with external scope that has a `where` clause, there cannot be any function definitions between the declaration and the initial declarations of other variables used in the bounds declaration for the variable or the optional `where` clause for the declaration. It is possible for the initial declaration of a variable with external scope to occur within the body of a function. In that case, there cannot be any statements or declarations of non-external variables with initializers between the initial declaration and the initial declarations of other variables used in the bounds declaration for the variable or the optional `where` clause for the declaration.

3.7 Size computations and integer overflow or wraparound

When objects are allocated dynamically in C, programmers have to compute the amount of memory to allocate for the objects. It is well-known that integer overflow or wraparound in these computations can lead to buffer overruns [49, 68, 69, 70, 30]. In Checked C, the explicit size computations are not enough to imply that the bounds for a newly-allocated object are valid. Additional side conditions that deal with integer overflow or wraparound are needed.

This section informally examines why and the additional conditions that are needed. We start by looking at an allocation using `malloc` with an old-style `char *` return type and a bounds declaration:

```
extern char *malloc(size_t s) : count(s);
```

An array of type T is allocated with:

```
array_ptr<T> p : count(e1) = (array_ptr<T>) malloc(sizeof(T) * e1);
```

The size computation in the count expression differs subtly from the explicit computation on the right-hand side. In the count expression, arithmetic with overflow checking is used, while the explicit computation does not have overflow checking. Intuitively, this leads to a mismatch when overflow or wraparound can happen, which causes static checking to fail.

We expand the count expression; to integer arithmetic to make its size computation clear. `count(e1)` expands to `bounds(p, p + e1)`. Following the rules in Section 2.10.2, the expansion of `p + e1` from pointer arithmetic to integer arithmetic depends on the type of `e1`:

- If `e1` is an unsigned integer, `p + e1` expands to `p +ovf sizeof(T) *ovf e1`.
- If `e1` is a signed integer, `p + e1` expands to `p +ovf ((signed_size_t) sizeof(T)) *ovf e1`.

The number of bytes added to `p` is the size computation of the count expression. We can compare the size computations and see when the values differ. We add casts for any implicit conversions that would occur in the `malloc` size computation also:

Type of <i>e1</i>	Count size computation	<code>malloc</code> size computation	Values differ?
Unsigned integer	<code>sizeof(T) *_{ovf} e1</code>	<code>sizeof(T) * e1</code>	On overflow
Signed integer	<code>(signed_size_t) sizeof(T) *_{ovf} e1</code>	<code>sizeof(T) * (size_t) e1</code>	On overflow or when <code>e1 < 0</code> .

For correctness, we want the count size computation and the `malloc` size computations to produce identical values. This implies that `malloc` did allocate the number of bytes expected by the count size computation. We add conditions on *e1* to do this:

Type of <i>e1</i>	Restrictions
Unsigned integer	<code>e1 <= UINT_MAX/sizeof(T)</code>
Signed integer	<code>e1 >= 0</code> and <code>e1 <= INT_MAX/sizeof(T)</code>

This has an interesting implication for any function that allocates an array of *T*. If the count of elements is constant, of course these conditions are trivial. If the count is non-constant, the function must do the following checks:

- If the count is a signed integer, the function must check that the count `>= 0` before trying to allocate the array.
- If the size of *T* is larger than 1 byte, the function must check that the count is less than the upper bound as well.

When retrofitting existing code to use checked pointers, the code may be unprepared for overflow or wraparound to happen during allocation. This suggests that uses of `malloc` should be replaced by slightly higher-level functions that takes the element count and the size of elements and handle overflow. C already has a function that is suitable for unsigned integer counts:

```
void *calloc(size_t nobj, size_t size);
```

A signed version is needed too:

```
void *signed_calloc(signed_size_t nobj, size_t size);
```

However, `calloc` also zeros the allocated memory. For the sake of efficiency, new allocation functions that compute sizes but do not zero memory may be needed.

3.8 Function types and function pointer types

Function types can be declared to have parameters and return values that have bounds declarations, just like functions. The bounds declarations become part of the function types. Here are simple examples of function pointer types with bounds declarations:

```
// Function that takes a pointer to a 5 element array and returns an
// integer.
int (array_ptr<int> arr : count(5))
// checked function pointer
ptr<int (array_ptr<int> arr : count(i), int i)>
// unchecked function pointer
int (*) (array_ptr<int> arr : count(i), int i)
```

Functions that take pointers to functions and arrays of function pointers can be declared also. A typedef for the function type is used in the following example to keep the syntax understandable:

```
typedef int fn(array_ptr<int> arr : count(5));

// Takes g and arg and calls g with arg.
int apply(ptr<fn> g, array_ptr<int> arg : count(5));

// Checked array of 10 function pointers
ptr<fn> dispatch_table checked[10];
```

Compatibility of function types is extended to take into account bounds declarations. Two function types are compatible if

- They are compatible types if all bounds declarations are removed from the type, and
- If either type contains a bounds declaration, both types have parameter lists, and
- They have bounds declarations on corresponding parameters, and
- They either both have or both do not have a bounds declaration for their return values, and
- The bounds declarations for corresponding parameters and for return values with checked types are equivalent. Parameter variables should be renamed so that the parameter variables in corresponding argument positions have the same name. The new names should be chosen to be different than other variables that are in scope.

For each pair of bounds declarations for corresponding parameters or the return values, the bounds declarations are equivalent if

- The bounds expressions for the bounds declarations are syntactically equal after being placed into a canonical form following the rules in Section 4.5.1, and
- For any non-parameter variable x to which both expressions refer, the variable is declared in the same scope.

Canonical forms place semantically equivalent but syntactically distinct expressions into the same form. This allows things like commutativity and constant folding to be taken into account:

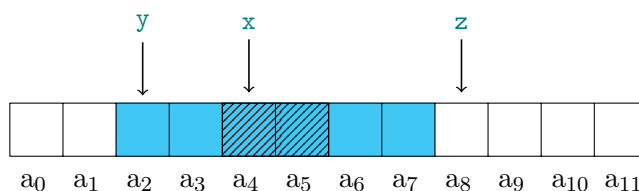
```
// These function types are equivalent taking into account commutativity.
int (array_ptr<int> arr : count(i + j), int i, int j)
int (array_ptr<int> arr : count(j + i), int i, int j)

// These function types are equivalent after constant-folding.
int (array_ptr<int> arr : count(5))
int (array_ptr<int> arr : count(2 + 3))
int (array_ptr<int> arr : count(4 + 1))
```

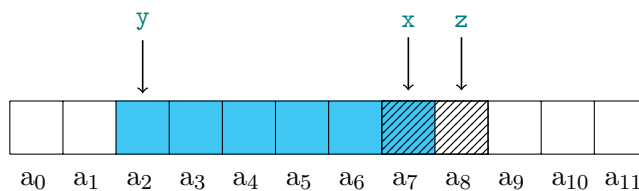

3.9 Bounds declarations for results of casts between array_ptr types

Typically `array_ptr` pointers and their bounds are relatively aligned. Together, they represent a view of an array of T , where the pointer has type `array_ptr<T>`. The bounds specify a range of memory that is exactly the size of some array of T and the pointer points exactly at an element of that array. For example, suppose short ints are 2 bytes in size and `x : bounds(y,z)`, where the types of `x`, `y`, `z` are `array_ptr<short int>`.

This illustration shows 12 consecutive bytes in memory beginning at address `a0`, where `y` and `z` bound a 3-element array and `x` points to the middle of the array. The memory occupied by the 3-element array is shaded in light blue, and the element pointed to by `x` is also cross-hatched. The distances in bytes between `x`, `y`, and `z` are all multiples of 2, the size of `short int`.



This simplifies bounds checking because there is no concern during a bounds check that a pointer will access memory at the end or beginning of the array that partially overlaps with the bounds. Suppose, for example, that `x` was not relatively aligned to `y` and `z` and points at `a7`. The object pointed to by `x` now straddles the array bounds. This illustration shows this:



When `x` is not relatively aligned, the bounds check for `x` becomes more expensive. With relative alignment, the bounds check is `y <= x` and `x < z`. Without relative alignment, the check for the upper bound needs to compute the highest address that will be accessed using `x`. For this example, the highest address accessed will be `(array_ptr<char>) x + sizeof(short int) - 1`, so the check becomes `y <= x` and `x + 1 < z`.

A pointer cast can create a pointer that is not relatively aligned to the referent type of the pointer type. This can happen when:

1. A pointer is cast to be a pointer to a larger type. For example, if an `array_ptr<short int>` is cast to be an `array_ptr<int>`, the resulting pointer may not be relatively aligned to its bounds for `int`. In the first illustration where `x` points to `a4`, `array_ptr<int>` `x` is not relatively aligned to `y` for `int`.
2. A pointer is cast to be a pointer to a smaller type, and the size of the original referent type is not a multiple of the size of the smaller type. For example, a pointer to a 12-byte struct may not be relatively aligned to its bounds when it is cast to a pointer to an 8-byte struct.

The use of struct types to illustrate the second case is intentional. For most C implementations, the

second case never happens for casts involving scalar types. Scalar types are powers of 2 in size (1, 2, 4, and 8 bytes). This means that for a cast from a larger scalar type to a smaller scalar type, the larger scalar type will always be a multiple of the smaller scalar type.

In general, an `array_ptr<T>` that is relatively aligned for T is guaranteed to be relatively aligned for `array_ptr<S>` only when `sizeof(S)` is a common factor of `sizeof(T)`. In other cases, programmers need to supply additional information using program invariants to show that an `array_ptr` pointer is relatively aligned to its bounds. Of course, programmers who are doing casts to use operations on larger types instead of operations on smaller types (for example, `int` instead of `char`) usually already are doing these checks.

3.9.1 Representing relative alignment in bounds declarations

Bounds expressions are extended with an optional relative alignment clause to represent situations where an `array_ptr<T>` is not relatively aligned to its bounds for type T :

bounds-exp:

```
...
bounds(non-modifying-exp, non-modifying-exp) relative-alignment-clauseopt
```

relative-alignment-clause:

```
rel_align(type)
rel_align_value(constant-exp)
```

This clause is only added to bounds pairs because (by definition) count expressions always describe pointers that are relatively aligned to their bounds. `rel_align` and `rel_align_value` are identifiers. The optional clause specifies a relative alignment type T or the required relative alignment in bytes. Given x : `bounds(e1, e2) rel_align(T)`, $((\text{array_ptr}\langle\text{char}\rangle) x - (\text{array_ptr}\langle\text{char}\rangle) e1) \% \text{sizeof}(T) == 0$ and $((\text{array_ptr}\langle\text{char}\rangle) e2 - (\text{array_ptr}\langle\text{char}\rangle) x) \% \text{sizeof}(T) == 0$ must be true. If the number of bytes is specified, `sizeof(T)` is replaced by the constant expression. The relative alignment clause `rel_align(type)` is just short-hand for `rel_align_value(sizeof(type))`.

3.9.2 Effect on bounds checks

If the default relative alignment has been overridden and $e1$: `bounds(e2, e3) rel_align(T)`, the compiler checks whether `sizeof(referent-type(e1))` is a common factor of `sizeof(T)`. If it is, it inserts the same runtime check as before. Otherwise, it inserts a runtime check that $e2 \leq e1 \ \&\& \ e1 + \text{sizeof}(T) - 1 < e3$.

3.9.3 Examples of uses of bounds declarations that specify relative alignment

Here are examples of the use of relative alignment clauses in conjunction with pointer casts. In the first example, there is an `array_ptr` to raw data consisting of characters. The pointer is cast to be an `array_ptr<int>`. However, the relative alignment remains `char`:

```
// cast data to be an array_ptr<int> instead
array_ptr<char> raw_data : bounds(lower, upper) = ...
array_ptr<int> data : bounds(lower, upper) rel_align(char) =
```

```
(array_ptr<int>) raw_data;
```

In the second example, the code starts with an `array_ptr<int>`. The pointer is cast to be an `array_ptr<char>`. That `array_ptr` is then cast back to be an `array_ptr<int>`. In the second cast, the `rel_align` clause is omitted because the default relative alignment for an `array_ptr<int>` is `int`.

```
array_ptr<int> data : bounds(lower, upper) = ...
array_ptr<char> byte_data : bounds(lower, upper) rel_align(int) = (
    array_ptr<char>) data;
array_ptr<int> finish : bounds(lower, upper) = (array_ptr<int>) byte_data;
```

The third example illustrates a subtlety when an `array_ptr<T>` has a relative alignment that is larger than the actual size of `T`. The use of pointer arithmetic may require that relative alignment be lowered. Suppose that the size of `short int` is 2 bytes and the size of an `int` is 4 bytes:

```
array_ptr<int> d : bounds(lower, upper) = ...
array_ptr<short int> e : bounds(lower, upper) rel_align(int) = (array_ptr<
    short int>) d;
array_ptr<short int> f : bounds(lower, upper) rel_align(short int) = e +
    1;
```

While `e` can have relative alignment of `int`, `f` cannot because pointer arithmetic is done at the granularity of `short int`.

The final example illustrates the use of a dynamic check to allow an `array_ptr<char>` to be cast to a larger type with a larger relative alignment. It is a function that does a memory copy and uses an optimized aligned copy if possible. For simplicity, it is assumed that the memory pointed to by `dst` and `src` does not overlap and that `sizeof(int)` is 4:

```
void copy(array_ptr<char> dst : bounds(dst, dst + num),
          array_ptr<char> src : bounds(src, src + num),
          size_t num)
{
    if (num % 4 == 0) {
        array_ptr<int> aligned_dst : bounds(dst, dst + num) rel_align(char) =
            (array_ptr<int>) dst;
        array_ptr<int> aligned_src : bounds(src, src + num) rel_align(char) =
            (array_ptr<int>) src;
        int n = num / 4;
        for (int i = 0; i < n; i++) {
            aligned_dst[i] = aligned_src[i];
        }
    }
    else {
        for (int i = 0; i < num; i++) {
            dst[i] = src[i];
        }
    }
}
```

However, `num % 4 == 0` implies that `aligned_dst` and `aligned_src` are relatively aligned to their bounds, so the relative alignment can be changed:

```
void copy(array_ptr<char> dst : bounds(dst, dst + num),
          array_ptr<char> src : bounds(src, src + num),
```

```

        size_t num)
{
    if (num % 4 == 0) {
        // num % 4 == 0 implies that aligned_dst and aligned_src are
        // relatively aligned to their bounds.
        array_ptr<int> aligned_dst : bounds(dst, dst + num) rel_align(int) =
            (array_ptr<int>) dst;
        array_ptr<int> aligned_src : bounds(src, src + num) rel_align(int) =
            (array_ptr<int>) src;
        int n = num / 4;
        for (int i = 0; i < n; i++) {
            aligned_dst[i] = aligned_src[i];
        }
    }
    else
        ...
}

```

Of course, the `rel_align(int)` is redundant and can be omitted.

3.9.4 Relative alignment and constant counts

When an `array_ptr` with a constant count is cast to another `array_ptr` type, all the facts about relative alignment are easily checkable at compile time. This means that a pointer to data can easily be cast to be a pointer to a larger type. Suppose in the following example that the size of integers is 4 bytes. A pointer to 8 bytes of characters can be converted easily a pointer to 2 integers:

```

char a[] = "0123456";
array_ptr<char> p : count(8) = a;
array_ptr<int> r : count(2) = (array_ptr<int>) p;

```

3.10 Extent of bounds declared at statements

Variables that have bounds declared for them at expression statements have dataflow-sensitive bounds declarations. There are two aspects to dataflow-sensitive bounds: extent and consistency. The extent of a flow-sensitive bounds declaration is the part of the program to which a flow-sensitive bounds declaration applies. Within the extent of a flow-sensitive bounds declaration, the bounds for the variable for memory dereferences are given by the bounds declaration. Consistency is that all the flow-sensitive bounds declarations flowing to a statement agree with each other.

As mentioned in Section 3.2.3, a dataflow-sensitive bounds declaration extends to the next assignment to any variable occurring in the bounds declaration. There are exceptions for pointer increment and decrement. If an assignment

- increments or decrements a pointer variable (`++`, `--`, `+=`, `-=`), and
- the bounds expression for the pointer variable has the form `bounds(e1, e2)`, and
- the pointer variable does not occur in `e1` or `e2`,

then no bounds declaration is needed at the statement containing the assignment.

The reason for this exception is that there is obviously a connection between the old and the new value of the pointer in the case of a pointer increment or decrement. These kinds of assignment statements move a pointer within an area of memory and it is reasonable to assume that bounds remain the same. However, with other kinds of assignments, the before and after values may be unrelated, so re-using bounds could lead to unexpected bounds checks failures.

3.10.1 Definition of extent

We first define the set of flow-sensitive bounds declarations that apply to a component of a function. A component is an expression statement, variable declaration, or a compound statement. For any flow-sensitive bounds declaration for a variable v , if

1. There is some path from the bounds declaration to the component, and
2. v occurs in the component, and
3. there is no other flow-sensitive bounds declaration for v along the path

then

1. if all the variables occurring in the bounds declaration are in-scope at the component, and
 - (a) No expressions or statements on the path modify a variable occurring in the bounds declaration
 - (b) or
 - i. The only expressions or statements on the path that modify a variable occurring in the bounds declaration are pointer increments or decrements of v , and
 - ii. v does not occur in the bounds expression, and
 - iii. the bounds expression is not a count expression
 then the bounds declaration applies to the component
2. Otherwise, the bounds declaration v : `bounds(unknown)` applies to the component.

3.10.2 Consistency

These conditions ensure the consistency of bounds declarations:

1. *Agreement of bounds declarations*: If a variable occurring in a function component has more than one bounds declaration that applies to it at the component, then all the bounds declarations applying to it at the component must be syntactically identical. This avoids ambiguity about which bounds declaration applies to an occurrence of a variable. It an error for the bounds declarations to disagree.
2. *No missing bounds declarations*: If a bounds declaration for a variable applies to a function component, then all paths from the beginning of the function to the function component must have a bounds declaration for the variable along each path.

3.10.3 Examples

In the following example, a function modifies a variable `end` used in the bounds expression for the variable `start` and then uses the variable `start` after that. This function will be rejected by the compiler.

```

/* buggy function */
/* sum integers stored between start and end, where end is not included */
int sum(array_ptr<int> start : bounds(start, end), array_ptr<int> end)
{
    end = end + 1; // bounds(start, end) does not hold after this, so
                  // program is
                  // rejected
    start[5] = 0;
    ...
}

```

A correct function declares new bounds for `start`:

```

/* sum integers stored between start and end, where end is not included */
int sum(array_ptr<int> start : bounds(start, end), array_ptr<int> end)
{
    end = end + 1 where start : bounds(start, end - 1);
    start[5] = 0; // program accepted by compiler; may fail bounds check
                  // at run time
    ...
}

```

The following example shows the extents of the two bounds declarations for `start`. The bounds declaration at the declaration of `start` and its extent is highlighted in blue. The bounds declaration at the assignment to `end` and its extent is highlighted in yellow:

```

/* sum integers stored between start and end, where end is not included */
int sum(array_ptr<int> start : bounds(start, end), array_ptr<int> end)
{
    start[5] = 0; // bounds checked using (start, end)
    end = end + 1 where start : bounds(start, end - 1);
    start[5] = 0; // bounds checked using (start, end - 1)
    ...
}

```

Figure 3.1 expands on the `choose` function earlier. There are 4 explicit bounds declarations for `c`. The bounds declarations and their extents are also color-coded. Three bounds declarations for `c` have the form `c : count(clen)`. They must be syntactically identical because there are statements that they cover in common. Their extents are highlighted in blue. Another bounds declaration has the form `c : count(clen - 1)`. Its extent is highlighted in yellow. It covers code where `c` is incremented and the length is decremented. The increment invalidates the bounds declaration `c : count(clen)`. A different bounds declaration for `c` is needed after the increment.

3.10.4 Computing extent

This section is primarily for compiler implementers. Those readers primarily interested in the language may skip it safely. It describes how a compiler can determine efficiently which bounds declaration applies to uses of variables that have flow-sensitive bounds declaration.

The inference process can be done for all `array_ptr` variables in a function with dataflow-sensitive bounds using a forward dataflow analysis [3]. The bounds declarations for all occurrences of `array_ptr` variables in a function can be computed in worst-case $O(N^2 * M)$ time. N is the number

```
/* use either a or b depending on val */
int choose(int val, array_ptr<int> a: count(alen), int alen,
           array_ptr<int> b : count(blen), int blen)
{
    array_ptr<int> c;
    int clen;
    int result = 0;

    if (val) {
        clen = alen;
        c = a where c : count(clen);
    }
    else {
        clen = blen;
        c = b where c : count(clen);
    }

    if (clen > 1) {
        result = c[0];
    }

    if (cond && clen > 1) {
        c = c + 1 where c : count(clen - 1);
        clen = clen - 1 where c : count(clen);
        result += c[0];
    }
    ...
    return result;
}
```

Figure 3.1: An expanded version of the choose function from earlier, with extents of different bounds declarations color-coded.

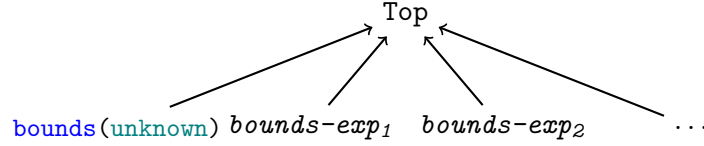


Figure 3.2: The lattice of values used in dataflow computation of extent

of statements in a function and M is the number of `array_ptr` variables in the function. In functions that do not have loops in their control-flow, the dataflow analysis can be done in $O(N \cdot M)$ time.

The dataflow analysis uses a lattice of values, assigning one lattice value to each variable at each program point in the function. Figure 3.2 shows the lattice of values. It includes singleton values consisting of the bounds expressions in the flow-sensitive bounds declaration for variables in the function, `bounds(unknown)` (indicating absence of bounds information), and `Top` (indicating contradiction or error):

For an assignment to an `array_ptr` variable, the existing lattice value for the `array_ptr` variable is killed, unless the special conditions described in Section 3.10 are met. A new lattice value is generated for the `array_ptr` variable. If the assignment declares bounds for the `array_ptr` variable, the new lattice value is the bounds expression in the bounds declaration. Otherwise, it is the value `bounds(unknown)`.

A declaration of a variable is handled similarly to an assignment, except that there will not be any lattice value to kill. Lexical hiding of variables involved in bounds declarations is not permitted. If the declaration declares bounds for the `array_ptr` variable, the new lattice value is the bounds expression in the bounds declaration. Otherwise, it is the value `bounds(unknown)`.

A variable going out of scope kills any existing lattice values in which that variable occurs.

At control-flow split points, the lattice values for the `array_ptr` variables flow to all branches of the split. The propagation is dataflow-sensitive but not control-flow sensitive. At control-flow join points, the lattice values are unioned (moving upward in the lattice). If the lattice values for an `array_ptr` variable are not the same, the resulting value is `Top`.

3.11 Bounds declarations and loops

Loops often operate on variables declared outside of loops. They may read the variables and then update the variables. When these variables are `array_ptr` variables they must have bounds and the bound must be loop invariants.

The common case is that the bounds expression is invariant across all iterations of the loop. The earlier `sum` example illustrates this. The variable `current` is declared with bounds before a loop. The loop modifies `current`, but the bounds for `current` do not change:

```

/* sum integers stored between start and end, where end is not included */
int sum(array_ptr<int> start where start : bounds(start, end), array_ptr<
    int> end)
{
    int sum = 0;
    array_ptr<int> current : (start, end) = start;

```



```

    while (current < end) {
        sum = *current;
        current += 1; // bounds do not need to be redeclared here.
    }
}

```

A programmer can declare bounds expressions that change on each iteration of the loop. This may be necessary if an `array_ptr` variable is modified to point to different memory during a loop iteration. It also may be desirable for performance reasons. In either case, there needs to be a loop-invariant bounds declaration.

The following example illustrates this. It is an implementation of lexicographic comparisons of two arrays, using one pointer to scan each array. The bounds at the variable declarations serve as loop invariant bounds. The lower bounds for a variable are declared using the variable itself, to reduce register pressure in the loop. This can enable compilers to generate better code. Note that an optimizing compiler will eliminate the runtime bounds checks easily.

```

/* lexicographic comparison of two arrays of integers */
int compare(array_ptr<int> x : bounds(x, x_end),
            array_ptr<int> y : bounds(y, y_end)
            array_ptr<int> x_end, array_ptr<int> y_end)
{
    while (x < x_end && y < y_end) {
        if (*x == *y) { // bounds check: x >= x && x < x_end; easily
                        // optimizable.
                        // bounds check: y >= y && y < y_end; easily
                        // optimizable.
            x++;
            y++;
        }
        else if (*x < *y) { // bounds checks here are easily optimizable too.
            return -1;
        }
        else {
            return 1;
        }
    }
    if (x == x_end && y == y_end) {
        return 0;
    }
    else if (x != x_end) {
        return 1;
    }
    else {
        return -1;
    }
}

```

Chapter 4

Checking validity of bounds declarations for variables

This chapter describes basic rules for determining the validity of bounds declarations in a C translation unit. In general, these rules do not include any inference steps. Inference steps for reasoning about bounds are described in Chapter 8.

Section 4.2 describes how to determine the bounds for an expression of type `array_ptr` that does not have any assignments within it. We start with a set of bounds that are true about variables before the evaluation of the expression, called the context, and describe the bounds for the value of the expression. Section 4.3 then describes handling assignment expressions, assuming that no assignments are nested within the expression. For an assignment expression, we must determine the updated context in addition to the value of the expression. The updated context contains new bounds for any variables assigned to by the expression. Section 4.4 combines the concepts and describes handling expressions with nested assignments expressions. Section 4.5 describes how to validate expression statements. Section 4.8 describes validating function call arguments.

Because this section covers bounds for `array_ptr` variables, not data structures with `array_ptr` data, certain expressions are not covered here. This includes member references and expressions that load or store `array_ptr` values through pointers. These expressions are covered in Chapters 6 and 7. Section 3.4 does discuss how to insert bounds checking at uses of the indirection operator (*). This is different than discussing the bounds of the values *returned* or *stored* through the indirection operator.

4.1 Preparing a translation unit for checking

To simplify the rules for checking, some syntactic transformations are done on a translation unit before checking. First, some syntactic cases are replaced with semantically-equivalent cases. This reduces the number of cases that must be covered by the checking rules. In-line return bounds expressions are replaced with the form that uses a name for the return value. The form `f(...) : e1` is changed to `f(...) where return_value : e1`. The `count` and `byte_count` bounds expressions are also expanded to bounds expressions. The form `x : count(e1)` is replaced with `x : bounds(x, x + e1)` and `x : byte_count(e1)` is replaced with `x : bounds((array_ptr<char>) x, (array_ptr<`

`char> x + e1`). For now, we ignore the additional side conditions on count expressions. Checking of these conditions will be addressed in Chapter 8.

Also, relative alignment is made explicit for all bounds declarations: $x : \text{bounds}(e2, e3)$ is expanded to $x : \text{bounds}(e2, e3) \text{ rel_align_value}(\text{sizeof}(\text{typeof}(x)))$. For code without explicit or implicit casts of `array_ptrs`, relative alignment can be ignored.

In the checking rules, sometimes shorter syntactic forms are used for brevity. The shorter forms should be replaced with their full forms before using the rules.

Second, lexical hiding of variables is eliminated by renaming variables so that hiding no longer happens¹. If a variable with block scope that does not have external linkage has the same name as a variable with file scope or a variable with an enclosing block scope, the variable should be renamed to be distinct from other variables. Similarly, parameter variables that have the same name as a variable with file scope or a variable with an enclosing block scope should be renamed.

4.2 Inferring valid bounds for expressions without nested assignment expressions

We first discuss determining valid bounds for expressions that do not have assignment expressions nested within them. The bounds for an expression is always determined with respect to a context (bounds for variables read by the expression). We will use \vdash to denote the valid bounds for an expression. The notation $e \vdash \text{bounds-exp}$ means that expression e has valid bounds bounds-exp .

At times, we need to discuss bounds that are given in terms of the value of the current expression. For example, a function call expression may return an `array_ptr` pointer to an array of constant size n . The bounds for that pointer value would be (the `array_ptr` pointer, the `array_ptr` pointer + n). We use the special variable `expr_current_value` to denote the “current value of the expression.”² The bounds for an expression may involve using the bounds for a subexpression where the special variable `expr_current_value` occurs. If the “current value” of the expression changes, the uses of `expr_current_value` from subexpressions must be adjusted to counter the change. Bookkeeping rules for making this adjustment will be described in sections that treat expressions with subexpressions.

4.2.1 Null pointers

The bounds for 0 is the `any` bounds:

$0 \vdash \text{bounds}(\text{any})$

4.2.2 Variables

Suppose there is a use of some variable x .

¹Note that compilers typically do not need to rename variables. Compilers already disambiguate variables with the same name and the disambiguation mechanisms can be used in the implementation of the checking rules. For example, some compilers use distinct objects to represent each variable declaration.

²We are open to suggestions on the name for this special symbol. We considered the term ‘self’, but chose not to use because it is anthropomorphic and not particularly descriptive. We also considered the term ‘this’, but that has specific meaning to programmers who also use object-oriented languages, so it is likely to cause confusion.

- If x has type `array_ptr`, the bounds are the result of the analysis in Section 3.10.1 for this occurrence of x .
- If x has type `ptr<T>`, $x \vdash \text{bounds}(x, x + 1) \text{ rel_align}(T)$. On the right-hand side, x is reinterpreted as having `array_ptr` type.
- If x has an array type, the rules depend on whether x is a parameter variable. Typechecking in C treats a parameter variable with the type “array of T ” as though it has the type “pointer to T ”. It does not enforce at function calls that actual arguments have the required dimension size. This means that the declared outermost bounds cannot be trusted for parameters with unchecked array types. In contrast, local variables and externally-scoped variables are allocated space for their declared types. Declared dimension information for them can be trusted regardless of whether they have checked or unchecked array types. Checking of bounds declarations for checked arrays enforces that actual arguments meet the required dimension size.
 - If
 - * x is a local variable or an externally scoped variable
 - * or x is a parameter variable with a checked array type
 and x has a known number of elements n , then $x \vdash \text{count}(n)$.
 - Otherwise, the bounds are the result of the analysis in Section 3.10.1 for this occurrence of x .
- Otherwise x has `bounds(unknown)`.

4.2.3 Address-of expressions

There are three kinds of address-of expressions:

- Address of a variable ($\&x$): a variable x with type T whose address is taken is considered to be an array of one element:

$$\&x \vdash \text{bounds}(\&x, \&x + 1) \text{ rel_align}(T).$$
- Address of a pointer dereference operation ($\&*e$): The address-of operation and the pointer dereference operation cancel. The bounds are the bounds of the underlying expression. If $e \vdash \text{bounds-exp}$, then $\&*e \vdash \text{bounds-exp}$.
- Address-of a subscripting expression ($\&e1[e2]$): This is the same as taking the address of a pointer dereference operation. According to the C semantics, $e1[e2]$ is equivalent to $*(e1 + e2)$. If $e1 + e2 \vdash \text{bounds-exp}$, then $\&e1[e2] \vdash \text{bounds-exp}$.

4.2.4 Function calls

Let f be the name of a function that returns an `array_ptr` value (pointers to functions will be handled later). Suppose there is a function call expression of the form $f(e1 \dots en)$:

1. If f has a bounds declaration for the return value of the form `return_value : exp1`, then

- Any arguments that correspond to formal parameters occurring in *exp1* must be valid non-modifying expressions. If they are not, $f(e1 \dots en) \vdash \text{bounds}(\text{unknown})$.
 - Otherwise, substitute *e1* ... *en* for the formal parameters of *f* occurring in *exp1*. Also substitute the special symbol `expr_current_value` for `return_value`. These substitutions produce *exp2*. $f(e1 \dots en) \vdash \text{exp2}$.
2. If *f* does not have a bounds declaration for its return value, then $f(e1 \dots en) \vdash \text{bounds}(\text{unknown})$.

The special variable `return_value` may appear in *exp1*. It is the value of the function call expression, so it is replaced with the special variable `expr_current_value`.

There needs to be validation that the bounds for argument expressions match the required bounds for formal parameters. This is described in Section 4.8.

The following code provides examples of function call expressions where bounds need to be computed. In the code, the programmer wraps a call to `malloc` in an allocation helper, `alloc_helper`. The function `alloc_helper` returns an `array_ptr` value that is passed as an argument to `init`, which initializes the array and returns the `array_ptr` value.

```
array_ptr<int> alloc_helper(int n) : count(n)
{
    array_ptr<int> result : count(n) = malloc((sizeof(int) * n);
    return result;
}

array_ptr<int> init(array_ptr<int> target : count(s),
                  int s) : count(s)
{
    for (int i = 0; i < count; i++) {
        target[i] = i;
    }

    return target;
}

void go(int size)
{
    array_ptr<int> x : count(size) = init(alloc_helper(size), size);
    ...
}
```

First, syntactic forms for bounds expressions are expanded to eliminate count expressions and in-line return expressions, as well as make relative alignment explicit.

```
array_ptr<int> alloc_helper(int n)
where return_value : bounds(return_value, return_value + n) rel_align(int)
{
    array_ptr<int> result : bounds(result, result + n) rel_align(int) =
        malloc((sizeof(int) * n);
    return result;
}

array_ptr<int> init(array_ptr<int> target : bounds(target, target + s)
```

```

                                rel_align(int),
                                int s)
where return_value : bounds(return_value, return_value + s) rel_align(int)
{
    for (int i = 0; i < count; i++) {
        target[i] = i;
    }

    return target;
}

void go(int size)
{
    array_ptr<int> x : bounds(x, x + size) rel_align(int) =
        init(alloc_helper(size), size);
    ...
}

```

The valid bounds for the call to `init(alloc_helper(size),size)` in `go` are computed using the return bounds for `init`:

```
return_value : bounds(return_value, return_value + s) rel_align(int)
```

First, there is a check that all the actual arguments corresponding to the formal parameters used by the return bounds expression are valid non-modifying bounds expressions. This check succeeds even though the first actual argument `alloc_helper(size)` is not a valid bounds expression. The formal parameter `target` is not used by the return bounds expression.

Next, the actual arguments are substituted for the formal parameters and `expr_current_value` is substituted for `return_value`. The argument `size` is substituted for `s`, producing

```
init(alloc_helper(size), size) ⊢ bounds(expr_current_value,
    expr_current_value + size) rel_align(int)
```

It would not be possible to represent the bounds if `size` were a function call too:

```
array_ptr<int> x = init(alloc_helper(getsize()), getsize());
```

Function calls are not valid in bounds expressions:

```
bounds(expr_current_value, current_expr_value + getsize()) // illegal
```

The solution would be to assign the result of `getsize()` to a variable:

```
int tmp = getsize();
array_ptr<int> x = init(alloc_helper(tmp), tmp);
```

The parameters to the call to `init` also need to be validated (see Section 4.8). This requires determining the valid bounds for `alloc_helper(size)`. The return bounds for `alloc_helper` are used:

```
return_value : bounds(return_value, return_value + n) rel_align(int)
```

First, there is a check that the actual arguments that correspond to formal parameters used in the return bounds are valid non-modifying expressions. The only argument is the variable `size`,

so this check succeeds. Next, `size` is substituted for `n` and `expr_current_value` is substituted for `return_value`, producing:

```
alloc_helper(size) ⊢ bounds(expr_current_value, expr_current_value +
    size) rel_align(int)
```

4.2.5 Pointer arithmetic

The range of memory accessible through pointer arithmetic expressions remains unchanged from the underlying pointer. In other words, for $x \vdash \text{bounds-exp}$, the bounds expression for any pointer arithmetic involving x is the same as the one for x . This is because that C semantics for pointer arithmetic is that if x points to an object at runtime, any pointer arithmetic involving x must produce a pointer to the same object. The bounds of the object in memory are not changed by the pointer arithmetic.

We first cover the typical situation where the relative alignment type for a pointer in a pointer operation matches the referent type of the pointer. Given a pointer operation of the form $x \text{ op } e1$, where x has an `array_ptr` type, $e1$ has an integral type, and op is addition or subtraction, the memory that can be accessed through $x \text{ op } e1$ is the same memory that can be accessed through x :

- If x is a pointer to T and $x \vdash \text{bounds}(e2, e3) \text{ rel_align}(T)$, then $x \text{ op } e1 \vdash \text{bounds}(e2, e3) \text{ rel_align}(T)$.

This can be extended to pointer operations of the form $e4 \text{ op } e1$, where $e4$ has type `array_ptr<T>` as follows:

- If $e4$ is a pointer to T and $e4 \vdash \text{bounds}(e2, e3) \text{ rel_align}(T)$ then $e4 \text{ op } e1 \vdash \text{bounds}(e2, e3) \text{ rel_align}(T)$

Here is the full rule that handles the situation where the relative alignment of the pointer differs from the size of the referent type of the pointer. GCD computes the greatest common divisor of two integers. The prior rules are just special cases of this rule:

If $e4$ is a pointer to T and $e4 \vdash \text{bounds}(e2, e3) \text{ rel_align}(c)$ then $e4 \text{ op } e1 \vdash \text{bounds}(e2, e3) \text{ rel_align}(\text{GCD}(c, \text{sizeof}(T)))$.

4.2.5.1 Pointer arithmetic for unchecked pointer types

Pointer arithmetic involving an `array_ptr` value checks that the value is non-null and generates a runtime error if it is. This check is important because a null pointer may have invalid bounds (this follows from the definition of the meaning of bounds in Section 3.1). It prevents a null pointer that has invalid bounds from being used to create a non-null pointer with valid bounds, which could then be used to access memory.

Because the meaning of unchecked pointers has not changed, pointer arithmetic involving a null unchecked pointer may not generate a runtime error. The rules for `array_ptr` pointer arithmetic can be applied to unchecked pointer arithmetic, however, provided that a side condition that the pointer expression is non-null is added:

If e_4 is a pointer to T and it can be proved that $e_4 \neq 0$ and $e_4 \vdash \text{bounds}(e_2, e_3) \text{ rel_align}(\text{GCD}(c, \text{sizeof}(T)))$, then $e_4 \text{ op } e_1 \vdash \text{bounds}(e_2, e_3) \text{ rel_align}(\text{GCD}(c, \text{sizeof}(T)))$.

Chapter 8 provides a general framework for checking side-conditions as part of checking bounds declarations.

4.2.5.2 Treatment of `expr_current_value`

If the special variable `expr_current_value` occurs in `bounds(e2, e3)`, then `expr_current_value` must be adjusted as follows:

- If `op` is `+`, substitute `expr_current_value - e1` for all occurrences of `expr_current_value` in `bounds(e2, e3)`
- If `op` is `-`, substitute `expr_current_value + e1` for all occurrences of `expr_current_value` in `bounds(e2, e3)`.

The reasoning behind this is that the current value of the expression has changed as the result of `op e1`. An adjustment in the opposite direction of equal magnitude must be made for occurrences of `expr_current_value`.

The following example illustrates the treatment of `expr_current_value`. Consider the prior example that had a function called `alloc_helper` that returned some newly-allocated memory. Suppose there is an expression that offsets a pointer returned by a call to `alloc_helper`:

```
alloc_helper(size) + 2
```

To compute the bounds for this expression, first the valid bounds for `alloc_helper(size)` are computed:

```
alloc_helper(size) ⊢ bounds(expr_current_value, expr_current_value +
    size)
```

Next, `expr_current_value - 2` is substituted for `expr_current_value` yielding:

```
alloc_helper(size) + 2 ⊢ bounds(expr_current_value - 2,
    expr_current_value - 2 + size)
```

Now, suppose the pointer is being adjusted to insert some blank padding at the beginning of the newly-allocated object. We can remove the occurrence of `expr_current_value - 2` in the upper bound by over-allocating in the expression:

```
alloc_helper(size + 2) + 2
```

The valid bounds for `alloc_helper(size + 2)` are:

```
alloc_helper(size + 2) ⊢ bounds(expr_current_value, expr_current_value +
    size + 2)
```

The valid bounds for the entire expression are:

```
alloc_helper(size + 2) + 2 ⊢ bounds(expr_current_value - 2,
    expr_current_value - 2 + size + 2)
```

which can be simplified to:


```
alloc_helper(size + 2) + 2 ⊢ bounds(expr_current_value - 2,
    expr_current_value + size)
```

As we will explain in Chapter 8, it is fine to narrow a bounds by adding a positive constant to the lower bounds. This allows us to adjust the bounds to what would be desired when extra padding is inserted:

```
alloc_helper(size + 2) + 2 ⊢ bounds(expr_current_value,
    expr_current_value + size)
```

4.2.6 Cast expressions

Given a cast expression of the form $(T) e$, the bounds for e are determined. The bounds for e are used as the bounds for the entire expression.

If the special variable `expr_current_value` appears in the bounds for e ,

- If T is an integral type large enough to hold a pointer or a pointer type, let S be the type of e . The expression $(S) \text{expr_current_value}$ is substituted for all occurrences of `expr_current_value`.
- Otherwise, the bounds of e are altered to `bounds(unknown)`.

4.2.7 Conditional expressions

Given an expression of the form $e1 ? e2 : e3$, the bounds for $e2$ and $e3$ are determined. They must be syntactically identical (after putting the bounds into a normal form). The bounds for $e2$ are used as the bounds for the entire expression.

If the special variable `expr_current_value` occurs in the bounds for $e2$, it is left unchanged. The conditional expression does not change the value returned by one if its branches, so no adjustment to `expr_current_value` is needed.

This is an expression where a conditional bounds expression could be used to represent the resulting range. Another alternative that works with current syntax would be to create upper/lower-bound expressions that use $e1$ such as $(e1 ? \text{lower-bound}(e2) : \text{lower-bound}(e3), e1 ? \text{upper-bound}(e2) : \text{upper-bound}(e3))$. For now, we defer discussion of both alternatives.

4.2.8 Comma expressions

Given an expression of the form $e1, e2$, the bounds for $e2$ are determined. The bounds for $e2$ are used as the bounds for the entire expression.

If the special variable `expr_current_value` occurs in the bounds for $e2$, it is left unchanged.

4.3 Bounds for assignment expressions

For an assignment expression of the form $x = e$, where x is a variable and e is an expression, we start with a context that is true before the evaluation of the assignment expression. We determine the context that will be true after the evaluation of the assignment expression and the bounds for the value returned by the assignment expression.

This seems straightforward at first. If x has type `array_ptr`, compute the bounds for e and update the context so that the bounds for x is the bounds of e . However, there is a problem. The bounds for e is determined *before* x changes value. When x changes value, the bounds for e may no longer be true if x appears in the bounds. The context could contain uses of x also in bounds expressions.

A simple solution is to invalidate bounds expressions where x appears in the bounds. This does not work well when a variable that appears in its own bounds declaration is incremented or decremented. Consider the following example:

```
array_ptr<int> x : bounds(x, high) = ...
int sum = 0;
while (x < high) {
    sum += *x;
    x++; // bounds for x would be undefined for the simple solution
}
```

A possible solution is to require programmers to copy variables in loops that are modified using only pointer arithmetic to temporary variables before the loop. The temporary variables could then be used in bounds. However, this might increase register pressure and worsen performance.

One can do better than that for loop induction variables, which are variables that are incremented or decremented by a constant in a loop. Condit *et al.* observe that some assignment expressions are invertible: the old value of a variable can be calculated from the new value. One can update the bounds by substituting the inverted expression in place of the variable. The updated bounds can then be narrowed to satisfy loop bounds invariants. Invertible expressions include the addition and subtraction expressions that update loop induction variables.

The updated context will be determined in three steps. First, if x has type `array_ptr`, the context is updated for x using bounds expressions that use the *old* value of x :

1. If $e \vdash exp$, then the context is updated with $x : exp$.
2. Otherwise, the context is updated with $x : \text{bounds}(\text{unknown})$ to indicate that x has no valid bounds.

Second, the context is updated to reflect the change in the value of x :

- If the expression being assigned is invertible, the right-hand side of any bounds expression that uses x will be updated to use an expression that inverts the new value to compute the old value.
- Otherwise, any bounds expression that involves x is invalidated

An assignment expression in C has a value. The bounds of the assignment expression will be the bounds of x at this point.

Third, the special variable `expr_current_value` is eliminated from the bounds of x , if it was introduced because it occurred in $e : exp$. Recall that `expr_current_value` stands for the current value of an expression whose bounds is being determined. Because the value of e has been assigned to x , x is substituted for `expr_current_value` in the bounds for x .

4.3.1 Invertibility

The following examples illustrate invertibility and updating bounds. For the first example, suppose there is a declaration of an `array_ptr` variable followed by a decrement of a variable involved in the bounds:

```
array_ptr<int> a : count(len) = ...
len = len - 1
```

The original value of `len` can be computed from the new value. In this case, a valid new bounds after the decrement of `len` is `count(a) == len + 1`. The bounds for `a` after the assignment are:

```
len = len - 1
where a : count(len + 1);
```

For the second example, consider an update to a pointer variable that appears in its own bounds:

```
array_ptr<int> p : bounds(p, high) = ...
while (p < high) {
    ...
    p = p + 1;
}
```

First, the new bounds expression for the expression `p + 1` is computed. It is the same as the original bounds expression `bounds(p, high)`. Because `p` is modified by the assignment, the inverted expression for `p + 1` is substituted into `(p, high)`. The inverted expression for `p + 1` is `p - 1`. This leads to bounds of the form `bounds(p - 1, high)`:

```
while (p < high) {
    ...
    p = p + 1 where p : bounds(p - 1, high);
}
```

Bounds validity is preserved when the range of a bounds expression is narrowed. `(p - 1, high)` implies that `(p, high)` is a valid bounds expression. This reestablishes the loop bounds invariant for `p` of `(p, high)`.

```
while (p < high) {
    ...
    p = p + 1 where p : bounds(p, high);
}
```

The correctness of narrowing depends on pointer arithmetic overflow for checked pointer types being a runtime error. For a lower bound `e1` in a bounds expression, we can only substitute `e2` for `e1` as the lower bound if `e2 >= e1`. The identity `p > p - 1` holds only if overflow is a runtime error.

4.3.2 Invertible expressions

An expression is invertible with respect to a variable x if:

1. The expression is x
2. or
 - (a) The operator in the expression is an addition, subtraction, one's complement, unary minus, unary plus, exclusive-or, a bit-preserving cast operator, or a widening cast operator, and
 - (b) The variable x occurs only in one argument of the operation and that argument is an invertible expression with respect to x
 - (c) Any other argument of the operation is a non-modifying expression, excluding non-modifying expressions that are or include member references, indirect member references, or pointer dereferences.

The addition and subtraction operations must be for checked pointer arithmetic or unsigned integer arithmetic. An implementation may allow integral addition and subtraction operations to be invertible if integral addition and subtraction are defined as two's complement arithmetic where extra bits are discarded on overflow. However, this introduces the possibility of non-portable code.

Given the expression $x = e$, where x occurs once in e , mathematical rules are applied to solve for x in e . We generalize the left-hand side from x to an expression f and define `inverse(f , e)` as follows:

Given <code>inverse(f, e)</code> , where	the result is:
$e = x$	f
$e = \sim e1$	<code>inverse($\sim f$, $e1$)</code>
$e = -e1$	<code>inverse($-f$, $e1$)</code>
$e = +e1$	<code>inverse($+f$, $e1$)</code>
$e = (t1) e1$, where $e1$ has type $t2$ and $(t1)$ is not a narrowing cast	<code>inverse($((t2) f$, $e1$)</code>
$e = e1 + e2$, where x occurs in $e1$	<code>inverse($f - e2$, $e1$)</code>
$e = e1 + e2$, where x occurs in $e2$	<code>inverse($f - e1$, $e2$)</code>
$e = e1 - e2$, where x occurs in $e1$	<code>inverse($f + e2$, $e1$)</code>
$e = e1 - e2$, where x occurs in $e2$	<code>inverse($e1 - f$, $e2$)</code>
$e = e1 \wedge e2$, where x occurs in $e1$	<code>inverse($f \wedge e2$, $e1$)</code>
$e = e1 \wedge e2$, where x occurs in $e2$	<code>inverse($f \wedge e1$, $e2$)</code>

Given `inverse(x , e)`, the rules are applied repeatedly until the original value of x in e has been computed. Here is an example of computing the inverse of $x = (x + 4) + 5$:

```
inverse(x, (x + 4) + 5) =
  inverse(x - 5, x + 4) =
    inverse((x - 5) - 4, x) =
      (x - 5) - 4
```

4.4 Bounds for expressions with nested assignment expressions

C allows assignment expressions to be nested within other expressions. This means that the approach of Section 4.3 has to be extended to walk expressions recursively and update the context during the walk.

Given some expression e that has subexpressions $e_1 \dots e_n$, start with the context for e . Compute a new context and the bounds expression for e as follows:

- Traverse $e_1 \dots e_n$ in an order that respect the sequence points of [50]. For each subexpression, take the context and compute the updated context and the bound expression (if any) for the subexpression.
- If e is an assignment expression, apply the rules in Section 4.3 to compute an updated context and a bounds expression for e
- Otherwise, apply the rules in Section 4.2 to compute an updated bounds expression for e .

4.5 Expression statements

Expression statements need to be checked for consistency with their expected bounds declarations. If an expression statement is within a bundled block, the checking is deferred to the end of the bundled block.

To check an expression statement, the analysis of Section 3.10.1 is used to determine the context for the expression in the statement (the bounds for variables before the statement is evaluated). The rules in Section 4.4 are then used to determine the updated context.

The updated context is then checked against the bounds declarations that must be true after the expression statement. For each `array_ptr` variable x in scope, the expected bounds is computed:

- If the expression statement has a bounds declaration for x , the bounds expression in that bounds declaration is used.
- Otherwise, the analysis of Section 3.10.1 is used to determine the expected bounds expression for x .

We will refer to the bounds expression for x in the updated context as the updated bounds expression. It must imply that the expected bounds expression holds. Implication is checked in this section using by placing non-modifying expressions into a canonical form and checking for syntactic equality. If two expressions have the same canonical form, any values that they have at runtime will always be identical. Chapter 8 describes more general techniques for checking that context bounds imply the expected bounds.

The updated bounds expression implies that the expected bounds expression holds if:

- The expected bounds expression is `bounds(unknown)`, or
- The updated bounds expression is `bounds(any)`, or
- The updated bounds expression and the expected bounds expression are equal syntactically after placing the expressions into canonical forms,

- The canonicalized expressions differ syntactically only in their relative alignment, and the context bounds implies the expected relative alignment `c`. This is true if:
 - The context relative alignment is an integer multiple of the expected relative alignment,
 - or given a context bounds expression of the form `bounds(e1,e2) rel_align(d)`,
`((array_ptr<char>) x - (array_ptr<char>) e1) % c` canonicalizes to 0, as does
`((array_ptr<char>) e2 - (array_ptr<char>) x) % c`.

4.5.1 Canonicalization of expressions in bounds expressions

Most readers can skip this section safely and come back to it as necessary. This section is for compiler implementers and for programmers who want to understand when expressions are regarded as identical by canonicalization.

Canonicalization guarantees the following: if two non-modifying expressions have the same canonical form and if they produce values when evaluated at runtime, the two values will be equal. There are two important things to understand about this definition. First, two C expressions may have different canonicalized forms and still always produce the same value at runtime (in the terminology of logic, canonicalization is incomplete). Second, canonicalization does not guarantee that an expression will actually produce a value at runtime. It may still have a runtime fault. The runtime correctness of bounds expressions is implied by transitivity: a bounds expression must be implied by another bounds expression, and so on, until a bounds expression is implied by an allocation. The allocation must have involved an expression that actually produced a value.

This has a surprising consequence: integer arithmetic operations that check for overflow can be regarded as following mathematical rules during canonicalization. A compiler could not reassociate `((a +ovf b) +ovf c)` to `(a +ovf (b +ovf c))` and replace the first expression with the second one because it could cause an overflow where none occurred before. For canonicalization, though, reassociation is fine.

Signed integer operations do not follow certain mathematical identities. This is because according to the rules in Section 2.12, they may produce a value on overflow, but the properties of the value are not specified. Signed addition is not associative: `(a + b) + c` is not guaranteed to produce the same result as `a + (b + c)` in the presence of overflow. The expression `a + b` may overflow, while `b + c` may not overflow or the reverse may occur. In addition, for signed integers, it is not guaranteed that `a - b = a + (-b)` or that `-(-(a)) = a`.

The canonicalization rules need to disambiguate between signed and unsigned operators for integers, as well as operators that check for overflow. All integer operators will be subscripted by whether they apply to signed or unsigned integers and whether they check overflow using the subscripts `signed`, `unsigned`, and `ovf`. For example, the expression `(a + b) + c` involving signed integers will be written as `(a +signed b) +signed c`.

The overflow checking operators introduced in Section 2.10.2 only include operators that can occur in practice. For canonicalization, it is useful to have a complete set of operators, including `+ovf` and `-ovf` that take two integers (both signed or unsigned) and produce an integer that has the same type as the arguments, as well as unary negation that takes a signed or unsigned integer and produces a signed integer.

In the rules for canonicalization, when a subscript on an integer operator is omitted, the rule applies to all forms of the operator. Sometimes the subscript *kind* will be used on operators. Either *unsigned* or *ovf* should be substituted for *kind* in the rule.

The first step in canonicalization is to convert non-modifying expressions to an initial representation:

1. All expressions involving operators are fully parenthesized and unnecessary parenthesis on variables and constants are removed. For example, *e1 op1 e2 op2 e3*, is replaced by $((e1\ op1\ e2)\ op2\ e3)$ or $(e1\ op1\ (e2\ op2\ e3))$, depending on the precedence of *op1* and *op2*.
2. Implicit cast operations are made explicit.
3. The pointer dereference *** and pointer indirection operators (*->*) are implicitly annotated with their pointer types. This is necessary because converting pointer arithmetic to integer arithmetic will erase the type information needed by these operators.
4. Unary plus operations are removed.
5. Array references of the form *e1 [e2]* are converted to $*((e1) + (e2))$
6. Pointer arithmetic is expanded to integer-based arithmetic.
7. Binary subtraction expressions are canonicalized to use unary minus when possible: *e1 -kind e2* is converted to *e1 +kind -kind e2*.

For the second step of canonicalization, two sets of binary arithmetic operators are defined

- The set of commutative and associative operators (CA operators). This includes:
 - The operators *+_{unsigned}*, **_{unsigned}*, *+_{ovf}* and **_{ovf}*item The bitwise operators *|*, *&*, and *^*.
 - The Boolean operators *||* and *&&*.
- The set of commutative-only operators (CO): *+_{signed}* and **_{signed}*.

The following rules are applied until no further changes occur:

1. Removing pointer casts and identity casts on integral types (casts from a type to itself). Pointer casts do not change the values of pointers.
2. Folding constant integral expressions. The following expressions are constant-folded:
 - (a) Any constant expression that uses only overflow-checking arithmetic operators and that mathematically evaluates to an in-range integer value. The value is the mathematical result.
 - (b) Any constant expression involving integers that produces a defined result according to the C language standard or the C implementation rules.
3. Applying algebraic identities to simplify expressions
 - (a) Arithmetic identities
 - i. $e + 0 = e$, $e - 0 = e$, $0 - e = (-e)$, $0 * e = 0$, $1 * e = e$, $e / 1 = e$, $e / -1 = -e$, $e \% 1 = e$
 - ii. For a positive constant *c*, $(e *_{kind} c) \% c = 0$
 - (b) Bitwise identities: $e \& 0 = 0$, $e | 0 = e$, $e \wedge 0 = e$, and $\sim(\sim e \text{---}) = e$
 - (c) Boolean identities: given a non-zero constant *c*, *e && c* simplifies to *e*, *e || c* simplifies to 1, and *!c = 0*. When *c = 0*, *e && c* simplifies to 0, *e || c* simplifies to *e*, and *!c = 1*.
 - (d) Double negation: $-_{kind}(-_{kind} e) = e$.
 - (e) Cancelling terms: $e -_{signed} e$ simplifies to 0 and $e +_{kind} (-_{kind} e)$ simplifies to 0. This is applied more generally to a sequence of addition operations of the form $(\dots (e1 +_{kind} e2) \dots +_{kind} -_{kind} e1 \dots)$.

When identities have commutative versions, those are applied as well.

4. Applying associativity commutivity, and distributivity rules to put expressions in canonical forms:
 - (a) For each operator *op* in CA, repeatedly rewriting any expression of the form *e1 op (e2 op e3)* to *(e1 op e2) op e3* until no further rewrites are possible.
 - (b) For each operator *op* in CA, for each sequence of operations $(\dots ((e1 \text{ op } e2) \text{ op } e3) \dots \text{ op } en)$, reordering the operands so that *e1* ... *en* appear in lexicographic order. Constants should appear lower in the lexicographic order than more complex expressions.
 - (c) For each operator *op* in CO, commuting the operands in *e1 op e2* so that *e1* is lower in the lexicographic order.
 - (d) Applying the following distributivity rules:
 - i. Rewriting $-_{kind}(e1 +_{kind} e2)$ to $(-_{kind} e1) + (-_{kind} e2)$,
 - ii. Rewriting $(e1 +_{kind} e2) *_{kind} e3$ to $(e1 *_{kind} e3) +_{kind} (e2 *_{kind} e3)$
 - iii. Rewriting $(e1 | e2) \& e3$ as $(e1 \& e3) | (e2 \& e3)$ and rewriting $e3 \& (e1 | e2)$ as $(e3 \& e1) | (e3 \& e2)$
 - iv. Rewriting $!(e1 || e2)$ as $((!e1) \&\& (!e2))$ and $!(e1 \&\& e2)$ as $((!e1) || (!e2))$
 - v. Rewriting $(e1 || e2) \&\& e3$ as $(e1 \&\& e3) || (e2 \&\& e3)$ and rewriting $e3 \&\& (e1 || e2)$ as $(e3 \&\& e1) || (e3 \&\& e2)$

The distributivity rules expand the size of expressions, potentially increasing size exponentially. Implementations may have a reasonable limit on the size of canonicalized expressions. A minimum required limit will be determined based on an empirical evaluation of C programs.

4.5.2 An example of canonicalization

Here is how bounds for the following declaration and statement will be checked:

```
array_ptr<int> x;
x = malloc(sizeof(int)*5) where x : count(5);
```

The function `malloc` is assumed to have the bounds declaration:

```
array_ptr<void> malloc(size_t num) : byte_count(num);
```

even though in practice it will have a bounds-safe interface that does not use a checked pointer type.

First, the implicit casts are made explicit and `count` is expanded to `bounds`:

```
x = (array_ptr<int>) malloc(sizeof(int)*(size_t) 5) where x : bounds(x, x
+ 5);
```

Next, the bounds for the right-hand expression are computed. The bounds declaration for `malloc` is expanded to:

```
array_ptr<void> malloc(size_t num)
where return_value : bounds((array_ptr<char>) return_value,
                             (array_ptr<char>) return_value + num)
```

The bounds for `malloc` are used to compute the bounds for the function call `malloc(sizeof(int)*(size_t)5)`. The actual argument `sizeof(int)*(size_t)5` is substituted for `num` in the bounds expression for the return value of `malloc`:


```
return_value : bounds((array_ptr<char>) return_value ,
                    (array_ptr<char>) return_value + sizeof(int)*(size_t)
                    ) 5)
```

Next, `expr_current_value` is substituted for `return_value` :

```
expr_current_value :
  bounds((array_ptr<char>) expr_current_value ,
        (array_ptr<char>) expr_current_value + sizeof(int)*(size_t) 5)
```

Then, the bounds for `(array_ptr<int>)malloc(sizeof(int)*(size_t)5)` are computed. The inverse cast `(array_ptr<void> expr_current_value)` is substituted for `expr_current_value`:

```
expr_current_value :
  bounds((array_ptr<char>) ((array_ptr<void>) expr_current_value),
        (array_ptr<char>) ((array_ptr<void>) expr_current_value) +
        sizeof(int) * (size_t) 5)
```

Finally, `x` is substituted for `expr_current_value` :

```
x : bounds((array_ptr<char>) ((array_ptr<void>) x),
          (array_ptr<char>) ((array_ptr<void>) x) +
          sizeof(int) * (size_t) 5)
```

Now, it has be shown that the computed bounds for `x` imply the expected bounds for `x` of `bounds(x, x + 5)`. The bounds expressions are both converted to use integer arithmetic:

```
// computed bounds
bounds((array_ptr<char>) ((array_ptr<void>) x),
      (array_ptr<char>) ((array_ptr<void>) x) +_ovf
      sizeof(int)*unsigned(size_t) 5))

// expected bounds
bounds(x, x +_ovf (5 *_ovf(signed_size_t) sizeof(int)))
```

Next, unnecessary pointer casts are removed:

```
// computed bounds
bounds(x, x +_ovf (sizeof(int) *_unsigned (size_t) 5))
// expected bounds
bounds(x, x +_ovf (5 *_ovf (signed_size_t) sizeof(int)))
```

After that, constant folding is done. If `sizeof(int)` is 4, the result is:

```
// computed bounds
bounds(x, x +_ovf 20)
// expected bounds
bounds(x, x +_ovf 20)
```

We must also show the expected bounds imply that the `rel_align(int)` requirement is met. This is straightforward for a constant-sized array. It involves showing given the variable `x` with `bounds(e1, e2)` that `((array_ptr<char>)x - (array_ptr<char>)e1) % 4` canonicalizes to 0, as does `((array_ptr<char> e2 - (array_ptr<char>) x) \% 4`.

For the first expression, `((array_ptr<char>)x - (array_ptr<char>)x) % 4` simplifies to `0 % 4`, which constant-folds to 0. For the second expression, `((array_ptr<char>)(x + 5) - (array_ptr<char>)x) % 4` simplifies to `((x +_ovf 20) -_ovf_diff x) % 4`. This simplifies to `20 % 4`, which constant-folds to 0.

If we change the example to make the number of elements variable instead of constant, we can see how canonicalization breaks down in the presence of integer wraparound. Suppose the number of elements is given by a variable `k`. We would have:

```
// computed bounds
bounds(x, x +_ovf (sizeof(int) *unsigned (size_t) k))
// expected bounds
bounds(x, x +_ovf (k *_ovf (signed_size_t) sizeof(int)))
```

After converting pointer arithmetic to integer arithmetic, we have:

```
// computed bounds
bounds(x, x +_ovf (4 *unsigned (size_t) k))
// expected bounds
bounds(x, x +_ovf (k *_ovf 4))
```

Canonicalization of the upper bounds expressions produces:

```
// computed bounds
x +_ovf (4 *unsigned (size_t) k))
// expected bounds
x +_ovf (4 *_ovf k)
```

The expressions are not identically syntactically, so bounds expression checking fails. The additional side conditions that `k >= 0 && k <= UINTPTR_MAX/4` are needed to show that the computed upper bound implies the expected upper bound. More general techniques from Chapter 8 are needed to show that the context bounds imply the expected bounds.

4.5.3 Extending canonicalization to two's complement signed integer arithmetic

In some widely-used C compilers, signed arithmetic implemented as two's complement arithmetic is available under a compiler flag. In this case, the expected arithmetic properties hold, which enables more expressions to be canonicalized to the same form.

4.6 Declarations

Declarations also need to be checked for consistency with their bounds declarations. If the declaration is within a bundled block, the checking is deferred to the end of the bundled block.

C distinguishes between declarations and definitions of variables. A declaration declares the type and storage class for a variable. It may or may not cause storage to be allocated for the variable. A definition is a declaration of a variable that causes storage to be allocated for the variable as well. Definitions may have initializers that initialize the storage for the variable.

We first describe checking definitions, which is similar to checking assignments. For a declaration, we assume that there is an ordered list of `array_ptr` variables and their optional initializers, and the list of bounds declarations in the where clause for the declaration. The list is ordered by the order of variable declarations.

First, the current context is computed before the declaration. Then, for each variable `v` in the list,

- If v has an initializer, the current context is updated by traversing the assignment expressions in the initializer using the analysis from Section 4.4. The bounds for each individual assignment expression are recorded as well. Note that if v is a static variable, the assignment expressions must actually be constant expressions, so the context will not change.
- If v has an `array_ptr` type or an incomplete array type, the context is updated to record the new bounds for v :
 - If v has no initializer, then
 - * If v is a static variable, then v will be initialized to 0. The context is updated to map v to `bounds(any)`.
 - * If v is an automatic variable then v will have an indeterminate value. The context is updated to map v to `bounds(unknown)`.
 - If v has an initializer, the initializer must have the form e or $\{ e \}$. In both cases,
 - * If `expr_current_value` appears in the bounds for e , v is substituted for it.
 - * The context is updated to map v to the updated bounds.

The current context is then checked against the bounds declarations that must be true after the declaration using the analysis in Section 4.5

Declarations that are not definitions are not checked, other than to verify that all the declarations of a variable in a translation unit have the same bounds declaration (or lack of a bounds declarations) for the variable.

4.7 Bundled declarations and statements

To check bundled declarations and statements, the current context is determined before the bundled block. The current context is then updated for each expression statement and declaration following the rules for updating contexts in Sections 4.5 and 4.6. The analysis of Section 3.10.1 is used to determine the expected bounds expression for each variable at the end of the bundled block. The current context is checked against the bounds declarations that must be true at the end of the block using the analysis in Section 4.5

When an expression with `array_ptr` type is dereferenced within an expression statement in a bundled block, the current context before the statement is used to determine the bounds for the expression. This may cause an expression to have a different bounds than it normally would have based on bounds declarations.

For example, suppose a pointer assignment is introduced into the middle of the earlier example. The pointer assignment is highlighted in blue. The bounds for `parr` at that point in the program based on the current context will be `bounds(parr, parr + size)`.

```
int arr[DEFAULT_SIZE];
array_ptr<int> parr : count(len) = arr;
int plen = DEFAULT_SIZE;

f(int size) {
    if (size > DEFAULT_SIZE) {
```

```

    bundle {
        parr = malloc(sizeof(int) * size);
        *parr = 314;
        plen = size;
    }
}

```

If the code were slightly rearranged, there would be a compile-time error. The assignment to `plen` invalidates the bounds for `parr` in the context at the point of the assignment.

```

f(int size) {
    if (size > DEFAULT_SIZE) {
        bundle {
            plen = size;
            *parr = 314; // error: parr has bounds of none.
            parr = malloc(sizeof(int) * size);
        }
    }
}

```

A function call within a bundled block require special treatment: the bounds declarations for variables with static storage must be valid before the call. The called function is assuming that the declared bounds are valid. This means that the context before the function call must imply that bounds declarations for variables in scope that have static storage are valid.

4.8 Function call arguments

Function call arguments also need to be checked for consistency with expected bounds declarations. This is similar to checking of expression statements with where clauses. For each call $f(e_1 \dots e_n)$ to a function $f(x_1 \dots x_n)$ that has bounds declarations for one or more parameters,

- A statement of the form

$x_1 = e_1, x_2 = e_2, \dots, x_n = e_n$ where *conditions*;

is constructed, where *conditions* contains all the bounds declarations on parameters. Parameters are renamed if necessary so that they have different names from variables in scope at the function call.

- The context for the function call is constructed. The statement is checked in that context using the rules in Section 4.5
- A subtle point is that the order of evaluation for argument expressions in C is not defined (Section 4.11 discusses order of evaluation issues in depth). A check is done also that the values of argument expressions used in checking the bounds declaration do not depend on the order of evaluation of arguments:
 - The set of parameters that occur in bounds declarations for parameters is computed.
 - Any argument expression corresponding to a parameter in this set cannot read a variable that is assigned to by another argument expression. If one does, the function call is rejected as not checking.

4.9 Return statements

A return statement has the form `return e`, where `e` is optional. The bounds for `e` are computed. If the special variable `expr_current_value` occurs in the bounds, the special variable `return_value` is substituted into the bounds in its place. It is then checked that the updated bounds for `e` imply the return bounds for the function using the rules in Section 4.5

4.10 Other statements

There are a variety of other statements in C. These statements are built from zero or more expressions, statements, and declarations:

- Labeled statements of the form `case constant-expression : statement`, `default : statement`, and `identifier : statement`.
- Selection statements of the form `if (expression) statement else statement` and `switch (expression) statement`.
- Iteration statements such as `while (expression) statement` and `for (declarationopt expressionopt; expressionopt ; expressionopt) statement`.
- Jump statements of the form `goto identifier`, `continue`, and `break`.
- Compound statements of the form `{ ... }` where `...` are zero or more declarations or statements.

The nested statements and declarations can be checked individually.

For the expressions used in the statements, the context is determined before the evaluation of the expression. No way is provided for a direct expression occurring in a statement to have new bounds declared for any bounds in it. This means that the bounds declarations in the context will be expected to be true after the evaluation of the expression too.

The rules in Section 4.4 are used to determine the updated context after evaluation of the expression. The rules in Section 4.5 are used to check that the updated context implies the expected bounds declarations.

4.11 Avoiding undefined expressions and undefined bounds

The order of evaluation of side-effects in subexpressions of an expression is defined in C only in certain circumstances (these are described in Section 6.5 and Annex C of [50]). Otherwise, the order of evaluation of side-effects is undefined. Although nested assignment expressions help the brevity of programs, they lead to expressions whose meaning or bounds are undefined. To avoid compromising the integrity of bounds information, compilers must produce errors when they encounter these expressions.

The meaning of an expression is undefined if:

1. There are multiple assignments to the same variable within an expression where the order of evaluation of the assignments is undefined, or

2. There is an assignment to a variable that is also used by the expression, where the order of evaluation of the assignment and the use is undefined.

The following statements illustrate these problems:

```
y = (x = 5) + (x = 6);  
i = i++ + 1;  
a[i++] = i;
```

In the first case, the value of the right-hand side expression is 11, yet at the end of the expression, the value of `x` could be 5 or 6. In the second case, there are two assignments to `i` and the order is undefined. In the third case, it is not clear when `i` is read vs. when it is modified.

Bounds checks can lead to a subtle version of the second problem: an expression may have an assignment through a pointer that require a bounds check. The bounds for the pointer expression may include a variable that is modified in the expression, where the order of evaluation of the assignment through the pointer and the variable assignment is undefined. This means that the order of evaluation of the bounds check and the variable assignment is undefined.

This example illustrates this problem:

```
w = ...  
where w : bounds(x, x + y);  
int t = *w + (y = tmp);
```

The variable `y` is an integer variable that is a count of elements. It is overwritten during the evaluation of an expression that dereferences `w`, whose bounds include `y`.

We define these situations to be compile-time errors. Define an ambiguous variable in an expression `e` as:

- A variable that has multiple assignments to it within `e` such that the order of evaluation of those assignments is undefined, or
- A variable that has an assignment to it and a use of the variable such that the order of evaluation of the assignment and the use is undefined, or
- A variable that has an assignment to it, where there is some subexpression `*e1` of `e` where the variable appears in the bounds of `e1` and the order of evaluation of `*e1` and the assignment to the variable is undefined.

It is a compile-time error for an expression to have an ambiguous variable.

Chapter 5

Interoperation

Code that uses checked pointer types must be able to interoperate with code that uses unchecked pointer types. This chapter describes support for this. Section 5.1 starts with conversion operations: how different kinds of pointers can be converted to other kinds of pointers. Section 5.3 describes how existing code that uses unchecked pointers can be modified to present a safe interface. The key insight is that the interface must be both checked and unchecked, depending on context. For existing code that uses unchecked pointers, the interface is descriptive, but correctness is not enforced by the language. For code that uses checked pointers, proper usage of the interface is checked and enforced.

5.1 Conversions between pointers to objects of different types

Conversions from a pointer to one type to a pointer to a different type introduce two issues. First, there is type safety. Given a pointer to *S* that has been converted to be a pointer to *T*, is it valid to treat the memory pointed to by the pointer as being an object of type *T* instead of type *S*? Second, there is bounds safety. Given the pointer, what range of memory can be accessed validly using that pointer? This section focuses on bounds safety.

Type safety is not addressed by this technical report. Of course, violating type safety can lead to violations of bounds safety. This can happen when there is a conversion between a checked pointer to an object of structure type that contains a bounds-checked member and a pointer to an object of another type. A programmer can use the pointer to the other type to modify the bounds-checked member or its bounds in an inconsistent fashion. For now, it is the programmer's responsibility to update bounds-checked members and their bounds properly when using a checked pointer that results from such a conversion. Conversions between checked pointers to integral types, floating-point types, or structures that contain only integral types or floating-point types cannot lead to violations of bounds safety by themselves.

5.1.1 Cast operators

This section describes casts to pointer types. A conversion of a value from one checked pointer type to a value of another checked pointer type is valid when the following rules hold:

Operator	Description
$(T *)$	The C cast operator. Additional static checking rules ensure pointer casts to checked pointer types are correct with respect to bounds.
<code>dynamic_bounds_cast</code>	Does dynamic checks to ensure bounds safety. It produces a runtime error if the checks fail.
<code>assume_bounds_cast</code>	Declares new bounds for the value that are trusted without verification. Because it is unchecked, it is not allowed in <code>checked</code> blocks.

Table 5.1: Cast operators for pointer types

- If the destination pointer is a `ptr<T>` type, the range of memory that can be accessed beginning at the source pointer is large enough to hold a value of type T .
- If the destination pointer is an `array_ptr<T>` type, the bounds for the destination pointer are equal to or within the range of the memory accessible through the source pointer.

Casts between checked pointer types should preserve bounds safety by default. The cases where it does not should be the unusual cases. For this reason, C cast operations to checked pointer types are required to be provably correct with respect to bounds at compile-time. It is straightforward to check casts between checked pointers to constant-sized objects. The rules that are used to check bounds and lightweight invariants are used to check casts as well. For cases where static checking cannot prove bounds safety of casts, we add two new operators. Table 5.1 describes the operators.

The syntax of the new operators is similar to the syntax of C++ type conversion operators, where the destination pointer type is specified by placing a type argument $\langle T \rangle$ after the operator: `dynamic_bounds_cast<T>` and `assume_bounds_cast<T>`. A relative alignment type or constant can be specified using an optional second argument: `dynamic_bounds_cast<T, A>` or `assume_bounds_cast<T, A>`. Of course, macro-like syntax could be used as well.

For C cast operations from checked pointer types to unchecked pointer types, it is not possible to prove that the uses of the resulting unchecked pointers are correct at compile-time. At the same time, it is desirable to catch the programming error of converting an out-of-range checked pointer to an unchecked pointer and then trying to use the unchecked pointer to access memory. For this reason, we take the stance that if the destination pointer is a $T *$ type, the range of memory that can be accessed beginning at the checked pointer should be provably large enough at compile time to hold a value of type T .

C does allow an unchecked pointer to point one element past the end of an array. However, it is illegal to dereference that pointer. This case mainly arises from loops that stride through an array and end up creating a pointer one past an element of an array. It would be unusual for a programmer to convert a checked pointer to an unchecked pointer and then stride downwards through an array, predecrementing the pointer. Because of that, C cast operations from checked pointer types to unchecked pointer types that would create a pointer one element past the end of the array pointed to by the checked pointer are rejected at compile time. A programmer may use an `assume_bounds_cast` operation do this instead.

5.1.2 Description of cast operators

This section describes each of the cast operators and the static and runtime checking that is done for each operator.

For C cast operators, the checking is only static. Here are the rules for cast operators of the form $(D) e$, where e has source type S . The rules are applied in addition to any existing C typing rules that apply to the cast.

- If D and S are compatible types or D and S are unchecked pointer types, checking succeeds.
- Otherwise, if D is not a function pointer type and D is
 - `ptr<T>`: the bounds of e are computed using the rules in Section 4.4.
 - * If the bounds are `bounds(unknown)`, checking fails with a compile-time error.
 - * Otherwise, if the bounds are `bounds(any)`, checking succeeds.
 - * Otherwise, the bounds must be `bounds(lb, ub)` (or convertible to that form). It must be provable statically that $e \geq lb$ and that $((char *) ub - (char *) e) \geq sizeof(T)$. If `sizeof(T)` is not defined because T is `void`, 1 is used instead.
 - `array_ptr<T>`: No new rules are needed. The rules in Chapter 4 already cover this case.
 - $T *$: If the source type S is
 - * `ptr<T>`, the checking succeeds. This handles the case where T is an incomplete type.
 - * Otherwise, the rules for `ptr<T>` are followed.
- Otherwise, if D is a function pointer type,
 - If e is a null pointer, checking succeeds.
 - Function names with unchecked function pointer types can be cast to have corresponding checked pointer types. If D is `ptr<T>`, S is $U *$, and T and U are compatible types, and one of the following, then checking succeeds:
 - * e is a function name.
 - * e has the form $*e1$, such that the `*` operator does not change the value of $e1$, and checking succeeds for $(D) e1$ (this requires that $e1$ has function pointer type).
 - * e has the form $\&e1$, such that the `&` operator does not change the value of $e1$, and checking succeeds for $(D) e1$ (This requires that $e1$ has function type).
 - * e is a cast that does not change the value of the cast operand, and checking succeeds for the cast operand.
 - Otherwise, checking fails with a compile-time error.

These rules allow casts that could cause type safety violations even in code that uses only checked pointer types. They allow casts between pointers to unrelated types and to and from void pointer types. We are working on an extension that will provide a type-safe replacement for casts between checked void pointers. When this is complete, we will disallow these casts. We also plan to revisit casts between pointers to unrelated types.

The `dynamic_bounds_cast` operator takes a type argument D and 1 or 2 expressions as arguments:

- `dynamic_bounds_cast<D>(e1)` converts $e1$ to either a `ptr` or `*` type. D is the target `ptr` or `*` type. D cannot be a function pointer type.
- `dynamic_bounds_cast<D>(e1, bounds-exp)` converts $e1$ to an `array_ptr` type with bounds $bounds-exp$. D is the target `array_ptr` type.

The bounds of $e1$ are computed using the rules in Section 4.4. If the bounds of $e1$ are `bounds(unknown)`, it is a compile-time error. If the bounds of $e1$ are `bounds(any)`, no runtime checks are needed. Otherwise the bounds must be `bounds(lb, ub)` (or convertible to that form). The following runtime checks are done:

- Check whether $e1$ is 0. If so, no further runtime checking is needed.
- Otherwise, if the operator has the form:
 - `dynamic_bounds_cast<D>(e1)`: D is pointer to some type T . Check that there is room for at least one element of T by doing the check for `dynamic_bounds_cast<array_ptr<T>>(e1, count(1))`
 - `dynamic_bounds_cast<D>(e1, bounds-exp)`: Expand $bounds-exp$ to the standard form `bounds(target-lb, target-ub) rel_align_value(v)`. Check that $lb \leq target-lb \ \&\& \ target-ub \leq ub$. Also check that $e1$, $target-lb$, and $target-ub$ are relatively aligned with respect to v .

The `dynamic_bounds_cast` operator is not strictly needed. Programmers could write checks by hand. It is convenient to have, though, because it avoids programmers having to write down the bounds of the source expression.

The operator `assume_bounds_cast<D>` declares bounds that are trusted without verification:

- `assume_bounds_cast<D>(e1)` converts $e1$ to a `ptr` or `*` type. D is the target `ptr` or `*` type.
- `assume_bounds_cast<D>(e1, bounds-exp)` converts $e1$ to an `array_ptr` type with bounds $bounds-exp$. D is the target `array_ptr` type.

For the second form, the relative alignment must be statically provable: expand $bounds-exp$ to the standard form `bounds(target-lb, target-ub) rel_align_value(v)` and check that $e1$, $target-lb$ and $target-ub$ are relatively aligned to v .

If any rule requires knowing the size of an incomplete type, the cast operation that uses the rule shall fail to check at compile-time.

A subtle point about the C cast operator and `dynamic_bounds_cast` are that they allow *bounds-safe casts* of an expression e of unchecked pointer type to an `array_ptr` type. This is provided that the bounds for e can be determined. Only a few kinds of expressions with unchecked pointer types have bounds that can be determined: address-of expressions involving variables and uses of array variables.

5.1.3 Examples

Here are examples of uses of C cast operators to cast unchecked pointers to checked pointers. The static checking rules are straightforward to apply. The examples assume that integers are 4 bytes in

size:

```
int x = 0;
ptr<int> px = (ptr<int>) &x;
array_ptr<char> pax : count(4) = (array_ptr<char>) px;
array_ptr<char> odd_pax : count(3) = (array_ptr<char>) px;

char data[12];
ptr<int> pfirst = (ptr<int>) data; // pointed to 1st element as an integer
array_ptr<int> pdata : count(3) = (array_ptr<int>) data;

void swizzle(ptr<int> p) {
    array_ptr<char> bytes : count(4) = (array_ptr<char>) p;
    char t0 = bytes[0], t1 = bytes[1], t2 = bytes[2]; t3 = bytes[3];
    bytes[0] = t3, bytes[1] = t2, bytes[2] = t1, bytes[3] = t0;
}
```

The `dynamic_bounds_cast` operator is used typically when converting code to Checked C. The existing code may make assumptions about buffers being large enough that are potentially wrong. It would be better to check for errors directly, but the code may not be structured to handle errors:

```
void f(array_ptr<char> buf : count(len), int len) {
    // We expect buf to have enough space for at least 12 integers.
    array_ptr<int> intbuf : count(12) =
        dynamic_bounds_cast<array_ptr<int>>(buf, count(12));
    ...
}

extern void copy(array_ptr<char> dest : count(n),
                array_ptr<char> src : count(n),
                size_t n);

void fill_buffer(array_ptr<char> dest : count(destlen),
                size_t destlen,
                array_ptr<char> src : count(srclen),
                size_t srclen) {
    // Existing code just assumed that dest was large enough; let's add a
    // dynamic_bounds_cast to be sure.
    array_ptr<char> target : count(srclen) =
        dynamic_bounds_cast<array_ptr<char>>(dest, count(srclen));
    copy(target, src, srclen);
}
```

Here are examples of using the `assume_bounds_cast` operator:

```
// Memory-mapped hardware location where an integer can be written.
ptr<int> output_loc = assume_bounds_cast<ptr<int>>(0x5055);
// Memory-mapped hardware buffer starting at 0x6000 that stores 128
// integers.
array_ptr<int> output_buf : count(128) =
    assume_bounds_cast<array_ptr<int>>(0x6000, count(128));
```

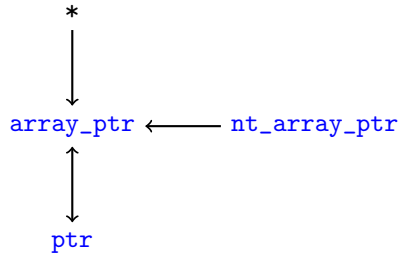


Figure 5.1: Implicit conversions between different kinds of pointers

5.1.4 Non-examples

Here are examples of incorrect uses of C cast operators to cast unchecked pointers to checked pointers. These examples are rejected because the source bounds are not large enough to justify the destination bounds or there are no source bounds. In this example, `&x` points to only one integer:

```

int x = 0;
// fails to check: source not large enough
array_ptr<int> pax : count(5) = (array_ptr<int>) &x;

```

In this example, the result of `random()` has no bounds:

```

char *random(void);

void f(void) {
    // fails to check: random() has no bounds
    array_ptr<char> sp : count(1) = random();
}

```

5.2 Implicit conversions involving checked pointer types

C allows implicit conversions at assignments, function call arguments, and conditional expressions. This makes programs shorter and easier to read. Implicit conversions describe when an expression of type S is allowed where an expression of type T is expected, allowing additional programs to typecheck. This section defines implicit conversions that are allowed for checked pointer types.

One kind of pointer type can be converted to another kind of pointer type provided that bounds safety is maintained. Figure 5.1 shows the kind conversions that are allowed. Any kind can be converted to another kind that is reachable following arrows. For example, it makes sense to allow an unchecked pointer type to be converted to an `array_ptr` or `ptr`.

Each pointer type has a referent type (the type to which the pointer refers). For example, `array_ptr<T>` points to T . For an implicit conversion, the source referent type and the destination referent type must be the same type or be *assignment compatible*. Informally, the destination referent type must be at least as checked as the source referent typing. Losing checking is not allowed.

A destination referent type D is assignment compatible with a source referent type S if

- D and S are compatible types, or

- D is `void` and S is not a function type, or
- S is `void` and D is not a function type, or
- D is an array of E and S is an array of T and:
 - D and S are both checked arrays, both unchecked arrays, or D is a checked array and S is an unchecked array, and
 - D and S have the same number of elements, and
 - E is assignment compatible with T .

There are several important points about these conversions:

- While an implicit conversion may allow typechecking to succeed, checking of bounds declarations may still fail. Implicit conversions are treated as though they are explicit C cast operations during the checking of bounds declarations.
- Implicit conversions from checked pointer types to unchecked pointer types are not allowed because that would cause a loss of bounds safety. There is an important exception: they are allowed at bounds-safe interfaces, where an lvalue is treated as having both an unchecked and checked type (Section 5.3).
- The rules for assignment compatibility allow conversions to and from checked void pointers, provided that bounds safety is maintained. These rules subsume the existing C rule for void pointers. As mentioned in Section 5.1.2, we plan to disallow conversions between checked void pointers eventually.
- We do not allow implicit conversions to `nt_array_ptr<T>` because of the possibility of null terminators being overwritten via pointer aliases. If we had a way of controlling aliasing of pointers, we could allow those conversions.

5.2.1 Assignments and calls

An expression that occurs as the right-hand side of an assignment or as a call argument may be implicitly converted to another type, provided that the rules just discussed are met. The type of the left-hand side of the assignment or the corresponding parameter is the destination type for the conversion.

5.2.2 Conditional expressions

For a conditional expression with the form $e1 ? e2 : e3$, the arms of the conditional expression may be implicitly converted so that their types match. The concept of source and destination types does not make sense here because the arms should be treated symmetrically.

We take a different approach. Given two arms with different pointer types, we try to choose a pointer type that meets the restrictions of both arms. For example, if an arm has `ptr` type, pointer arithmetic should not be possible on the result of the conditional expression. We order pointer types by restrictiveness and choose the “greatest lower bound” of the pointer types of the arms (if one exists).

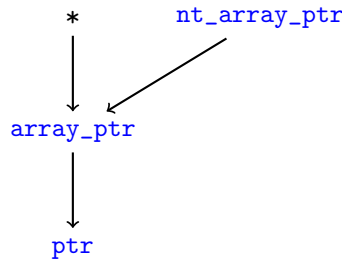


Figure 5.2: Ordering of pointer kinds by restrictiveness of operations and allowed conversions.

First, the greatest lower bound of the pointer kinds is determined. Figure 5.2 shows an ordering of pointer kinds by restrictiveness and allowed conversions. A kind at the destination of an arrow is below a kind at the source of an arrow. We choose the highest such kind that is at or beneath the kinds of both arms. For example, the greatest lower bound kind of `ptr` and `*` is `ptr`. The greatest lower bound kind of `*` and `nt_array_ptr` is `array_ptr`.

Second, the greatest lower bound of the pointer referent types for the arms is computed. If the pointer referent types are the same type, that type is the greatest lower bound. Otherwise, the greatest lower bound is the referent type that is at least as checked as the other referent type and is otherwise compatible. Given referent types S and R , we check assignment compatibility using each type as the destination. We choose the referent type for which assignment compatibility is valid. If assignment compatibility is not valid for either type, no greatest lower bound exists and the implicit conversion is not allowed.

Void referent types are treated specially. They are considered to be lower than corresponding non-void referent types because fewer operations are allowed on void referent types. We require that the source referent type in the assignment compatibility test not be the void type. This matches the existing C rules for conditional expressions. Those rules state that if one arm has void pointer type, the other arm must be implicitly cast to void pointer type. Implicit casts from void pointers to other pointer types are not allowed for conditional expression arms.

Here are some examples of greatest lower bounds:

- For arms with the types `array_ptr<int>` and `ptr<int>`, it is `ptr<int>`.
- For arms with the types `array_ptr<void>` and `int *`, it is `array_ptr<void>`.
- In contrast, for arms with the types `array_ptr<float>` and `array_ptr<int>`, none exists: `float` is not assignment-compatible with `int`.

5.2.3 Between checked pointers and integers

The null pointer (0) can be converted implicitly to any checked pointer type. A checked pointer can be converted implicitly to the `_Bool` type.

Some C compilers extend C by allowing implicit conversions between pointers and integers or between pointers to incompatible types. Implicit conversions from integers to checked pointers are typically not useful in Checked C because the checking of bounds declarations fails or the resulting pointer cannot be used to access memory. The rules for checking bounds declarations only allow the target type to be `array_ptr` type and the bounds of the expression to be `bounds(unknown)`.

5.2.4 Examples

The following code shows examples of implicit conversions. In these examples, the right-hand sides of assignments have the type “unchecked pointer to T ”, while the left-hand sides have the type “checked pointer to T ”. Implicit conversions are done at those assignments.

```
int x = 0;
ptr<int> px = &x;
array_ptr<int> pax : count(1) = &x;

int a[5] = { 0, 1, 2, 3, 4};
ptr<int> pa = a;
array_ptr<int> apa : count(5) = a;
array_ptr<int> middle : bounds(a, a + 5) = a + 2;
```

An unchecked multidimensional array can be passed to a function expecting a checked multidimensional array:

```
int b[3][3] = { { 0, 1, 2}, { 3, 4, 5}, { 6, 7, 8}};
extern void f(int arg checked[3][3]);
f(b);
```

The mechanics behind this are somewhat complicated. Parameters with type “array of T ” are actually treated as having type “pointer to T ”. Parameters with the type “checked array of T ” are treated as “checked pointer to T ”. The actual type of the parameter of `f` is

```
extern void f(array_ptr<int checked[3]> arg);
```

Local variables with type “array of T ” are treated as having type “unchecked pointer to T ” when they are used. The type of `b` at `f(b)` is “unchecked pointer to an array of 3 integers”. At the call to `f(b)`, there is an implicit conversion from an “unchecked pointer to an unchecked array of 3 integers” to a “checked pointer to a checked array of 3 integers”:

```
int (*pb)[3] = b;
array_ptr<int checked[3]> param : count(3) = pb;
```

This implicit conversion is allowed because `int checked[3]` is assignment compatible with `int[3]`. Assignment compatibility allows other interesting implicit conversions:

```
array_ptr<int[3]> t1 : bounds(b, b + 3) = b;
array_ptr<int> t2 : bounds(b, b + 3) = t1[1];
array_ptr<int> t3 : bounds(b, b + 3) = b[1];
```

5.2.5 Non-examples

Implicit conversions must still pass the bounds rules for the corresponding explicit C cast operation. Implicit conversions where the source bounds are not large enough will be rejected during bounds declaration checking:

```
int x = 0;
// fails to check: source not large enough
array_ptr<int> pax : count(5) : &x;
```

Implicit conversions of unchecked pointers with no bounds to checked pointers will also be rejected:

```
char *random(void);

void f(void) {
    // fails to check: random() has no bounds
    array_ptr<char> sp : count(1) = random();
}
```

5.3 Bounds-safe interfaces to existing unchecked functions and variables

The new pointer types capture specific properties of pointers. We would like to update existing C code to use the new pointer types. This would be problematic for library and operating system APIs that have backward compatibility constraints, however. Consider what would happen if the signature for `memcpy` were changed to use `array_ptr`. The function

```
void *memcpy(void *dest, const void *src, size_t count);
```

would become

```
void *memcpy(array_ptr<void> dest, array_ptr<const void> src,
             size_t count);
```

This would break existing code that uses `memcpy`. The code would no longer type check. The reverse problem also exists: suppose the signature for `memcpy` is not updated. Then every checked method that calls `memcpy` would need to cast the arguments to unchecked pointer types.

Given that changing the types of existing APIs is problematic, we take an approach that does not change types, yet enables new checked code to be written easily and that maintains the checking of the new code. We allow programmers to declare *bounds-safe interfaces* that extend existing declarations with additional bounds information.

Bounds-safe interfaces can be specified for declarations of functions, global variables, and data structures. They can also be specified for function types. The interfaces describe the expected behavior and the assumptions of existing code about bounds. The types remain the same. It is assumed but not verified that existing code meets the specified interfaces. A bounds-safe interface allows checked code to use existing unchecked code safely with respect to bounds, assuming that the interface and existing code are correct.

Type checking is modified to insert implicit conversions between checked types and unchecked types at bounds-safe interfaces. The additional bounds information is used during checking of bounds declarations to ensure that checked code is using existing declarations properly. It is also used to insert bounds checks in checked code. This allows new checked code to use existing unchecked code, once a bounds-safe interface has been added to the existing code.

1. In checked scopes, code is limited to using pointer types that are checked pointer types or unchecked pointer types with bounds-safe interfaces. This makes the code in checked scopes straightforward to understand: the unchecked pointer types are regarded as checked pointer types, all memory accesses are bounds checked or in bounds, and bounds-safe interfaces are trusted and respected.

2. In unchecked scopes, checked and unchecked pointer types can be intermixed within expressions. When that happens, the bounds-safe interfaces are used during checking of bounds declarations to determine bounds of expressions and the required bounds for assignments and function calls. Section 5.2 already explained when implicit conversions from unchecked pointer types to checked pointer types may be inserted. Implicit conversions of expressions from checked pointer types to unchecked pointer types are inserted when necessary at bounds-safe interfaces.

The sections on bounds-safe interfaces are organized as follows. Section 5.3.1 describes how to specify bounds-safe interfaces. Section 5.3.2 has examples that show the use of bounds-safe interfaces. Section 5.3.5 explains how existing functions and variables can be redeclared with bounds-safe interfaces. Section 5.3.6 and 5.3.7 cover technical details about type checking and checking bounds declarations that are interesting to language designers and compiler writers. Programmers interested in using the Checked C extension can skip those sections.

5.3.1 Specifying bounds-safe interfaces

Bounds-safe interfaces for declarations are specified by adding bounds declarations or type annotations to declarations. They can be added to function declarations, function types, globally-scoped variables, and declarations of members of structure and union types. A declaration can have both a bounds declaration and a type annotation, although it is less common to need both.

We describe adding bounds declarations first and then describe adding type annotations. Functions that have parameters with unchecked pointer or array types or that return values with unchecked pointer types can have bounds or type annotations declared for the parameters and return values. At calls to these functions, implicit conversions from checked types to unchecked pointer types are inserted for the corresponding argument expressions.

Here is a bounds-safe interface for `memcpy`:

```
void *memcpy(void *dest : byte_count(len),
             const void *src : byte_count(len),
             size_t len)
    where return_value : bounds((char *) dest,
                                (char *) dest + count);
```

The correctness of bounds information is enforced at compile-time when `memcpy` is passed checked pointer arguments. It is not enforced when `memcpy` is passed unchecked pointer arguments.

Variables at external scope with unchecked pointer or array types can have bounds or type annotations declared for them. The declarations must follow the rules in Section 3.6.4.

For data structures, members with unchecked pointer type or array types can have bounds or type annotations declared for them. Implicit conversions from `array_ptr` type to unchecked pointer type are inserted at assignments to unchecked pointer type members.

Here are the bounds for a structure that is a counted buffer of characters.

```
struct S {
    char *arr : count(len);
    int len;
}
```

It is important to understand that the *semantics of unchecked pointers and arrays do not change in unchecked scopes even when bounds or type annotations are declared for the pointers and arrays*. The declared bounds or type annotations are used for expressions that mix checked and unchecked pointer types. Unchecked pointer dereferences do not have bounds checks added to them. Similarly, uses unchecked arrays still convert to unchecked pointer types. A function that has a bounds-safe interface and whose body does not use checked pointer or array types is compiled as though the bounds-safe interface has been stripped from its source code.

A type annotation describes an alternate checked type to use in checked code in place of an unchecked type. It is used, for example, when a variable with an unchecked pointer type should be treated as having a `ptr` type. Syntactically, a bounds declaration can have a bounds expression, a type annotation, or both a bounds expression and a type annotation.

A type annotation is specified using the following syntax:

```
type-annotation:
    itype (type name)
```

The keyword `itype` is short for bounds-safe interface type.

The syntax for an inline bounds specifier is extended to allow a type annotation or a bounds expression and a type annotation:

```
inline-bounds-specifier:
    : bounds-exp
    : type-annotation
    : bounds-exp type-annotation
    : type-annotation bounds-exp
```

A type annotation can be used to declare that an unchecked pointer to a structure should be treated as a `ptr` in checked code. Here is a declaration for a function `count_char` that takes an unchecked pointer to the struct `S` defined earlier, with a type annotation. `count_char` counts the number of occurrences of `arg` in `S`. Checked code must pass a value that is a valid `ptr` to `count_char`:

```
int count_char(S *str : itype(ptr<S>), char arg);
```

A type annotation can be used to declare that an unchecked array member should be treated as a checked array in checked code:

```
struct S {
    int a[5] : itype(int checked[5]);
};
```

Here are functions from the C Standard Library with type annotations. In the examples, type annotations for return types are placed after the parameter list, the same way that bounds expression for return values are placed:

```
void modf(double value, double *iptr : itype(ptr<double>));
int fclose(FILE *stream : itype(ptr<FILE>));
FILE *tmpfile(void) : itype(ptr<FILE>);
struct tm *gmtime(const time_t *timer : itype(ptr<const time_t>)) :
    itype(ptr<struct tm>);
```

A set of rules define interface type compatibility. The *type name* in a type annotation must be compatible with the original unchecked type when checkedness of pointers and arrays is ignored. The *type name* cannot lose checking. It must be at least as checked as the original type. Finally, the *type name* must be a checked type. Checked types are defined inductively: checked pointer and array types are checked types, array and pointer types constructed from checked types are checked types, and function types constructed from at least one checked type are checked types.

5.3.2 Examples

Here are some examples:

```
void copy(array_ptr<int> dest : count(len),
          array_ptr<int> src : count(len), int len)
{
    // dest, src will be converted implicitly to void * pointers.
    // Even though this is an unchecked context, the function call
    // arguments will be checked to make sure that they meet the
    // bounds requirements of memcpy. This is because the argument
    // expressions have checked pointer types.
    memcpy(dest, src, len * sizeof(int));
}

f(S s)
{
    int len = s.len;
    array_ptr<char> sp : count(len) = s.arr;
    ...
    if (len > 0) {
        sp[0] = 'a';
    }
}
```

This example will fail at compile time:

```
void bad_copy(int *dest, array_ptr<int> src : count(len), int len)
{
    // dest, src will be converted implicitly to void * pointers.
    // Because an argument had a checked pointer type, the function call
    // will be checked to make sure parameters meet the bounds
    // requirements. This will fail because dest has no bounds.
    memcpy(dest, src, len * sizeof(int));
}
```

In contrast, this example will compile:

```
void subtle_copy(int *dest, array_ptr<int> src : count(len), int len)
{
    // This function call will not be checked for bounds
    // requirements because no arguments have checked pointer
    // types. This shows both that the programmer has control
    // over checking by using types and why checked contexts
    // should be used with checked pointers when possible (perhaps
    // the programmer did not want to do this).
```

```
memcpy(dest, (void *) src, len * sizeof(int));
}
```

5.3.3 Parameter array types

In C, arrays are passed by reference as arguments. During type checking, the type of parameters with type “array of T ” are altered to $T *$. Before checking interface type compatibility for a parameter, if the interface type is an array type, it is altered to be a pointer type following the rules in Section 2.5.2. The checking is then done using the altered parameter type and altered interface type. The original unaltered interface type is used when inferring bounds and bounds requirements.

The following examples illustrate some possible bounds-safe interface declarations for a parameter of type `int **`:

```
void f(int **p : itype(ptr<ptr<int>>));
void f(int **p : itype(ptr<array_ptr<int>>));
void f(int **p : itype(array_ptr<ptr<int>>));
void f(int **p : itype(array_ptr<array_ptr<int>>));
void f(int **p : itype(ptr<int *>));
void f(int **p : itype(array_ptr<int *>));
void f(int **p : itype(ptr<int> checked[10]));
void f(int **p : itype(ptr<int> checked[]));
void f(int **p : itype(array_ptr<int> checked[10]));
void f(int **p : itype(int *checked[20]));
```

5.3.4 Bounds expression and type annotations

A bounds-safe interface declaration can have both a bounds expression and a type annotation. This allows programmers to declare bounds-safe interfaces for declarations involving nested pointer types.

Consider a bounds-safe interface for `char **p`. The checked type for the variable can be declared using a type annotation and the bounds for the variable can be declared using a bounds expression.

```
char **p : itype(ptr<ptr<char>>);
char **p : itype(ptr<nt_array_ptr<char>>);
char **p : count(len) itype(array_ptr<ptr<char>>);
char **p : count(len) itype(array_ptr<nt_array_ptr<char>>);
char **p : itype(nt_array_ptr<ptr<char>>);
char **p : count(4) itype(nt_array_ptr<nt_array_ptr<char>>);
```

If only a bounds expression is placed on a declaration of a variable with type $T *$, it implies that the type annotation is `array_ptr<T>`. If it is placed on a variable with an array type `T[D]`, it implies that the type annotation is `T checked[D]`. If an interface type and a bounds expression are both specified, the interface type must be an `array_ptr` type or checked array type.

5.3.5 Redefining existing functions and variables with bounds-safe interfaces

C allows variables or functions to be declared with types that are missing information. There can be other declarations of the variables or functions with types that are more complete and fill in the

missing information. The types that are missing information are said to be “compatible” with the more complete versions of the types. Multiple declarations of a variable or function are required to have compatible types, not identical types.

This notion of compability extends to bounds-safe interfaces naturally. We extend the definition of compatibility of function types in Section 3.8 as follows:

- Given corresponding parameters with compatible unchecked pointer types, one parameter may have a bounds declaration and one parameter may omit the bounds declaration.
- Given return values with compatible unchecked pointer types, one return value may have a bounds declaration and one return value may omit the bounds declaration.

The following are examples of declarations of functions with compatible types:

```
int f(int *);
int f(int * : count(5));

int g(int *a, int len, int *b);           // decl 1
int g(int *a : count(len), int len, int *b); // decl 2
int g(int *a, int len, int *b : count(len)); // decl 3
int g(int *a : count(len), int len, int *b : count(len)); // decl 4
```

The declarations of `g` are particularly interesting. They are all compatible declarations. The only version that could be used in a checked scope is declaration 4. For declarations 2 and 3, where bounds information is missing for a parameter, the argument passed to `g` for that parameter cannot have an `array_ptr` type. The typing rules prevent arguments with checked type from being used with parameters of `g` that are missing bounds information.

5.3.6 Type checking

Bounds-safe interfaces allow unchecked pointer types to be used where checked pointer types with assignment compatible referent types are expected and *vice versa*. To handle this, implicit pointer conversions are inserted during type checking. Section 5.2 covered implicit conversions from unchecked pointer types to checked pointer types.

Implicit conversions from checked pointer types to unchecked pointer types with assignment-compatible referent types are allowed at the uses of functions, variables, or members with bounds-safe interfaces, and at return statements. In this case, assignment compatibility is applied in a reverse fashion (assignment compatibility is defined in Section 5.2). The source referent type must be assignment compatible with the destination referent type. The conversions are done for rvalue expressions by inserting C cast operators to the desired unchecked types. They are done at:

- Function call arguments: If the function being called has a bounds-safe interface for parameters with unchecked pointer types, a parameter has an unchecked pointer type, the corresponding argument expression has a checked pointer type, and the argument referent type is assignment compatible with the parameter referent type, then the argument expression will be converted implicitly to the unchecked pointer type.
- Assignments to variables with external scope: if the variable being assigned to has an unchecked pointer type and a bounds-safe interface, the right-hand side expression has a checked pointer type, and the right-hand side expression referent type is assignment compatible with the

referent type of the variable, then the right-hand side expression will be converted implicitly to the unchecked pointer type.

- Member assignments: a similar conversion is done for member assignments.
- Return statements: if a function has an unchecked pointer return type and a return bounds-safe interface, and a return statement in the body of the function has an expression with a checked pointer type, and the return statement expression is assignment compatible with the return type of the function, then the return expression will be converted implicitly to the unchecked pointer type.

Implicit conversions at bounds-safe interfaces are allowed from checked pointer types to `void *`. This rule is likely to change in the future. There is not a design for checking type-safety of casts yet and the design will almost certainly affect `void *` casts.

Only one implicit pointer conversion is allowed for an expression at a bounds-safe interface. For example, an expression will not be coerced implicitly from `ptr<S>` to `void *` to `T *`, where `S` and `T` are different types.

5.3.7 Checking bounds declarations

The checking rules in Chapter 4 require only small changes to check code with bounds-safe interfaces. The checking is done after any implicit pointer conversions have been inserted.

- Contexts are extended to include unchecked pointer variables with bounds-safe interfaces.
- Inference of bounds of expressions (Section 4.2) incorporates information from bounds-safe interfaces:
 - Uses of variables (Section 4.2.2): if a variable with an unchecked pointer type is used and the context has a bounds for the variable, the bounds in the context are used as the bounds for the variable.
 - Function calls (Section 4.2.4): the rules in this section are also applied when a function returns an unchecked pointer value and the return value has a bounds-safe interface.
- The checking that an expression statement, declaration, or bundled block implies the declared bounds of variables includes:
 - In checked contexts, all variables with bounds-safe interfaces.
 - In unchecked contexts, all variables with bounds-safe interfaces that are modified by an assignment within the statement, declaration, or bundled block, where the right-hand side expression is converted implicitly from a checked pointer type to an unchecked pointer type.

For the included variables, bounds are tracked through the statement or bundled block.

- The checking of function call arguments in function calls (Section 4.8) includes parameters with bounds-safe interfaces:
 - In checked contexts.

- In unchecked contexts, when one or more argument expressions have been converted implicitly to unchecked pointer types.

The parameters are included by adding their bounds-safe interfaces to the declared bounds in the constructed `where` clauses.

- The checking of return statements (Section 4.9) includes return statements where there is a return bounds-safe interface for the enclosing function:
 - In checked contexts.
 - In unchecked contexts, when the return statement expression has been converted implicitly to an unchecked pointer type.

The return bounds-safe interface is used in place of the function return bounds.

The checking for assignments and function calls has some interesting implications in unchecked contexts. It is possible to have a statement, a declaration, or a bundled block that mixes different kinds of pointers in assignments to the same variable. Some right-hand sides could have checked pointer types and others could have unchecked pointer types. This is a programming practice that is discouraged. Nevertheless, the bounds declarations will be checked no matter which kind of assignment is the last one. This implies that if the last assignment has an unsafe pointer-typed right-hand side, it will still need to have valid bounds. It is also possible to mix argument expressions with checked and unchecked pointer types in one function call. The checking of bounds for function arguments is done for all arguments, so this also implies that the unchecked pointer-typed expressions will need to have valid bounds.

5.4 Conversions between pointers and integers

C allows pointers to be converted to suitably large enough integer types and then converted back to pointers. Integer operations can be done on the converted values before they are converted back. This is one of the features of C that leads people to say that C cannot possibly be made type-safe. In this section, we explain how casts between pointers and integers within expressions can be controlled and reasoned about.

5.4.1 Tagged pointers

We start with a motivating example, tagged pointers. C programs sometimes store information in unused bits of pointers to save on space in data structures. Other times this is done to achieve atomicity when reading or writing data. A program might store a tag in the least significant bits or most significant bits of some pointers, knowing that those bits are always zero otherwise.

The bounds of such a pointer are easy to describe: they are the bounds of the original pointer. If a pointer variable or member is used in its own bounds, the tag must be removed first. This is done by masking out the bits that are always 0.

For example, suppose there is the following structure:

```
struct S {  
    array_ptr<int> p : bounds(p, p + 4);  
    int tag : 2;
```

```
}

```

A programmer might know that on a machine with 32 bit pointers, the least 2 significant bits of `p` are always 0, so the tag could be stored within `p`. The bounds would be changed to:

```
struct S {
    array_ptr<int> p : bounds((array_ptr<int>) ((size_t) p & ~3),
                             (array_ptr<int>) ((size_t) p & ~3) + 4)
    rel_align(char);
}
```

There is one important caveat (for now): tags cannot be stored in null pointers. A null pointer may have bounds that are not valid. This is fine because the null pointer may not be used to access memory. However, tagging a null pointer could result in a non-null pointer with bounds that are invalid. This pointer could be used to access memory incorrectly.

5.4.2 Extending bounds checking rules to integral expressions

The inference of bounds for expressions disregards non-narrowing cast operators: the information flows through the operation, with adjustments if the bounds include `expr_current_value`. This makes it straightforward to extend the rules for inferring bounds to integral expressions:

- Given $e1 \text{ op } e2$, where op is an additive, multiplicative, or bitwise binary operator on integral types, the bounds of $e1$ and $e2$ can be computed:
 - If $e1 : b$, where b is not `bounds(unknown)`, and $e2 : \text{bounds(unknown)}$, and it can be proved that $e1 \neq 0$, then $e1 \text{ op } e2 \vdash b$.
 - If the special variable `expr_current_value` occurs in b :
 - * If op has an inverse operation $inverse\text{-}op$, then `expr_current_value` $inverse\text{-}op$ $e2$ is substituted for `expr_current_value`.
 - * Otherwise the bounds of the expression are altered to be `bounds(unknown)`.
 - Similar rules apply for the reverse situation where $e1 : \text{bounds(unknown)}$ and $e2 : b$, where b is not `bounds(unknown)`.
- Given $e1 \text{ op } e2$ where op is a shift operator, $e1$ is the integral value being shifted, and $e2$ is the shift amount,
 - If $e1 : b$, where b is not `bounds(unknown)`, and $e2$ has `bounds(unknown)`, and it can be proved that $e1 \neq 0$, then $e1 \text{ op } e2 \vdash b$.
 - If the special variable `expr_current_value` occurs in b , bounds of the expression are altered to be `bounds(unknown)`. Shift expressions are not invertible because they lose information.

5.4.3 An example

The following example shows functions for tagged pointers (where the tag is stored in the least significant bit) that create a tagged pointer and that set the tag to 1.


```

#define untagged_bounds(x) \
    bounds((array_ptr<int>) ((size_t) x & ~0x1), \
           (array_ptr<int>) ((size_t) x & ~0x1) + 1) rel_align(char)

array_ptr<int> create(void)
where untagged_bounds(return_value)
{
    array_ptr<int> x : bounds(x, x + 1) = malloc(sizeof(int));
    dynamic_check(x == (array_ptr<int>) ((size_t) x & ~0x1));
    // follows from substituting the right-hand side in the current bounds
    where x : untagged_bounds(x);
    return x;
}

// set tag to 1
array_ptr<int> set(array_ptr<int> x : untagged_bounds(x))
where untagged_bounds(return_value)
{
    if (x != NULL) {
        // ((size_t) x | 1) has the same bounds as x
        array_ptr<int> tmp : untagged_bounds(x) = (array_ptr<int>) ((size_t)
            x | 1);
        dynamic_check((size_t) tmp & ~0x1 == (size_t) x & ~0x1);
        // follows from substituting the right-hand side of the
        //dynamic check expression in the current bounds for tmp
        where tmp : untagged_bounds(tmp);
        return tmp;
    }
    return x;
}

```

5.4.4 Allowing bounds to be declared for integer-typed variables

We have described how bounds can be inferred for an expression with casts between pointers and integers. A programmer may want to introduce variables for the results of subexpressions of an expression or may not be able to do all of a computation within an expression. To allow more general handling of casts between pointers and integers, we allow bounds to be declared for integer-typed variables. This may seem confusing, but it is a natural extension to tracking the bounds for pointer values that have been cast to integers. The `set` function can be written to use temporary variables instead:

```

array_ptr<int> set(array_ptr<int> x : untagged_bounds(x))
where untagged_bounds(return_value)
{
    if (x != NULL) {
        size_t raw : untagged_bounds(raw) = (size_t) x;
        size_t tagged : untagged_bounds(raw) = raw | 1;
        dynamic_check(raw & ~0x1 == tagged & ~0x1);
        // bounds follow from substituting the right-hand side of the
        // dynamic check expression in the bounds for tagged.
        array_ptr<int> result : untagged_bounds(result) = (array_ptr<int>)
            tagged
    }
}

```

```
    return result;
}
return x;
}
```

5.5 Restricted interoperation with functions without prototypes

C allows declarations of functions that do not specify the type of their parameters (no-prototype function declarations). This provides backward compatibility between ANSI C from 1989 and earlier versions of C that did not check the types of arguments at calls. Using functions declared this way is dangerous. Arguments are passed based on their types and an incorrect call can be made where the types of arguments do not match the types of the parameters of the function definition. This could lead to bypassing of checking. Checked pointers could be converted silently to unchecked pointers or vice versa. Even worse, parameters could contain corrupted values or the stack could be corrupted.

We recommend strongly that programmers do not declare functions without prototypes. This feature is a backward compatibility feature and is used rarely now. The GCC and clang C compilers have warning flags that will detect the declaration of functions without prototypes.

For checked scopes, the declaration or use of functions with no prototypes is an error and is not allowed. In unchecked scopes, forbidding the use of function declarations without prototypes would violate the design goal of providing backward compatibility. Instead, we restrict the usage of no-prototype functions to reduce the possibility of bounds checking being bypassed accidentally in unchecked blocks.

Informally, we want to prevent values with checked types from being passed as arguments or returned from calls to no-prototype functions. This requires some care to define because of structures, unions, and function pointers. We define the set of types E that are an error to use with functions without prototypes by induction. It includes:

1. Checked pointer and array types.
2. Complete structure and union types with members that have types in E .
3. Pointers to function types that have argument or return types that are in E .
4. Complete structure and union types with members with bounds declarations (these are described in Chapter 6).
5. Pointers to function types with bounds declarations.

Clauses 4 and 5 handle the case of integer-typed values that have bounds declarations (note that bounds-safe interfaces on unchecked pointer types are not bounds declarations).

We define the following rules for unchecked scopes:

1. It is an error to call a function that is declared to have no prototype and pass or return a value whose type is in E .
2. A function declaration with no prototype is incompatible with a function declaration with a prototype that has parameter types or a return type in E or that has bounds declarations.

5.5.1 Examples of errors caught by rules

The rules catch common errors. They catch passing a checked pointer to a function with no prototype:

```
int f();

int g(ptr<int> a) {
    f(a); // error - passing a checked type to a function without a
          prototype
}
```

They also catch redeclaring a function with no prototype to have a checked parameter:

```
int f();

struct S {
    array_ptr<int> ap : count(len);
    int len;
}

// Error - incompatible definition of f with a prototype.
int f(S y) {
    ...
}
```

By rule 2, the definition of `f` is incompatible with the initial declaration of `f`, so this is an error. It is an error even if `S` is an incomplete type at the time of a prototype declaration for `f`:

```
int f();

struct S;

int f(S y); // Declarations involving incomplete types are allowed.

// Now define struct S.
struct S {
    array_ptr<int> ap : count(len);
    int len;
}

// Error - incompatible definition of f with the initial declaration of f.
int f(S y) {
    ...
}
```

5.5.2 Example of errors not caught by the rules

The rules are not foolproof, though. Checking can be bypassed by code that declares a function with no prototype in one compilation unit and defines it in another compilation unit:

```
Compilation unit 1:
```

```
int g(ptr<int> x) {  
    ...  
}
```

Compilation unit 2:

```
extern int g();  
void h(void) {  
    g(5); // Error  
}
```

The definition of `g` in compilation unit 1 is incompatible with the declaration in compilation unit 2, but there is no way for a compiler to detect this.

The checking could be deferred to linking. The compiler could decorate the linker names of functions whose argument types or return types are in *E* differently from the names of functions whose argument types and return types are not in *E*.

5.5.3 Unchecked pointers to checked types

There is a limited way in which no-prototype functions can interoperate with checked types. The definition of *E* allows unchecked pointers to checked pointers and arrays to be passed to or returned from no-prototype functions. It also allows unchecked pointers to structures or unions that have checked members to be passed to or returned from no-prototype functions. Finally, it allows unchecked pointers with bounds-safe interfaces to be passed to functions with no prototypes. This is necessary so that bounds-safe interfaces can be added to existing code without breaking the code.

Here are some examples:

```
int g();  
  
int g(ptr<int> *x);  
  
int f();  
  
struct S {  
    array_ptr<ptr> ap : count(len);  
    int len;  
}  
  
int f(S *arg);
```

There are three reasons to allow unchecked pointers that point to checked data to be passed to functions without prototypes. First, the unchecked pointer types indicate a lack of checking, so it is already clear from the types of the variables being used that there is some lack of checking. Second, we believe that this will support incremental conversion of code to use the Checked C extension. Finally, it would be difficult to enforce that an unchecked pointer does not point to a checked type. An unchecked pointer could point to an incomplete structure or union type. A compilation unit might never define the type. The type could even be unresolved during linking of a library if none of the library compilation units define the type.

Chapter 6

Bounds declarations for structure types

This chapter extends reasoning about bounds to objects with structure types by introducing bounds declarations for structure members. Structure types may have members with `array_ptr` types. Those members must have *member bounds declarations* associated with them in order for the values stored there to be used to access memory.

The declarations of structure members may include `where` clauses that declare member bounds. The member bounds declarations may also be placed inline. A structure declaration may also include `where` clauses at the same level as member declarations. Here are examples:

```
struct S {  
    array_ptr<int> data where data : count(num);  
    int num;  
};
```

or

```
struct S {  
    array_ptr<int> data : count(num);  
    int num;  
};
```

or

```
struct S {  
    array_ptr<int> data;  
    int num;  
    where data : count(num);  
};
```

Member bounds declarations are program invariants that are assumed to be true by default for objects of that type. A member bounds declaration may be suspended for a specific object to allow for initialization of the object or modification of the members involved in the member bounds declarations. The member bounds declaration is declared to hold again after the initialization or modification is done. Here is an example of variable of type `S` being initialized:

```

void f(int len) {
    S y
    where suspends(y.data);
    array_ptr<int> newarr : count(len) = malloc(sizeof(int) * len);
    y.data = newarr;
    y.num = len
    where holds(y.data);    // the member bounds for y.data now holds
    ...
}

```

`Suspends` and `holds` are dataflow-sensitive declarations of the states of the member bounds declarations for specific members of variables. They can be applied to variable members that have member bounds.

They also can be applied to variables or variable members with structure types as syntactic shorthand. In that case, they apply to the nested members of the variable or variable member. The example could also be written as:

```

void f(int len) {
    S y
    where suspends(y);
    array_ptr<int> newarr : count(len) = malloc(sizeof(int) * len))
    y.data = newarr;
    y.num = len
    where holds(y);    // the member bounds for y.data now holds
    ...
}

```

Making member bounds declarations be invariants provides a way to deal with issues caused by aliasing. There can be pointers to data structures or members of data structures. There may be multiple pointers to a single structure object in memory. When there are multiple pointers, the pointers are called aliases because they all name the same memory location. Aliasing makes it hard to reason about programs.

Consider the example:

```

f(S *q, S *r, bool b)
{
    if (b) {
        q->arr = malloc(sizeof(int)*5);
        q->len = 5;
    }
    else {
        r->arr = malloc(sizeof(int)*5);
        r->len = 5;
    }
}

```

Even when `b` is true, the value `r->arr` may still be changed by a call to `f`. This can happen when `q` and `r` are the same value and are aliases for the same memory location. Changing one named value (`q->arr`) can have the effect of changing some other value with a distinct name (`r->arr`). In general, it is difficult to know whether an assignment through one pointer variable is affecting the members of other pointer variables.

Member bounds declarations being program invariants for structure members allows localized reasoning about the members. A programmer can assume that the bounds declarations are true for members of objects of that type. The member bounds declaration may be suspended temporarily for specific objects while they are being initialized or modified.

The bounds declarations for variables with structure types and the `suspends` and `holds` declarations will be checked statically for validity. Section 6.6 extends the rules from Chapter 4 to variables with structure types and to `suspends` and `holds` declarations.

In the rest of this chapter, to simplify the description, assumptions about address-taken variables similar to those in Section 3.1 are made. It is assumed that none of the variables or members of variables on the left-hand side of bounds-declarations have their addresses taken. It is assumed also that the values of variables or members of variables whose addresses are taken are not used in bounds expressions.

6.1 Declaring bounds for structure members

Member bounds declarations have the form:

```
member-bounds-decl:
    member-path : member-bounds-exp
```

```
member-path:
    identifier
    member-path . identifier
```

A member path is a sequence of one or more member names, separated by the ‘.’ operator. The sequence of members must be a valid sequence of member accesses for the structure type. The common case of using a member of the structure type is simply a member path of length 1.

Member bounds expressions are similar to the bounds expressions described in Section 3.1, except that members of the structure type are used in place of variables in the non-modifying expressions. In addition, pointer indirection and indirect member references are excluded.

A structure member whose type is `array_ptr` or a checked array type may have at most one bounds declared for it. The typing rules for member bounds declarations are similar to those for variable bounds declarations. For bounds declarations of the form *member-path* : `count`(*e1*), the *member-path* cannot have the type `array_ptr<void>` and the expression *e1* must have an integral type. For bounds declarations of the form *member-path* : `bounds`(*e1*, *e2*), the types of *e1* and *e2* must be pointers to the same type. Typically *member-path* is also a pointer to that type or an array of that type. However, *member-path* can be a pointer to or an array of a different type.

A structure consists of a list of member declarations, each of which consists of a type specifier followed by one or more structure member declarators. Structure member declarators are changed to allow optional in-line specification of member bounds and `where` clauses.

```
struct-member-declarator:
    declarator where-clauseopt
    declaratoropt : constant-expression
    declarator : member-bounds-exp where-clauseopt
```

The list of member declarations is extended to include `where` clauses:

struct-member-declaration:

```
...  
where-clauseopt
```

The remaining syntax for specifying a structure remains unchanged:

struct-or-union-specifier:

```
struct-or-union identifieropt { struct-member-declaration-list }
```

struct-member-declaration-list:

```
struct-member-declaration  
struct-member-declaration-list struct-member-declaration
```

struct-member-declaration:

```
specifier-qualifier-list struct-member-declarator-list ;
```

struct-member-declarator-list:

```
struct-member-declarator  
struct-declarator-list , struct-member-declarator
```

A member bounds expression can use members and child members of the structure being declared. Any member paths occurring in the member bounds expressions must start with members of the structure type being declared. Here is an example of the use of child members:

```
struct A {  
    array_ptr<int> data;  
};  
  
struct N {  
    int num;  
};  
  
struct S {  
    A a  
    where count(a.data) == n.num;  
    N n;  
};
```

Allowing member bounds to use nested members of members complicates explaining concepts. Sometimes concepts will be explained using member bounds that use only immediate members and then generalized to handle nested members.

6.2 Bounds declarations for variables with structure types

To describe facts about members of specific variables, the left-hand sides of bound declarations are generalized to allow members of variables. The term *variable member path* stands for variables or

variables with member accesses. Variable member paths are used where variables were allowed:

```
bounds-decl:
    var-member-path : bounds-exp

var-member-path:
    identifier
    var-member-path . identifier
```

The first identifier in a variable member path must be the name of a variable. The rest of the path, if there is one, must describe a member path for the structure type that has an `array_ptr` type. The member path can be used as a name for its associated member bounds. Inline bounds declarations are still restricted to variables.

6.3 Declaring the state of member bounds declarations for variables

Programmers may declare the state of a member bounds declaration for a variable using two kinds of facts:

```
fact:
    ...
    suspends(var-member-path)
    holds(var-member-path)
```

If the *var-member-path* has an `array_ptr` type, it must have the form *x.path*, where *x* is a variable name. The fact `suspends(x.path)` means that the member bounds declared by the type of *x* for *path* may not hold for *x*. The fact `holds(x.path)` means that the member bounds declared by the type of *x* for *path* holds now for *x*.

As a convenient short-hand notation, the *var-member-path* can have a structure type. In that case, the declaration applies to all member bounds for the structure type and child members of the structure type.

6.3.1 Parameters and return values

The state of member bounds declarations can be declared for parameters and return values using `suspends` and `holds` as well. By default, the state is `holds`.

Consider the following structure type definitions:

```
struct S {
    array_ptr<int> data : count(num);
    int num;
}

struct T {
    S arr1;
    S arr2;
    array_ptr<float> weights : count(len);
}
```

```

    int len;
}

```

Here are some function declarations involving the state of member bounds:

```

T f(T x where holds(x)) where holds(return_value)    // the default

T f(T x where suspends(x.arr1))
where suspends(return_value.arr2)

T f(T x where suspends(x.arr1.data))
where suspends(return_value.arr1.data)

```

6.3.2 Extent of declarations of member bounds state for variables

Declarations of the state of member bounds declarations are dataflow-sensitive and follow rules similar to flow-sensitive bounds declarations.

We first define the set of state declarations that apply to a function component, where a function component is a statement or variable declaration.

The state declarations for variables and variable members with structure types are expanded to state declarations of the individual members with `array_ptr` type. It is assumed that declarations of automatic structure variables without initializers implicitly have `suspends` declarations for the variables. All other declarations of structure variables are assumed implicitly to have `holds` declarations for the variables. The other declarations are either automatic variables with initializers or variables with static storage, which are initialized to 0. Any `array_ptr` members initialized to 0 have `bounds(any)`, so they satisfy their member bounds declarations.

For any declaration of member bounds state for $v.mp$, where v is a variable and mp is a member path, if

1. There is some path from the declaration to the function component, and
2. v occurs in the function component, and
3. There is no other declaration of member bounds state for $v.mp$ along the path

then the declaration of member bounds state applies to the function component.

Member bounds state declarations must be consistent and agree along all paths to a function component. If a variable occurring in a function component has more than one state declaration that applies to it at the component, then all the state declarations applying to it at the component must be syntactically identical. This avoids ambiguity about which state declaration applies to an occurrence of a variable. It is an error for the member bounds state declarations to disagree.

The following example illustrates the declaration of member bounds state. The structure `S` represents a variable length array, where `data` holds a pointer to an array and `num` is the length of the array. The function `f` takes a length parameter `len` and creates an initialized instance of `S` in the variable `y`. It then copies `y` to `z`.

```

struct S {
    array_ptr<int> data
    where count(data) == num;
}

```

```
    int num;
};
```

Here is a version of `f` where all member bounds state declarations are made explicit. For structure variable members whose member bounds are suspended, the bounds declarations are made explicit as well.

```
void f(int len) {
    S y where suspends(y.data);
    S z where suspends(z.data);
    int i, j;
    array_ptr<int> newarr : count(len) = malloc(sizeof(int) * len);
    y.data = newarr
    where y.data : count(len);
    y.num = len
    where holds(y.data);    // the member bounds for y.data now holds
    z = y
    where holds(z.data);
}
```

This can be written more succinctly as:

```
void f(int len) {
    S y;
    S z;
    int i, j;
    array_ptr<int> newarr : count(len) = malloc(sizeof(int) * len);
    y.data = newarr
    where y.data : count(len);
    y.num = len
    where holds(y);    // y is initialized now
    z = y
    where holds(z);    // z is initialized now
}
```

6.4 Integration of member bounds and bounds for variables

A member of a structure variable may be covered by its member bounds declaration and a bounds declaration at the same time. This coexistence happens when a member is initialized to satisfy its member bounds declaration. Here is a version of `f` that is annotated with both member bounds and bounds declarations for variable members.

```
void f(int len) {
    S y;
    array_ptr<int> newarr : count(len) = malloc(sizeof(int) * len);
    y.data = newarr
    where newarr : count(len) && y.data : count(len);
    y.num = len
    where holds(y.data) && y.data : count(len) &&
        y.data : count(y.num);
    ...
}
```

After the assignment `y.num = len`, the member bounds holds for `y.data` and the bounds declaration `y.data : count(y.num)` holds as well.

6.4.1 Determining bounds for a use of an `array_ptr` member of a variable

When a member path `mp` of a variable `x` is used and `x.mp` has type `array_ptr`, the bounds for `x.mp` are determined using these rules:

- If the use is within the extent of a bounds declaration `x.mp : bounds-exp` and `bounds-exp` is not `bounds(unknown)`, `bounds-exp` is the bounds.
- Otherwise, if the state of the member bounds for `x.mp` is `holds`, the member bounds for `x.mp` is used.
- Otherwise, the bounds of `x.mp` is `bounds(unknown)`.

6.4.2 Suspends declarations and bounds for variables.

When the member bounds declaration `mb` for a variable member is suspended by a statement of the form:

```
e2 where suspends(x.mp);
```

where `x` is a variable and `mp` is a member path, there is an implicit bounds declaration for `x.mp` at the point of suspension. This happens unless `e2` modifies a member `m` of `x` that occurs in `mb`. In addition, the state of the member bounds for `x.mp` must be `holds` before the statement. The member bounds declaration `mb` is converted to a bounds declaration by prefixing each occurrence of a member path in `mb` with the expression “`x.`”.

For example, given

```
S copy_and_resize(S arg, int len) {
    array_ptr<int> newarr : count(len) = malloc(sizeof(int) * len)
    where suspends(arg);
    for (int i = 0; i < arg.num; i++) {
        newarr[i] = arg.data[i];
    }
    arg.data = newarr where arg.data : count(len);
    arg.num = len where arg.data : count(arg.num)
    where holds(arg);    // member bounds for arg holds now
    return arg;
}
```

There is implicitly a bounds declaration at the suspension of the member bounds for `arg`:

```
array_ptr<int> newarr : count(len) = malloc(sizeof(int) * len)
    where suspends(arg) && arg.data : count(arg.num);
```

If the suspends were done after the assignment to `arg.data`:

```
arg.data = newarr
suspends(arg);
```

there would not be an implicit bounds declaration because `arg.data` is modified by the assignment.

At a declaration of a structure variable `x`, no implicit bounds declarations are inserted if the declaration suspends the member bounds for a member of `x`. There was no point at which the member bounds was known to be true. For example,

```
f(S arg where suspends(arg))
```

does not have an implicit bounds declaration of the form `arg.data :count(arg.len)`.

6.4.3 Holds declarations and bounds for variables

At a `holds` declaration for a variable member path `x.mp`, the member bounds for `x.mp` must be implied by the bounds declarations that are true about members of `x` and any facts that true at the point of the `holds` declaration.

6.5 Bounds-safe interfaces

Just as existing functions can have bounds-safe interfaces declared for them, existing structure types can have bounds-safe interfaces declared for them. This allows checked code to use those data structures and for the uses to be checked. Existing unchecked code is unchanged. To create a bound-safe interface for a structure type, a programmer declares member bounds or interface types for structure members with unchecked pointer types.

Here is a member bounds declaration for a structure that is a counted buffer of characters:

```
struct CountedBuffer {
    char *arr : count(len);
    int len;
}
```

Here are bounds-safe interface types for members of a structure for binary tree nodes. The structure contains pointers to two other nodes. In checked code, pointer arithmetic on those pointers is not allowed.

```
struct BinaryNode {
    int data;
    BinaryNode *left : itype(ptr<BinaryNode>);
    BinaryNode *right : itype(ptr<BinaryNode>);
}
```

If bounds information is declared for one member of a structure with an unchecked pointer type, it must be declared for all other members of the structure with unchecked pointer types.

It is important to understand that the *semantics of unchecked pointers in unchecked contexts does not change even when bounds are declared for the pointers*. The declared bounds are used only by checked code that uses the data structure, when storing checked pointers into the data structure, and when converting unchecked pointers read from the data structure to checked pointers. Code in unchecked contexts that uses only unchecked pointer types is compiled as though the bounds-safe interface has been stripped from the source code.

6.6 Extending checking validity of bounds

This section describes how to extend the checking in Chapter 3 to check variables with structure bounds and expressions with structure operations such as member assignment and member access. This section is primarily of interest to compiler writers.

In Chapter 4, contexts map pointer variables to their bounds. Contexts are extended to map structure variables to descriptions of bounds for their members. The bounds for members of a variable will be described using a set of pairs, where the first element of each pair is a member path whose type is `array_ptr` and the second element of each pair is a bounds expression. The bounds expression may use variable member paths in addition to variables.

In Section 4.2, the inference of bounds for an expression determines the bounds expression that applies to the value of the expression. For structure-typed expressions, inference is generalized to determine the bounds expressions that apply to the `array_ptr` members of the value of the expression. This information is represented using the same representation used for contexts: a set of pairs, where the first element is a member path whose type is `array_ptr` and the second element is a bounds expression. Given this representation, it is easy to define the rules for inferring bounds for member accesses: a member access prunes the set of pairs and shortens the member paths.

In Section 4.3, checking of assignment expressions updates contexts. The contexts are then used to check that expression statements imply declared bounds. They are also used to check expressions nested within an expression that contain assignment expressions. Given the representation of contexts, the rules for updating contexts are extended to update contexts pointwise for structure variable assignments and member assignments. For a structure variable assignment, the entire set of pairs for a variable is updated. For an assignment to a member of a structure variable, only the set of entries associated with that member are updated. Both forms of assignment invalidate bounds expressions that use variable member paths that are changed by the assignment.

An expression statement is checked by determining the updated context for the expression statement, determining the expected context for bounds after the statement, and then checking that the updated context implies the validity of the bounds in the expected context (Section 4.5). For each variable in the expected context, it is checked that the bounds expression in the updated context implies the expected bounds expression. This is easily extended to a structure variable by checking for each member path for the variable that the bounds expression in the updated context implies the expected bounds expression.

6.6.1 Determining contexts

The context for every statement can be determined by using dataflow analyses extended pointwise to structure variables. Each structure variable is expanded into the set of variable member paths that represent all `array_ptr`-typed variable member paths beginning with the variable. First, an iterative forward dataflow analysis is done to determine the member bounds state at every point in a function, following the rules in Section 6.3.2. The analysis works on the set of variable member paths. It computes for each variable member path whether the member bounds are valid at each program point. It is a compile-time error if the analysis determines that the state of member bounds is inconsistent along different paths.

Second, a generalized version of the extent dataflow analysis of Section 3.10.4 is done. Each structure

variable is expanded into the set of variable member paths that represent all `array_ptr`-typed variable member paths beginning with the variable. The analysis assigns one lattice value to each of the variable member path for each program point in the function where the variable is in scope.

The context for a statement is computed using the results of the dataflow analyses. For each structure variable in scope for the statement, the set of `array_ptr`-typed variable member paths beginning at the variable is determined. The set is mapped to a set of pairs as follows:

- For the first element, the structure variable is removed from the beginning of the path to create a member path.
- For the second element, the extent dataflow analysis is consulted for the `array_ptr` member path. If the bounds expression is not `bounds(unknown)`, it is used. If it is `bounds(unknown)`, the result of the dataflow analysis for the member bounds state is examined. If the member bounds state is valid, the member bounds is used. It is transformed to use variable member bounds by prefixing the member paths that occur in it with the structure variable. Otherwise, `bounds(unknown)` is used.

6.6.2 Inferring bounds for expressions without assignments

This section describes extensions to Section 4.2 for determining bounds. The notation $e \vdash s$ is overloaded for expressions with structure types to mean that e has a set of member paths with individual bounds expressions.

- Variables: If x has a structure type, the context is consulted for x for the set s of pairs of member paths and bounds expressions. $x \vdash s$.
- Member access: Given an expression $e.m$, where m is a member name and $e \vdash s$,
 - If $e.m$ has a structure type, then
 - * The set s' is defined as follows. For each pair (mp, b) in s , if mp has the form $m.rp$, then (rp, b) is included in s' .
 - * Given s' , $e.m \vdash s'$.
 - Otherwise,
 - * If $s = \{(m, b)\}$, then $e.m \vdash b$
 - * Otherwise, $e.m \vdash \text{bounds(unknown)}$
- Function calls: *To be filled in*

6.6.3 Assignment expressions

To be filled in.

6.7 Compatibility of structure types with bounds declarations

The C Standard defines compatibility of two structure types declared in separate translation units [50, Section 6.2.7]. This definition is extended to include member bounds declarations and member bounds-safe interfaces. If the structure types are completed in both translation units, for each pair of corresponding members,

- If the members have unchecked pointer type,
 - If the members both have bounds-safe interfaces, the bounds-safe interfaces must either both be bounds expressions or both be interface types. If both have bounds expressions, the bounds expressions must be syntactically identical after being placed into a canonical form. If both have interface types, the interface types must be compatible.
 - Otherwise, one member must have a bounds-safe interface and the other member must omit a bounds-safe interface, or both members must omit bounds-safe interfaces.
- Otherwise, both members must have member bounds declarations or both members must not have member bounds declarations. If both members have member bounds declarations, the bounds expressions must be syntactically identical after being placed into canonical form.

Chapter 7

Pointers to data with `array_ptr`s

This chapter covers using pointers to data with `array_ptr`s. It also covers rules around pointers and bounds expressions. This includes dereferencing pointers in bounds expressions and rules around address-taken pointer variables and bounds expressions.. Three important scenarios for using pointers to `array_ptr`s to support are:

- Data structures: All linked data structures in C are built with pointers, typically using pointers to structures. This means there need to be ways to create pointers to structures that contain `array_ptr`s, to assign through pointers to structures, and to read from pointers to structures.
- Passing data by-reference to functions. C does not provide by-reference parameters. Programmers pass data by-reference by using pointers explicitly. To pass data of type T by reference, a programmer creates a parameter with type $T *$. Using checked pointers, a programmer create a parameter with type `ptr<T>`.
- Taking the addresses of variables. In C, programmers may take the addresses of variables. Typically, this is done to be pass data by-reference. If a variable is used in a bounds expression, what can be done with the pointer must be constrained so that bounds-safety is not accidentally broken.

7.1 Initialization of pointers in data

The term “referent data” will refer to the data that can be accessed directly through a pointer. The data may be an integer or floating-point number, a structure, a pointer, or an array of data. Any checked pointers in data must be initialized before the pointers are used.

For variables, this can be enforced using a static analysis of variables with checked pointer types that point to data with checked pointer types. For example, the Cyclone dialect of C [51] did this and languages like Java and C# have rules for ensuring that variables are definitely assigned before they are used. For a variable of `array_ptr` data, the compiler will insert code for initializing checked pointers in the data automatically to 0, which is always a valid pointer.

For heap-allocated data, we can require that allocators return data that has been zeroed. The initial implementation of Checked C will take this simple approach. Section 7.4 describes a proposal for supporting for allocators that return pointers to uninitialized data.

7.2 Pointers to structures

Pointers to structures can be supported by ensuring that modifications to members preserve type-level bounds invariants, following the approach of the Deputy system [19]. This in turn means that accesses through structure pointers return values that follow the type-level bounds invariants, provided that modifications are not interleaved. Complicated aliasing problems are avoided because the alias relationship of members within a structure is well-known. Expressions and statements that modify members must be relatively simple; they cannot access memory that may be aliased.

Just like a member bounds can be suspended for a variable, a member bounds can be suspended for an object that is referenced by a pointer. The syntax is:

```
fact:
    suspends(e->mp)
    holds(e->mp)
```

where *e* is a pointer to a structure type *S* and *mp* is a member of path. The syntax **e.mp* is equivalent to *e->mp* and can be used in its place. The syntax `suspends(*e)` suspends all member bounds for the object pointed to by *e* and the syntax `holds(*e)` means that all member bounds for *e* must hold.

The expression *e* must be a non-modifying expression to ensure that the *e* refers to the same object at `suspends` and `holds` declarations. It must meet the following additional restrictions:

- *e* cannot access memory via a pointer operation. It cannot contain a `*`, `->`, or a `[]` operation.
- No variable whose value is used *e* can be modified between the `suspends` and `holds` declarations.
- No variable whose value is used in *e* can have its address taken. This is to avoid indirect modifications of variables.

There are additional restrictions to avoid problems due to pointer aliasing (when two pointers may point to the same memory). We propose simple restrictions for correctness. Function calls are not allowed between `suspends` and `holds` declarations for *e->mp*. The function calls might depend on the object pointed to by *e* having a valid type-level invariant.

We continue to assume that the addresses of `array_ptr` members and members used in member bounds cannot be taken. It is undefined behavior for unchecked code to create pointers to the memory of those members. With this assumption, we can allow assignments through and reads via other pointer expressions between the `suspends` and `holds` declarations for *e->mp*. This is provided that the assignments do not modify *S.mp* or members in the bounds of *S.mp*. No pointers should alias *mp* or the other members, so the only aliases can be other structure pointers. Those can only be created through casting. It is the programmer's responsibility to update bounds-checked members properly in that case (Section 5.1).

The checking described in Chapter 6 is extended from operating over variable member paths to operating over expression member paths, where the initial variable is replaced by a non-modifying expression that dereferences a structure pointer.

7.3 Speculative idea: support for by-reference parameter passing of `array_ptrS`

It will be important to support by-reference parameter passing of `array_ptr`-typed variables in C. It is a common way that multiple values are returned from a function. By-reference parameter passing of `array_ptrS` will lead to programs where the addresses of local variables or struct members of type `array_ptr` are taken.

For example, a function that returns a newly-allocated buffer and its length could be written as:

```
void create(ptr<array_ptr<char>> pbuf where *pbuf: count(*len),
           ptr<int> plen)
{ ...
}
```

A caller would take the addresses of local variables to use this function:

```
void f(void)
{
    int len;
    array_ptr<char> buf : count(len) = NULL;
    create(&buf, &len);
}
```

We can gain insight into this problem by considering a related problem. When the address of a variable that occurs in a bounds declaration is taken, it is important to ensure that the invariants for the bounds declaration are not broken accidentally. Consider:

```
void bad_code(array_ptr<char> buf : count(len), int len)
{
    ptr<int> plen = &len;
    *plen = 5;
}
```

The problem with allowing the address of just `len` to be taken is that the lvalue for `len` actually has additional constraints. This suggests that pointer variables that hold addresses of address-taken variables should themselves have additional constraints. For example:

```
void constrained_code(array_ptr<char> buf : count(len), int len)
{
    ptr<int> plen = NULL;
    ptr<array_ptr<char>> pbuf = NULL where *pbuf : count(*plen);
    bundle {
        plen = &len;
        pbuf = &buf;
    }
    bundle {
        array_ptr<int> a = malloc((sizeof(char)*5);
        *plen = 5;
        *pbuf = a;
    }
}
```

There are some interesting issues that arise from this idea:

- The bounds on the lvalues for `len` and `buf` must be invariant throughout the execution of the program. While we can put constraints on pointers that point to those lvalues, we do not know when the lvalues will be updated. The implication of this is that only local variables with invariant bounds declarations (Section 3.2.4) can have their addresses taken. Local variables with flow-sensitive bounds declarations cannot have their addresses taken. The function could alter the bounds declarations for the local variables so that they disagree with constraints on the pointers.
- Once the address of a variable involved in a bounds declaration is taken, we cannot add new bounds declarations involving the variable. The pointer-level bounds declarations would not reflect the new constraint.
- The constraints on the pointers must fully capture all the constraints on the underlying variables.
- Finally, constraints on the pointers cannot be dropped.

The operations that could be done while updating address-taken variables or assigning through pointers with constraints on them must be limited. To maintain the bounds declaration, we must ensure that variables are not modified unexpectedly via aliases. Without aliasing information, function calls could not be allowed. Updates to address-taken variables could not be intermingled with reads or writes through pointers with constraints to avoid the possibility of aliasing.

Taking the addresses of members that are used in member bounds fits nicely into this approach for supporting by-reference parameters. The lvalues involved there do have invariant bounds through the execution of the program, which is the same requirement that we have placed on local variables.

7.4 Speculative idea: tracking initialization state of data

In the long run, it is unsatisfactory to require that allocators always return zeroed data. Some allocators such as `malloc` return pointers to uninitialized data. This improves efficiency when data is simply overwritten by the caller. For example, it is not necessary for bounds safety for arrays of characters to be zeroed.

Here we describe a strawman proposal for addressing this issue. We could add a way to track the initialization state of ranges of memory that contain pointers. We already have a way of describing ranges of memory: bounds expressions. We can add predicates that use bounds expressions to describe the initialization state of memory pointed to by a variable:

- Three predicates can be used in `where` clauses to describe the initialization state of a `array_ptr` or `ptr`-typed variable: `_init_data`, `_uninit_data`, and `_zero_data`. A predicate applies to a variable if it is combined using the `:` notation: `x : _uninit_data` means that `x` points to data that is uninitialized.
- The predicates also have range versions that take bounds expressions as arguments by suffixing the predicate name with `_range`. For example, if we want to express that the first `n` elements of `x` are initialized and the remaining elements are not, we could have `x : init_data(x, x + n)&& x : uninit_data(x + n + 1, x + len)`, where `len` is the length of the array pointed to by `x`.
- The default state of data is that it is assumed to be initialized. Data must explicitly have another state declared for it to be in another initialization state.

- We need to address aliasing: static checking must ensure that areas of memory do not have contradictory initialization states. At a minimum, we would need a way to specify that a variable holds a unique pointer to memory that no one else has [51].
- There will be local rules for expression and statements that deduce that a new initialization state declaration is valid after a statement. We leave the rules to be worked out later.
- Additional static checking rules will be added to ensure the correctness with respect to bounds of casts to checked pointer types that have pointer types embedded within them.

Here are potential bounds-safe interfaces for `malloc` and `calloc`. We omit notation for describing that `malloc` and `calloc` produce pointers to new memory:

```
void *malloc(size_t len)
where return_value : byte_count(len) && return_value : _uninit_data;

void *calloc(size_t num, size_t size)
where return_value : byte_count(num * size) && return_value : _zero_data;
```

A cast from the result of a `malloc` call to a checked pointer type with pointer types would propagate the `_uninit` predicate:

```
struct S {
    int len;
    int array_ptr<char> chars : len;
}

void f(void)
{
    S *s = malloc(sizeof(S)) where s : _uninit_data;
    s->chars = NULL where s : _init_data;
    ...
}
```

Of course we might want inference rules that add annotations automatically.

It might be possible to use ranges to write code that tracks at a fine grain that data is being zeroed:

```
array_ptr<char> zero_mem(array_ptr<char> x : count(len) where x : _uninit,
    size_t len)
where x : _zero_init
{
    array_ptr<char> p : bounds(x, x + len) = x
        where p : _init_data(x, p) && p : _uninit_data(p, x + len);

    while (p < x + len) {
        *p++ = 0;
    }
    return;
}
```

Chapter 8

Reasoning about bounds and simple program invariants

Programmers and compilers will need to reason about bounds as variables are modified. In doing so, they will also need to reason about simple program invariants. This section introduces extensions to C to support reasoning about program invariants.

There are a variety of reasons why programmers and compilers may need to reason about bounds:

- A programmer may wish to narrow the area of memory that can be accessed via an array pointer by modifying the bounds of the pointer.
- A programmer may introduce a temporary variable and may wish to re-express existing bounds in terms of that new variable.
- A programmer may write a loop that depends on a variable with bounds and also modifies one or more variables used in those bounds. Some simple reasoning may be needed to show that the loop body preserves the bounds.
- A programmer may do a dynamic check to ensure that a bounds can be satisfied.
- A compiler may need to check that the arguments to a function call satisfy the bounds requirements of the function parameters.
- A programmer may want to write performance-critical code that is free of dynamic bounds checks. The programmer may introduce checks outside the performance-critical code that guarantee no dynamic checks are needed. The compiler may need to check that the bounds are statically satisfied in the performance-critical code.

We incorporate reasoning about bounds into the language because checking the correctness of bounds statically is often the only practical choice. If we were to ignore the correctness of the reasoning about bounds, we would have to track the bounds for all pointer values dynamically to ensure correct operation of programs. C programs often operate at such a low level in the system that there may be no practical way to do this.

Because the reasoning about bounds is part of the language, compilers will check the correctness of the reasoning, just as they check the correctness of types. They must do so predictably and efficiently. Two compilers for C with these extensions should always produce the same answer.

Compile times should be relatively unaffected and checking should scale to code bases with millions of lines of code. This rules out incorporating program verification techniques that are heuristic-based or computationally expensive.

The computational limits for production compilers are severe. For production compilers, compiler developers aim for algorithms that are $O(N)$ or $(N \lg N)$ time in terms of the size of a method or a program. Compilers may encounter methods that have hundreds of thousands of lines of code and whole programs that have millions of lines of code. Production compiler developers use $O(N^2)$ time algorithms for individual functions only with great care, typically including code to disable an algorithm, reduce precision, or switch to an alternate algorithm that has better behavior at the expense of producing worse code.

To handle the computational limits of compilers, we view the compiler's job as one of proof checking. The compiler will check that individual steps in a proof are correct. It will do limited inference in the process of checking those steps. It will not try to infer which of the many possible facts about a large method are relevant; the programmer will need to state the relevant facts to use in inference.

8.1 Facts about program points

We start with facts about program points that a programmer may use to reason about bound. A fact is a bounds declaration or a relational statement about a variable and a non-modifying expression.

```
fact:
    bounds
    variable relop non-modifying-exp
    non-modifying-exp relop variable
```

Facts may be declared as part of `where` clauses. Chapter 3 included relational facts in the grammar for `where` clauses but did not say anything about them. For expression statements, the compiler will check that relational facts in the `where` clause are true using the facts true before the expression statement and the effect of the expression. For a parameter, the `where` clause becomes a precondition that must be true at the call site. The compiler will check this precondition at the call sites.

A `where` clause may be used as a stand-alone statement, in which case it stands on its own as a set of invariants and bounds declaration:

```
where x >= 0 && x <= 10;
```

This is just a special case of an expression statement that omits the expression but still has `where` clause.

Facts are automatically inferred for the clauses of if-statements, the cases of switch statements, and from assignment statements. For if-statements, the test has to have the form of a fact. For a switch statement, a fact is deduced from the switch expression and the case statement. For assignments, the left-hand side must be a variable and the right-hand side must be a non-modifying expression.

Here are some simple examples where the fact created by a control-flow statement is explicitly declared using redundant `where` clauses:

```
if (x < 5) {
    where x < 5;
```

```
}  
else {  
    where x >= 5;  
}  
  
switch (x) {  
    case 0: {  
        where x == 0;  
        break;  
    }  
    case 1: {  
        where x == 1;  
        break;  
    }  
    default: {  
        where x != 0 && x != 1;  
        break;  
    }  
}
```

Here is a simple example that introduces the fact that `i` is always `>= 0`:

```
int sum10(array_ptr<int> buf : count(10)) {  
    int sum = 0;  
    int i = 0  
    where i >= 0;  
    while (i<10) {  
        sum += buf[i];  
        i = i + 1  
        where i >= 0;  
    }  
}
```

From this fact, it can be deduced that the access to `buf` is always in range. A `where` clause can be used double check this:

```
int sum10(array_ptr<int> buf : count(10)) {  
    int sum = 0;  
    int i = 0  
    where i >= 0;  
    while (i<10) {  
        where (i>= 0 && i<10);  
        sum += buf[i];  
        i = i + 1  
        where i >= 0;  
    }  
}
```

8.2 Checking facts

The compiler checks facts in a `where` clause by gathering known facts before an assignment statement and checking that the facts declared in the `where` clause can be inferred (easily) from known facts

and the effect of the assignment statement. The compiler finds known facts by examining each path from the beginning of the function to the statement and identifying facts that are true along all paths. Facts are introduced by **where** clauses, control-flow statements, and simple assignments. Facts are removed by assignments to any variable in a fact.

A programmer can find the facts that are available before an assignment statement by looking at assignments that precede the statement. The programmer usually only has to look at assignments to variables in the **where** clause for the assignment statement. The programmer can then check the facts along all paths from those assignments to the statement.

This analysis of facts available before a statement is similar to the “available expression” analysis done by optimizing compilers for common-subexpression elimination. For common-subexpression elimination, a compiler looks at all expressions. For analyzing available facts, a compiler only looks at expressions in **where** clauses, expressions inferred from control-flow statements, and simple assignments.

8.2.1 Algorithm for checking correctness of facts

To infer whether a fact is true in a **where** clause, the compiler first computes the set of facts that are true after the expression statement. We describe the common case where the expression is an assignment of the form $x := e1$.

1. If $e1$ is invertible and must have a well-defined value (cannot overflow or fails on overflow), the compiler takes the facts true before the statement and substitutes the inverse expression of $e1$ for any occurrences of x in the facts.
2. If $e1$ is not invertible or may not have a well-defined value, the compiler takes the facts before the statement and removes any facts where x occurs.
3. If $e1$ is a valid non-modifying expression, the compiler adds the fact $x == e1$ to the set of facts.

For variables that are declared to be equal, the compiler chooses one of them as the representative variable and substitutes it for all the other variables. That is, given $x == y$ and $y == z$, the compiler chooses one of the variables (say, x) and substitutes it for y and z . The compiler applies this substitution to both the set of facts and the fact that is being checked.

The compiler then reduces the set of relational operators to the set $<$, $<=$, $==$, and $!=$ by swapping operands and replacing $>$ and $>=$ with $<=$ and $<$ instead.

The compiler then puts each bounds declaration into a normal form so that syntactic identity can be used to compare facts. For example, operands for addition operations are commuted so that constant operands appear first, followed by the remaining subexpressions in lexicographic order. Integer subtraction $a - b$ is turned into $a + (-b)$. Additions with only constant operands are simplified and algebraic identities for addition and subtraction such as $x + 0$ are applied.

The compiler next checks if the fact being checked is in the set of facts. If it is not, it applies transitivity rules involving $<$, $<=$, and $==$. It also checks to see if $<$ implies $!=$ is true, and if $<=$ and $>=$ imply $==$.

8.2.2 Bounds declarations and facts

Bounds declarations are treated the same way as other facts. During the checking process, the same simplifications that are applied to other facts are applied to the right-hand side bounds expressions: the compiler chooses representative variables and puts the non-modifying expressions that make up a bounds expression into normal forms.

The rules for checking bounds declarations include rules for transitivity. For $x : \text{bounds}(e1, e2)$, if $e1 \leq e3$, then $e3$ can be substituted for $e1$. If $e4 \leq e2$, $e4$ can be substituted for $e2$. For $x : \text{count}(e1)$, if $e2 \leq e1$ and $e2 \geq 0$, $e2$ can be substituted for $e1$.

8.2.3 Pointer arithmetic and facts

The rules used to check facts include the identities $x < x + k$ for positive k and $x + k < k$ for negative k , where k is a constant and x is a variable that has a new pointer type (`ptr` or `array_ptr`). These identities are true because pointer arithmetic overflow is defined as a runtime error for new pointer types. This guarantees that adding x and k produces either an in-range value or a runtime error (no value).

8.2.4 Integer arithmetic and overflow

Integral arithmetic may overflow or wraparound. A consequence of that is that the rules used to check facts do not include the identities $x < x + k$ for positive k and $x + k < x$ for negative k , where k is a constant and x has an integral type. These identities are not true in C. For signed integer types, the computation $x + k$ may overflow. According to C language rules, program behavior is undefined in that case. For unsigned integer types, computations are performed modulo one plus the maximum unsigned integer.

To use these identities for integers, the compiler needs to prove for positive k that $x + k \leq \text{MAXINT}$ and for negative k that $\text{MININT} \leq x + k$. There are four rules that can be used to prove this:

- Given an integer c and a positive integer k , if $x \leq c$ and $c + k \leq \text{MAXINT}$, then $x + c \leq \text{MAXINT}$.
- Conversely, given an integer c and a negative integer k , if $c \leq x$ and $c + k \geq \text{MININT}$, then $\text{var } x + k \geq \text{MININT}$.
- Given $x < y$, where y is any variable, then $x + 1 \leq \text{MAXINT}$.
- Conversely, given $x > y$, where y is any variable, then $x - 1 \geq \text{MININT}$.

8.2.5 Checking function calls

A function call is checked by substituting the actual parameters for the formal parameters in the `where` clause for parameters. The resulting `where` clauses must be checked to see if they are true, given the facts true before the clause. For the `where` clause for the returned value, the actual parameters are substituted for the formal parameters. The set of facts in the clause are then added to the set of facts true after the call.

8.2.6 Avoiding bounds checks at runtime

It can be important to avoid dynamic bounds checks at runtime. The built-in method `in_bounds(e)` can be used to do this. It can be applied to expressions of type `array_ptr`. At compile time, the compiler checks that the bounds expressions for `e` are always true given the facts true before the evaluation of `e`. At runtime, `in_bounds(e)` simply returns the value of `e`. The compiler generates code for `*in_bounds(e)` with no dynamic bounds checks. The prior example can be written as:

```
int sum10(array_ptr<int> buf : count(10)) {
    int sum = 0;
    int i = 0
    where i >= 0;
    while (i < 10) {
        sum += *in_bounds(buf + i);
        i = i + 1
        where i >= 0;
    }
}
```

8.3 Examples

Here is a simple example of capturing the lower bounds of an `array_ptr` variable using another variable:

```
int sum(array_ptr<int> buf : bounds(buf, end), array_ptr<int> end) {
    array_ptr<int> tmp = buf;
    where buf : bounds(tmp, end); // substitute tmp for buf
    int sum = 0;
    while (buf < end) {
        sum += *buf;
        buf = buf + 1; // buf bounds do not change, do not need to be
                       // redeclared
    }
    return sum;
}
```

Here is a more complicated example where `buf` is incremented *and* `buf` is the lower bound:

```
int sum(array_ptr<int> buf : bounds(buf, end), array_ptr<int> end) {
    int sum = 0;
    while (buf < end) {
        sum += *buf;
        buf = buf + 1
        where buf : bounds(buf, end);
    }
    return sum;
}
```

Here are the steps that the compiler goes through, illustrated using `where` clauses. First, the compiler computes the facts true after `buf = buf + 1`. The compiler computes the inverse expression for `buf + 1`, which is `buf - 1`. It substitutes it into the bounds expression that is true before the increment, producing the set of facts after the increment of `buf` : `bounds(buf - 1, end)`:

```
int sum(array_ptr<int> buf : bounds(buf, end), array_ptr<int> end) {
  int sum = 0;
  while (buf < end) {
    sum += *buf;
    buf = buf + 1
    where buf : bounds(buf - 1, end);
  }
  return sum;
}
```

The next step is for the compiler to show that that `buf : bounds(buf - 1, end)` implies `buf : bounds(buf, end)`. The transitivity rule for bounds expressions implies that the compiler must show `buf - 1 <= buf`. This follows from the identity $x - k < x$, completing the validation of the bounds expression:

```
int sum(array_ptr<int> buf where bounds(buf) == (buf, end),
        array_ptr<int> end) {
  int sum = 0;
  while (buf < end) {
    sum += *buf;
    buf = buf + 1
    where bounds(buf) == (buf, end)
  }
  return sum;
}
```

Chapter 9

Related work

The C family of programming languages is used widely for system programming. The lack of bounds checking in C and related languages such as C++ has had serious practical consequences for computer security and software reliability. There has been extensive research and work in industry addressing the lack of bounds checking in C. In this section, we discuss related work and explain how Checked C relates to it.

The work falls into 5 categories:

- Runtime-based approaches. The compiler or runtime system or both are changed to detect out-of-bounds access at runtime. No source code changes are made. These approaches rely on general mechanisms for detecting bounds errors, such as side-data structures or altering the representation of pointers. These approaches are attractive from an “ease-of-adoption” perspective, but they have performance and compatibility issues that make them unsuitable for use for production code. They are widely used for testing purposes. Checked C requires program source code changes, but avoids the overhead of general-purpose mechanisms, making it suitable for production code.
- Security mitigations. These attempt to detect memory corruption after it has happened or prevent an attacker from taking over a system after a memory corruption. Some of them are used widely in practice, such as data-execution prevention, stack canaries, and address-space layout randomization. They do not protect against data modification or data disclosure attacks in general and are vulnerable to being circumvented using those attacks. Checked C addresses the underlying issue of data modification or data disclosure via out-of-bounds memory accesses, closing off an entire line of attack. Checked C programs remain vulnerable to memory management errors and incorrect pointer type casts, so Checked C complements these mitigations; it does not replace them.
- Static analysis. These analyze programs without running them and identify potential out-of-bounds memory accesses. They are attractive from an “ease-of-adoption” perspective. However, they may both miss errors and report errors that do not exist (false positives). False positives are a problem because programmers end up ignoring or missing genuine errors. Checked C provides a way to write code in C that is guaranteed to be bounds-checked.
- Program verification: this is a general-purpose approach that can be used to guarantee that programs only access in-bounds memory. Widespread adoption of verification technology for

C has its own hurdles, requiring that programmers integrate the use of a theorem prover into development. In contrast, Checked C can be integrated directly into compilers. Most programming languages rely on runtime checking of bounds. Checked C matches this level of functionality and does not require changes at uses of pointers and arrays. In contrast, programmers using verification technology who merely want runtime checking of bounds would have to manually put checks in at uses of pointers and arrays.

- Programming languages: several projects have proposed type-safe dialects of C. The Cyclone and CCured projects propose changes that break compatibility, either by changing the meaning of existing programs or changing data layout. The Deputy project proposes using dependent types to declare the bounds of pointers without changing data layout. Checked C builds on the Deputy approach, but decouples bounds information from types. This avoids the complexity of modifying the C type system to support dependent types. Dependent types would likely be difficult for programmers to understand.

9.1 Runtime-based approaches

The C specification leaves the semantics of out-of-bounds pointer arithmetic and out-of-bounds pointer access undefined. This makes it possible to implement runtime-based approaches that are consistent with the semantics of C and that do not require source code changes. It is also possible use probabilistic or fault-tolerant approaches to tolerate out-of-bounds memory accesses.

There are two general approaches used in runtime-based approaches. The first is to change the representation of pointers to carry bounds with them. The second uses a side-data structure to hold bounds information. There are several different kinds of side-data structures that can be used. One kind tracks blocks of memory that are valid to use. The blocks are typically powers of 2 and can range in size from a byte to up to 32 bytes. This is used to track “red zones” around objects that are invalid to access. These are useful for detecting buffer overruns caused by loops, but may not detect other out-of-bounds accesses. Another kind tracks the start and end locations of objects and can be used to provide object-level bounds checking. A third approach uses a shadow memory to track bounds information for individual pointers, splitting the bounds information from the pointer.

These approaches work well for testing purposes, but they have issues that prevent them from being used for production systems. There are issues with performance, backwards-compatibility, and constraints on memory management and layout. Most fundamentally, all of these approaches add runtime data to programs, which in turn increases memory accesses, processing time, and memory footprint. They have to pay for generality regardless of whether it is needed or not. In contrast, Checked C allows re-use of existing data. It incurs no data overhead for constant-sized arrays or pointers on which no pointer arithmetic is done. Approaches that change pointer representations have difficulty interoperating with existing systems because that changes the layout of data that must be passed across boundaries. Approaches that track data on the side generally require modifying memory allocators. A number of these approaches constrain memory layout and object sizes to speed up the lookup of the side data.

These approaches also take control of checking away from the programmer. Runtime-based checking *always* checks, unless the check can be proven redundant by compiler optimization. With Checked C, programmers have a range of options. The default behavior is to check. For performance-critical code, programmers can rely on static checking that proves the checks are unnecessary or omit checks

entirely.

We first describe approaches that change the representation of pointers. The `bcc` source-to-source translator [54] and the `rtcc` compiler [98] were used to find bounds errors and other errors during debugging. Each changed the representations of pointers to be 3 words: the pointer itself and an upper and lower bound. Steffen [98] reports that the `rtcc` compiler generated code that was 3 times larger and ran about 10 times slower than the original code, likely reflecting the simple nature of the optimizer for the PCC compiler. Data layout compatibility is an issue. Bounds information has to be removed at calls to standard library functions and added at returns from standard library functions. Austin *et al.* [5] describe a pointer representation that adds a capability in addition to bounds information. The capability prevents accesses to de-allocated objects. The runtime system tracks capabilities that are valid (memory that has not been deallocated).

Fail-Safe C is a memory-safe compiler for ANSI C [79]. It supports all operations in ANSI C, including cast operations. It represents pointers as pairs, where each pair consists of the base address of an object and an integer offset from the base address. It changes the representation of integers to be pairs as well so that pointers can be cast to integers and back. It also changes the representation of memory blocks in C to dynamically track their types. This supports the C notion that memory locations are dynamically typed; the type of the value in a memory location depends on the type of the last value stored there. It uses conservative garbage collection to ensure the safety of memory deallocations. With the data layout changes, programmers no longer directly control memory representations. This makes Fail-Safe C unsuitable for low-level system programming. It is suitable for applications programs, provided that wrappers for system calls are provided. Bytemark benchmarks are 2 to 4 times slower. OpenSSL RSA speed tests are 2 to 4 times slower, while AES speed tests are 5 times slower.

Grimmer *et al.* [45] propose executing C programs within a Java Virtual Machine. They represent pointers as pairs consisting of the base address of an object and the element count offset from the base address. They do not allow pointers produced by casting integers to pointers to be used to access memory.

We next describe approaches that use side-data structures. We first describe approaches that track what memory is valid to access. Purify [47, 101] detects some bounds checking problems as well as uses of uninitialized memory and memory leaks. It is meant for use during development and debugging. Purify uses a table that keeps track of the state of each byte in memory, using 2-bits to represent the state of memory. It inserts a small “red zone” before and after each dynamically allocated object and between statically-allocated objects. It also inserts red zones between stack frames. All memory accesses are instrumented to check or update the state for a byte. The instrumentation is inserted by rewriting binary code before linking. Purify detects out-of-bounds memory reads and writes involving red-zone memory. It does not detect out-of-bounds reads or writes that occur entirely within valid memory for other objects or stack frames. It cannot detect out-of-bounds memory accesses at the sub-object level. Hastings *et al.* report a slowdown of more than 2 times due to the instrumentation. However, this includes additional checking for memory leaks and the use of uninitialized memory.

There are a number of other similar commercial or open-source tools available that detect out-of-bounds memory accesses. Tools based on binary rewriting include Bounds Checker [65], Dr. Memory [11, 32], Intel Inspector [22], Oracle Solaris Studio Code Analyzer [80], and Valgrind Memcheck [74, 102]. Insure++ [82] inserts instrumentation using source-to-source rewriting. It also provides a mode that does not require recompilation, although details of how that works are not described.

AddressSanitizer [93] is a tool similar to Purify that is incorporated into the LLVM and GCC compilers. It uses a table stored in shadow memory that tracks that state of 8-byte chunks of memory, using 1/8 of the virtual address space. It also relies on inserting “red zones”. Because it has been implemented in a compiler, it is able to place red zones around stack-allocated objects. It cannot detect out-of-bounds memory accesses at the sub-object level and cannot reliably track out-of-bounds accesses for objects smaller than 8 bytes. For SPEC CPU2006, average program execution time increases by 73% when checking reads and writes and 26% when only checking writes. For SPEC CPU2006, average memory usage is 3.37 times larger.

Light-weight Bounds Checking [46] is an optimized implementation of bound checking that uses “red zones”. It focuses solely on bounds checking. It uses a bitmap to track which bytes in memory correspond to allocated objects and which do not. It uses a two-level table to avoid allocating a table equal to 1/8 of the address space. It optimizes memory reads by filling red zones with special values. If a memory read returns a special value, then a check is done to ensure that the address was not a red zone address. It is implemented in a compiler and can guard stack objects. For SPECINT 2000, average program execution time increases by 23%. For SPECINT 2000, its memory overhead ranges between 0.2% and 44% with an average of 8.5%.

Next, we describe approaches that use side-data structures to track object bounds. Jones and Kelly [53] use a splay tree to track the bounds for objects in a side data structure. They insert checks for pointer arithmetic to make sure that pointers stay within valid bounds for objects. If a pointer goes out of bounds, it is converted to a value that cannot be dereferenced and that is not allowed to go back in bounds. They change checked code to call modified versions of `malloc`, `free`, and system-level allocators. The compiler modifies code generation for stack allocated objects to call functions that update the bounds information. In a production system, all custom allocators would have to be modified to update the object bounds information.

Jones and Kelly implemented their approach in GCC. The approach easily allows interoperation between checked and unchecked code. Objects that are not allocated by checked code are not tracked. Untracked and tracked objects are treated as distinct memory regions. Operations in checked code on untracked objects are not allowed to produce pointers to checked objects, providing some protection to untracked objects.

Their implementation increases program running times by a factor of 7.7 to 12 [71] for a set of 23 benchmarks that includes programs from SPEC and the Olden benchmark. There are other drawbacks to this approach. Because bounds are tracked at the granularity of objects, it cannot track bounds for arrays nested within structures. There are also issues with handling pointers to one element past the last element of an array. Their approach inserts padding between objects to have a gap. In some cases, such as parameters passed on the stack, this is not possible.

The C Range Error Detector (CRED) [89] extends the Jones and Kelly approach to tolerate out-of-bounds pointers. They observe that 12 out of 20 open source programs totalling 1.2 million lines of C code break when out-of-bounds pointers are not allowed. This observation supports the design decision in Checked C to allow out-of-bounds pointers and only check bounds at memory dereferences.

CRED uses a proxy object that tracks the original pointer value and the object with which it is associated so that the pointer can go back in bounds. When a pointer goes out of bounds, it is replaced with the proxy object address. This requires additional checks on comparisons and pointer arithmetic computations. They find similar increases in program running times to those of Jones and Kelly. They suggest limiting bounds checking to only character pointers. With this restriction,

the increase in execution time ranges from 1% to 130% on a set of real-world programs. They do not report on changes in memory usage.

Dhurjati and Adve [29] describe an optimized implementation of CRED. It relies on a whole-program analysis to partition objects into separate pools. The pool information is used to partition the splay tree and to avoid having to create entries for single-element arrays or scalar objects in the splay tree.

Baggy Bounds Checking [4] provides a faster implementation of the side data structure in Jones and Kelly. The implementation calculates the bounds for any pointer in constant-time. To achieve this, the implementation constrains object sizes to be powers of 2. It also reserves $1/n$ of the virtual address space for a table, where n is the smallest allowed object size (16 in the implementation). The table stores the size of the enclosing object (if any) for each n -byte chunk of memory. Baggy Bounds Checking increases average execution time for SPECINT 2000 benchmarks by 60%. It increases average memory usage by 20%.

Parichack [110] stores a 2-byte label for each 32-byte chunk of memory. It reserves $1/16$ of the virtual address space for a table and increases the memory object allocation size to 32 bytes. It checks that pointer arithmetic stays in bounds by checking that the original pointer and the pointer computed by pointer arithmetic have the same label. For SPEC CPU2000, it increases average execution time 49% and average memory usage by 9.5%.

Low Fat Pointers [33] encode bounds information into 64-bit pointers by dividing memory into m regions of 4 GBytes each and storing the region information in the upper 32-bits of the pointer. Each region contains objects of some size k that are aligned to k . A table maps regions to their sizes. They measure the performance of SPEC 2006 programs and find that checking all pointer reads and writes increases average program execution time by 56% and checking only writes increases average execution time by 13%. In [34], the authors extended Low Fat Pointers to also provide stack bounds protection, incurring a 17% overhead when checking only writes. Low Fat Pointers for heap [33] and stack Duck2017 bounds protection were integrated and released as an open source research prototype available at <https://github.com/GJDuck/LowFat>.

Finally, we describe shadow memory approaches. Patil and Fischer [83] implement bounds checking using a second process that follows the execution of the original process. They separate the bounds and lifetime information from the original pointer and use shadow heaps and shadow stacks in the second process to track it. SoftBound [71] tracks bounds information for each memory location that contains a pointer by using a side table. As an example, given a pointer variable, the system tracks the bounds based on the address of the pointer variable. This allows the system to track sub-bounds within objects. The calling convention for values passed in registers is modified to have additional parameters for bounds. SoftBound uses either a hash table or a shadow copy of memory to track the bounds information. The shadow copy of memory generally has better performance. With the shadow copy of memory, SoftBound increases average program execution time for a set of benchmarks by 67%. SoftBound can check only writes, in which case average program execution time increases by 22%. SoftBound increases average memory footprint by 64%, although it can increase it by up to 200%.

MemSafe [96] provides bounds safety and lifetime safety for C. It too tracks bounds information for each memory location that contains a pointer using a side table. It uses capabilities to prevent the use of invalid pointers to access or free memory. It stores capabilities in the side table and keeps a map from valid capabilities to the bounds of the associated objects. MemSafe uses whole-program optimization to optimize dynamic checks, to avoid placing bounds and capability information in the side table, and to avoid tracking capabilities. For 30 programs from the Olden, PtrDist, and SPEC

benchmarks, MemSafe increases average execution time by 88% and average memory usage by 49%.

An alternate approach to dealing with out-of-bounds memory accesses is to use probabilistic techniques that allow programs to tolerate out-of-bounds memory writes. DieHard [7] randomizes the location and spacing of objects on the heap. It allocates a heap at least as twice as large as needed for program data. This causes some out-of-bounds writes to modify memory in gaps between objects. This provides good protection against modest buffer overflows. To protect against out-of-bounds memory reads, programs can be replicated, run in parallel, and text outputs compared. The replicated approach does not work for programs that have non-deterministic output. It is unclear how it would work for programs that are interactive.

9.2 Security mitigations

Security mitigations are another approach to dealing with programs that corrupt memory through out-of-bounds writes or that expose data through out-of-bounds reads. These employ runtime-only mechanisms to detect that memory has been corrupted or to prevent an attacker from taking control of a system after memory has been corrupted.

Attackers can use incorrect programs to attack the security of computer systems in the following ways:

1. Execution of arbitrary code: An attacker may be able to inject arbitrary machine code into a process and have the process execute that code.
2. Control-flow attacks: this a more subtle attack that avoids the need to inject arbitrary machine. An attacker manipulates program state to stitch together execution of a program of the attacker's choosing using existing machine code. For example, in return-oriented programming, an attacker finds segments of useful machine code that end in return instructions. The attacker manipulates the state of the program call stack to execute a series of small pieces of machine code and execute a arbitrary program. There are other ways to manipulate program state to change control-flow, such as changing the target of an indirect function call. This can be done by overwriting a function pointer or the virtual table of an object.
3. Data modification: an attacker may be able to write data to a process, causing the process to take an incorrect action on behalf of an attacker.
4. Data disclosure: an attacker may be able to read data from a process and obtain data, including data that is meant to be confidential.

Security mitigations that have been developed and deployed in practice include data execution prevention (DEP), address-space layout randomization (ASLR), stack canaries, shadow stacks, and control-flow integrity (CFI). DEP, ASLR, and CFI focus on preventing execution of arbitrary code and control-flow modification. Stack protection mechanisms focus on protecting data or return addresses on the stack.

Checked C provides protection against data modification and data disclosure attacks, which the other approaches do not. Chen *et al.* [16] show that data modification attacks that do not alter control-flow pose a serious long-term threat. The Heartbleed attack on OpenSSL illustrates the damage that is possible from even data disclosure attacks.

Checked C addresses the fundamental problem, which is incorrect programs with undetected errors. Checked C enhances existing security mitigations by providing protection against data modification and data modification attacks. ASLR, DEP, CFI, and stack canaries can be defeated by determined attackers using data modification and data disclosure attacks. Shadow stacks do not protect stack-allocated buffers or arrays, heap data, and statically-allocated data.

If a C program and its libraries use only checked pointers and checked arrays and the program is free of pointer type cast or memory management errors, Checked C provides a strong guarantee about memory reads and writes. Any pointer must have been constructed via a series of operations from a pointer to an object. Checked C ensures that the constructed pointer only accesses memory within that object.

Checked C programs remain vulnerable to incorrect pointer type casts, memory management errors, and race conditions that invalidate bounds information. They are also vulnerable to data modification by unchecked code in the same address space.

In the remainder of this section, we review security mitigations that have been deployed in practice. We discuss what they protect against and how they can be defeated by data modification and data disclosure attacks.

Data execution prevention (DEP) relies on hardware and OS-based approaches to prevent attacks that inject machine code into a process and then execute it. At the hardware level, virtual memory support provides a “no execute” bit for each virtual memory page that forbids the execution of instructions located on that page of virtual memory. This bit can be set by default for program stacks and for memory when it is first allocated. A process may have to request specifically that an area of virtual memory be made executable. DEP does not defend against control-flow, data modification, and data disclosure attacks. Control-flow attacks can be used to execute a system call and disable data execution protection.

DEP is deployed widely in production. It has been very successful protecting against “classic” buffer overrun attacks that overwrite stack contents with machine code and also overwrite the return address to jump to the machine code. Hardware support was incorporated into 32 and 64-bit processors for the Intel x86 architecture in 2005 and 2003, respectively. Windows and Linux have supported it from that time as well. For 32-bit programs on Windows, programs must opt-in. That is the default for programs compiled with the Microsoft Visual C++ compiler.

Software can emulate “no execute” support or provide approximations of it when hardware support is not available. Software fault isolation [15, 36, 64, 104, 109] injects checks into machine code, either during compilation or by rewriting binaries. It implements address spaces for fault isolation in software. Software components communicate via remote-procedure calls. Implementing address spaces in software avoids expensive hardware context switches. Wahbe *et al.* [104] describe how execution of data can be prevented by placing code and data in separate areas of memory and checking the targets of indirect jumps. Code running in a software-fault isolated address space, like code running in a hardware-supported address space, is vulnerable to control-flow, data modification, and data disclosure attacks.

ASLR [99, 108] provides protection against control-flow attacks. All major operating systems provide some form of ASLR. In ASLR, code sections from executable files are loaded in random locations in the address space of a process. In addition, data sections, stacks, and dynamically-allocated data are also placed in random locations in the address space of a process. This makes it harder for an attacker to identify the locations of fragments of code to be used in return-oriented programming.

However, ASLR does not protect against data modification or data disclosure attacks. For example, data may be located on the stack adjacent to a variable that is subject to a buffer overrun; the buffer overrun can be used reliably to overwrite or read the data.

ASLR can be compromised by data disclosure attacks. An attacker can obtain the location of a code section by reading data from the stack, for example, and obtaining function return addresses. The attacker can then craft an attack based on that data. A number of proposals suggested finer-grained randomization of code layout [9, 48, 55, 81, 107]. For example, code layout can be randomized at the instruction level or basic-block level. These too are vulnerable to data disclosure attacks [97].

The idea behind ASLR is to use randomization to protect code and data addresses. For randomization of addresses to be effective, it requires hardware architectures that have 64-bit addresses and virtual memory support [94]. With 32-bit addresses, there is typically at most 16 bits of entropy available for virtual memory allocation. Data is allocated at virtual memory page granularities or multiples of virtual memory page granularities and using upper bits fragments the virtual address space, which could cause large virtual memory allocations to fail. This amount of entropy is not enough to defend systems deployed at scale on the Internet. An attacker only needs on average 32,768 probes for one system or conversely 32,768 target systems to compromise one of them through a brute force attack. This limits the usefulness of ASLR in embedded domains where 64-bit address spaces are uncommon.

Another set of ideas is to protect the data that contains code addresses. Some ideas aim to protect against modification; others aim to protect against disclosure of the code addresses. Stack canaries [24, 26, 84] provide some protection against injection of arbitrary code and control-flow attacks. They protect against attacks that modify return addresses on call stacks by overrunning the bounds of a stack-allocated array. This kind of overrun can happen when using C string functions that do not validate parameter lengths, for example. A compiler injects code at function entry points and return points. Entry point code places a token on the call stack next to the return address. Return point code checks that the token has not been modified before executing the return instruction. The value of the token may be computed at run time and selected to have specific properties that aid in the detection of overflow attacks. This form of stack protection is available as a compiler option for the GCC and Microsoft Visual C++ compilers.

Canaries do not provide protection against data modification attacks that modify only the contents of stack-allocated variables, that precisely modify return addresses, or that modify other areas of memory such as the heap and global variables. They also do not provide protection against data disclosure attacks.

An alternative to stack canaries is shadow stacks [1, 6, 9, 17, 21, 36, 41, 56]. With shadow stacks, the stack is split into two stacks. One stack is the secure stack. It is accessible via a dedicated hardware register and placed at a random location in memory. The location of the secure stack is protected against disclosure by guaranteeing that all memory accesses to the secure stack are in bounds. For example, only scalar variables whose addresses are not taken may be stored on the secure stack. In addition, the addresses of locations on the secure stack are only stored on the secure stack. The other stack is the insecure stack. Its location is not protected against disclosure.

In some approaches, the secure stack is used to only hold return addresses. A return address is stored on the regular stack as well and there is a check that the return address is unmodified before doing a return. This incurs an overhead of about 10% because of the cost of having two stacks and checking return addresses [26]. The regular stack can be used as the secure stack and variables that may have out-of-bounds memory accesses or whose addresses are taken can be stored on the

insecure stack [9, 56]. Kuznetsov *et al.* [56] observe that this improves performance because many small stack frames do not even need shadow stack frames. For SPEC CPU 2006 benchmarks, they found that the performance cost ranges from -4.2% to 4.1%, with an average cost of less than 0.1%. They speculate that performance improvements are due to improved data locality for stack accesses from the placement of large arrays on the insecure stack. This form of stack protection is available as a compiler option for the LLVM compiler.

Shadow stacks do not prevent data modification and data disclosure attacks against the insecure stack or other areas of memory such as the heap and global variables. Shadow stacks also have backwards compatibility problems; all code used by a thread must be converted to prevent disclosure of the shadow stack location for the thread.

A shadow stack that uses the regular stack can be attacked in a subtle way, even if all memory accesses to the stack are guaranteed to be in bounds. An attacker can cause a calling convention mismatch, where the caller of a function and the called function disagree on the size of argument data that is passed on the stack or who is expected to make adjustments to the stack pointer. This corrupts the stack pointer, allowing a data modification or data disclosure attack against the shadow stack, including overwriting return addresses [43].

Like ASLR, shadow stacks that use the regular call stack may be vulnerable to brute-force data disclosure attacks on systems with 32-bit addresses. For example, on a 32-bit Windows system, the smallest possible stack size is 64K and the uppermost 1 GByte of virtual address space is not available by default. If an attacker is able to read a byte in memory at an attacker-selected location and the attacker randomly picks the location, an attacker has a 1 in 49,152 chance of reading a byte that is on a virtual memory page that contains a shadow stack location. With reads of nearby locations, an attacker can likely determine if the page containing the byte contains part of a stack.

Control-flow integrity (CFI) also provides some protection against return-oriented programming attacks [1]. CFI adds runtime checks to machine code to ensure that a program follows an approximation of the valid control-flow of the program. There have been many follow-up papers [4, 58, 59, 62, 75, 76, 77, 90, 100, 103, 105, 106, 111, 112, 114, 113]. In the description in [1], a compiler computes the target addresses of each indirect function call and each return instruction. The compiler groups addresses into equivalence classes: addresses are in the same class if they may be the target of the same call or return instruction. This is used to generate unique identifiers for the runtime control-flow check. Many different variants of CFI have been proposed, including coarse-grained CFI implementations that are less precise than the original description [105, 112, 113] as well as fine-grained CFI implementations [100, 106] and even context-sensitive CFI implementations [103]. CFI has been applied in production C and C++ compilers to indirect function calls and not applied to return instructions [42, 60, 67, 100]. Return instructions are protected via other means such as stack canaries or shadow stacks. CFI is implemented in various forms in production versions of the GCC, LLVM, and Microsoft Visual C++ compilers.

CFI does not defend against data modification or data disclosure attacks. It is also vulnerable to data modification attacks. Determined attackers can use a data modification attack to still construct a control-flow attack [14, 20, 38, 43]. The runtime control-flow checks are imprecise because the control-flow graph (CFG) is an approximation of the actual control-flow that is possible for a program. The computed CFG must allow at least all legal executions of a program. In fact it allows invalid executions of a program too. An attacker can take advantage of that difference to control execution of the program via a data modification attack.

CFI is based on the assumption that a precise control-flow graph can be constructed for C and C++

programs. According to Evans *et al.* [38], “this assumption is tenuous at best”. It is difficult to construct a precise CFG for programs with pointers that use function pointers and object-oriented language features. Coarse-grained CFI implementations make the checked CFG even less precise. They do this to reduce the cost of runtime checking or because of difficulties computing a precise CFG. For example, binary rewriting approaches have difficulty precisely computing possible targets for indirect jumps. This allows even more invalid executions. Coarse-grained CFI implementations were first shown to be vulnerable to an attack based on the imprecision of the checks [13, 27, 43]. Fine-grained CFI implementations are also vulnerable to the same kind of attack [14, 38].

Evans *et al.* [38] explain how constructing the CFG relies on a points-to analysis for pointers. Sound and complete points-to analysis is undecidable [85], so points-to analyses implemented in compilers must approximate the actual points-to behavior of programs. This leads to imprecise CFGs in practice.

It is also difficult to construct a precise CFG in the presence of separately-compiled dynamically-loaded libraries [75] or just-in-time compiled code [76]. Tice *et al.* [100] discuss the difficulties of implementing CFI for programs that use dynamically-loaded libraries. Hand-written assembly code also causes problems for constructing a precise CFG.

9.3 Static analysis tools

Static analysis tools are used widely to identify defects in C and C++ programs. The tools take the source code for a program (or, less frequently, binary code) and attempt to find possible bugs. They do so by analyzing the source code for the program. There are many available commercial static analysis tools available for C and C++, including CodeSonar, Coverity Static Analysis, HP Fortify, IBM Security AppScan, Klocwork, Microsoft Visual Studio Code Analysis for C/C++, and Polyspace Static Analysis [8, 12, 35]. These tools find many different kinds of bugs, including out-of-bounds array accesses.

Static analysis tools use several different approaches to identify bugs, including dataflow analysis [3, 95], simulating program execution [12], abstract interpretation [23], and model checking [57]. At a high level, they build a model of the program and prove properties about the model. This is a large area of study and describing it is well beyond the scope of this related work section. We focus only on how Checked C relates to static analysis tools.

Static analysis tools are imprecise. They may report that a program may have a defect, when it does not have that defect. The imprecision is inherent in static analysis. Deciding whether a program has a specific defect is undecidable in general. When a static analysis tool reports that a program has a defect and it does not, that is called false positive.

False positives are a significant problem for static analysis tools. Programmers need to spend time investigating them and consider it a waste of time when they discover that a “bug” is not actually a bug. Future runs of the tool still report the potential defect, so programmers need to suppress or ignore the defect. More problematically, programmers cannot distinguish easily between false positives and true positives, so they ignore or suppress genuine bugs [8]. Tools themselves may suppress error messages for true positives to avoid too many false positives.

Most static analysis tools make unsound assumptions about C programs. For example, they may inspect only a limited number of paths through a function [12]. They may also assume that signed

integer arithmetic expressions in C do not overflow. This is because it would be very difficult to prove in general that C arithmetic stays within bounds.

There are a few sound static analysis tools that aim to detect all possible out-of-bounds memory accesses in C programs with few false positives. Astrée [2, 10, 28] and Polyspace Code Prover [63] use abstract interpretation and other static analyses to diagnose possible integer overflows, division-by-zero, and out-of-bounds pointers in embedded C and C++ software. They can be used to show that a program is free from runtime errors. They each produce output that classifies code as free of runtime errors, definitely faulty, definitely unreachable, or possibly containing a runtime error. They are “black boxes”: a programmer must trust the output of the tool. In the case of Astrée, extensive detail about its analyses are available, but one must still trust its implementation. In the case of Polyspace, details about the analyses are not available.

To summarize, static analysis tools may miss errors and report errors that do not exist or errors that are ignored by programmers. They also function as “black boxes” not subject to independent verification.

Checked C occupies a different design point than static analysis tools. It provides a way to write C code that is guaranteed to be bounds-checked. It does not miss bounds errors for checked pointer types and it does static checking of bounds information in a sound fashion for sequential C programs. Checked C avoids problems with false positives by deferring bounds checks to runtime. It minimizes the information that must be checked statically by limiting it to bounds information. For cases where bounds checking failures are unacceptable, it allows programmers to opt-in to completely static checking. Finally, the checking is done using rules that are part of the language definition.

9.4 Program verification

Static analysis tools take programs “as is” and try to prove facts about them. Sound static analysis tools that produce no or few false positives act as program verifiers, of course. Program verification adds a specification of program behavior and programmer involvement in constructing a proof that the program satisfies the specification. Program verification efforts range in practice from simple efforts to show that a program is free from runtime faults to costly efforts to show full functional correctness.

Checked C aims at a level that does not even exist for most higher-level languages, where bounds checking is a built-in part of the language implementation. The goal is to show that information for checking runtime faults (that is, bounds information) is correct. Checked C also aims to support showing parts of programs are free of bounds failures or null check failures for performance or correctness reasons.

Extended static checking [39] aims to show that programs are free of runtime errors such as null check failures and array bounds errors and free of concurrency errors. ESC/Java [39] uses a modular checking approach where parts of the program (methods) are checked individually. This enables the checking to scale to large code bases or separately-compiled code. In ESC/Java, a programmer adds annotations in first-order logic to Java programs to specify invariants that assist in showing the correctness of programs. ESC/Java generates verification conditions for functions that imply that statements with runtime checks in the functions will not fail. It then invokes a theorem prover to attempt to show that the verification condition is true. The theorem prover may construct a proof,

construct a counterexample, or not terminate within a desired time bound. ESC/Java is unsound; it ignores integer overflow, for example.

Checked C, like ESC/Java, uses a modular checking approach. It checks individual functions. Checked C is intended to be sound for single-threaded programs. Unlike ESC/Java, Checked C uses a propositional logic, instead of a first-order logic. Checked C does not have quantifiers such as “forall” and “there exists” in the language of program invariants. This means that some statements about data structures cannot be expressed in Checked C. Because Checked C uses a propositional logic, it is decidable whether program invariants for Checked C functions are true. The variables used in the propositional logic range over finite-sized integers. Even though checking is decidable, it is NP-complete. Checked C uses a heuristic-based approach to check program invariants in reasonable time. Some program invariants that are true will not be shown to be true.

Checked C proposes extending C with types and static checking to ensure that pointer and array accesses are always in-bounds or checked to be in-bounds. An alternate approach would be to use a general-purpose program verifier. A C program would be annotated using program invariants about bounds and a theorem prover could be used to verify that pointer and array accesses are always in bounds or checked to be in bounds. Two program verifiers for C are Frama-C [40] and EscherC [37].

There are two issues with using this approach. First, it changes how software development is done by adding a theorem prover to the development process. This loses the immediacy of having the checking integrated into the compiler. Theorem provers are slow and prone to long running times and time outs. Second, most languages with bounds checking rely on runtime checking. It is difficult to prove that code always stays in bounds. The runtime checking would have to be inserted by the programmer at every use of a pointer produced via pointer arithmetic, making programs more verbose and requiring sweeping changes.

9.5 Programming languages

A number of programming languages include pointer types and the ability to do pointer arithmetic. This includes languages designed for system programming such as D [31] and Rust [88], as well as languages that can be used for system programming if garbage collection is acceptable, such as Go [44] and C# [66]. These languages strongly discourage the use of “raw” pointer types because of the potential for error. For example, in C# and Rust, raw pointer types can be used only in `unsafe` blocks. Checked C shows how these languages might be extended to support checked pointer operations.

The Cyclone, CCured, and Deputy projects have proposed new type-safe dialects of C. Cyclone [51] is a dialect of C that restricts C and also extends it. The goal is to create a type-safe system programming language. Cyclone has language changes that break existing C programs and cause them to no longer compile. For example, Cyclone does not allow pointer arithmetic on unchecked C types. In contrast, Checked C supersedes C. This makes it possible to use Checked C extensions incrementally, while Cyclone requires that a program to be converted in its entirety. Cyclone changes the representation of pointer types that allow arithmetic. It introduces a new pointer type that carries bounds information with it, similar to the `span` type described in Section 11.2 that we considered adding to Checked C. This causes compatibility problems when interoperating with existing code. Checked C allows programmers to declare bounds information separately from pointers using `array_ptr` types. Cyclone also changes memory management in C. It extends C with

regions to allow arena-based memory management. Checked C is addressing the safety problems in C one at a time, starting with bounds checking.

CCured [73] uses whole-program static analysis to identify different uses of pointers in C programs. It identifies pointers that are used to read or write values only (safe pointers), pointers that are used in pointer arithmetic also (sequence pointers), and pointers that are involved in possibly non-type safe casts (wild pointers). It uses a multi-machine word representation for sequence pointers and wild pointers. It also changes the representation of data pointed to by wild pointers. This changes data layouts and causes interoperability problems.

Deputy [19, 115] extends C with dependent types to avoid runtime layout changes for pointers involved in pointer arithmetic. Checked C is directly inspired by Deputy, although Checked C uses program invariants instead of dependent types to track bounds information. The dependent types in Deputy allow the bounds of the pointers to be specified as part of the types of the pointers and the bounds to depend on runtime values. Deputy requires programmers to annotate function parameters, data structures, and global parameters with dependent types. It then infers dependent type annotations for local variables and adds runtime checks to make the dependently-typed program type check. The runtime checks enforce that pointer values stay in bounds. The checks apply to pointer arithmetic and pointer dereferencing.

A dependent type is a type that may depend on a value at runtime. Dependent types are built using type constructors that are applied to types and values. The type constructors capture specific properties of runtime values. For example, Deputy introduces a type constructor `—Array—` that can be applied to an integer value (the length of the array) and an element type. `—Array 5 int—` describes the type of integer arrays with 5 elements. The `—Array—` type constructor can be applied to a program expression, so the type can depend on a runtime value. For example, `—Array n int—` describes the type of integer arrays with n elements.

There are several problems with using dependent types in C. First, dependent types are a big change to the C type system and C type checking. Dependent types are an abstract concept that may be hard for many programmers to understand. Second, even if programmers can understand dependent types, it makes type checking a complicated exercise. To type check a dependently-typed statement, the type checker must prove that certain runtime invariants are true before the statement. To illustrate this, consider the type checking rule for variable assignment from [19]. This rule requires that the type checker prove that certain invariants must be true at runtime before the statement. Type checking becomes entangled in general reasoning about program invariants. Finally, using dependent types makes programs verbose: explicit checks to enforce bounds safety have to be inserted throughout the code. There are no widely-used languages with array-bounds checking that requires this level of verbosity. In Java and C#, the checks are done implicitly. This is the case in older languages such as FORTRAN and Pascal, as well. For these reasons, Checked C uses program invariants instead of dependent types.

The C11 Standard supports variable-length arrays optionally. This is a form of dependent type. However, type checking for variable-length arrays in C is weak. It does not enforce that runtime values for lengths in types are equal. Program behavior is undefined if two variable length array types are supposed to be compatible and their length expressions differ at runtime [50, Section 6.7.6.2]. In addition, C ignores the variable length for function parameters. The current support for variable-length arrays does not set a precedent for using dependent types to represent bounds information in C.

Havoc [18] goes beyond Deputy and allows types to be combined with program verification. It

allows a programmer to specify program invariants that imply type safety and can verify these invariants statically. It can handle unsafe code such as using a pointer to a field to access a prior field in a data structure. Havoc shows that it can be very difficult to show the type safety statically of low-level system code. The code may be type-safe at runtime and a programmer may intuitively know that it is type-safe. However, writing down the invariants may be hard and may require deep knowledge of program verification techniques. For this reason, Checked C adopts an opt-in model for bounds checking, where code can be incrementally modified to use bounds checking.

Yarra [92] proposes an extension to C to prevent data modification and data disclosure attacks involving important data. Programmers can declare types as “critical” types. All other types are “non-critical” types. A pointer to a critical type T can be used to access only objects with runtime type T . Conversely, pointers to non-critical types cannot be used to access critical objects. The locations and types of objects of critical types are tracked at runtime. Runtime checks protect critical objects from modification by out-of-bounds memory writes. If the source code for a program and the libraries it uses are available, they can be recompiled with runtime checks at every memory access. Yarra places objects of critical type in separate areas of memory from non-critical types. For calls to unmodified libraries, Yarra uses virtual memory protection to prevent the libraries from accessing critical data.

Failure-oblivious computing [86] proposes a different approach for handling out-of-bounds memory accesses than what is proposed for Checked C. With Checked C, the program will be terminated or an error handler will be invoked. If the program terminates, this converts data modification and data disclosure attacks to denial-of-service attacks. Rinard *et al.* suggest discarding out-of-bounds writes and converting out-of-bounds reads to small integer values, cycling through a sequence of small integer values. They implement the runtime bounds checking suggested by [89] and show that their approach improves the availability of servers with memory corruption errors.

Chapter 10

Pending work and open issues

This chapter discusses work that needs to be done and open issues.

10.1 Pending work

This section describes work that should be done soon because it is needed for completeness or to simplify writing code:

- For structures, add wording that allows a single statement to update a variable member whose member bounds is expected to hold after the statement. Also add wording to allow a bundle block to do this.

10.2 Language and library features to be addressed

- Variable arguments
- We require initializers for variables that have checked pointer types that may be used to access memory. We also require initializers for variables that have members or elements that have checked pointers and that may be used to access memory. We want to relax this requirement so that fewer program changes are needed when porting legacy code to Checked C. We plan to allow delayed initialization by adding a *definite initialization* analysis similar to those for C# or Java for variables or members with checked pointer types. In programs for those languages, a variable may be declared without an initialization value, as long as it is definitely initialized before it may be used. A dataflow analysis prescribed by the language definition is used to determine when a variable is definitely initialized.
- Pointer casts that produce incorrectly aligned pointers have undefined behavior, according to the C11 standard. This hole should be filled in for checked pointer types. For checked pointer types, we should specify either (1) dereferencing an incorrectly aligned pointer shall cause a runtime error or (2) the cast itself shall check any alignment requirements. For case 1, note that pointer arithmetic for checked pointer types is already defined to preserve misalignment.

10.3 Concrete syntax

The current syntax for describing post-conditions places a `where` clause after the function parameter list declaration:

```
f( ... )
where cond1 ...
```

This syntax might lead to confusion. We might want to adopt an alternate syntax that makes this clearer. Some suggestions are the keywords `on_return` or `after`:

```
f( ... )
on_return cond1 ...
```

```
f( ... )
after cond1 ...
```

Section 11.1 describes alternate syntax proposals for pointer types.

10.4 Further out work

- Allow conditional bounds expressions. While conditional expressions are allowed in the non-modifying expressions in a bounds expression, there is not a conditional form of bounds expressions. This is useful for specifying that an expression only has bounds if some condition is true. This could be provided by adding a clause to bounds-exp that uses the same syntax as C conditional expressions:

```
bounds-exp :
    non-modifying-exp ? bounds-exp : bounds-exp
```

We would need to add descriptions of introduction and elimination forms, as well as enhance the rules for checking the validity of bounds.

- Allow bounds declarations to declare bounds for expressions. This would allow the system to easily support tagged null pointers. The bounds for the untagged pointer would be described. A tagged pointer could not be used to access memory. It would have to be untagged first to have valid bounds.
- Consider whether to allow functions to be parametric with respect to the state of member bounds. This might be useful to describe a function that sets one of the members of a structure type and does not affect the state of other members.
- We could allow signed integer expressions to be invertible by trying to prove that the expressions are in range, using the checking of facts in `where` clauses.

Chapter 11

Rejected design choices

This chapter describes design choices that we considered and rejected. A separate chapter is useful for three reasons. First, it makes it easier to learn the existing design because there is less to read. Second, it provides reasons for why the current design choices were made. Third, as we gather experience with the current design, we may want change the design choices that we made. This chapter provides a starting point of alternative designs. For example, support for non-relatively aligned pointers originally started in this chapter as a rejected design choice. After looking at OpenSSL code that used pointer casts, we changed our mind and incorporated the material into the main design.

11.1 Alternate syntax for pointer types

Instead of using the C++ template instantiation syntax, we considered allowing the new pointer names to be used in place of *. For example, given a declaration of the form `int *pi;`, this could be changed to declare a `ptr` to an integer by substituting `ptr` for *, producing `int ptr pi;`.

This seems to make code less readable. This is apparent for type names that consist of several words: `const unsigned int ptr g` is more difficult to parse quickly than `ptr<const unsigned int> g`. The use of symbols like < and > can be recognized visually more quickly than the use of an identifier.

Another possible approach is to treat the new kinds of pointer types as new modifiers for pointers. For example, `int * ptr pi;` would declare a `ptr` to an integer. This is also difficult to parse and makes code even more verbose.

A drawback to using C++ template instantiation syntax is that it interacts poorly with mixed C declarators. In the syntax of C declarators, * is used as a prefix to an identifier to modify the type of an identifier. A mixed declarator is a declarator where different identifiers have different types because of different modifiers. An example of a mixed declarator is the declaration `int i, *pi;`. The C++ template instantiation produces a type, so “mixed” declarators must be broken across multiple lines instead. The resulting declarations would be `int i; ptr<int> pi;` On the other hand, non-mixed declarators are fine: `int *pj, *pi;` becomes `ptr<int>pi, pj;`.

11.2 Span pointer types

We considered introducing a type called `span` for pointer types that carry their bounds with them dynamically. We decided to postpone this for now because `span` is a type that seems appropriate to be defined in a library. The `span` type can be implemented using `array_ptr` types, but not *vice versa*. The main issue is that C does not provide support for generic types. Indeed, in C++, which has templates, a `span` type has already been proposed for the C++ Standard Library [61]. While the name `span` is new, the idea of a span type itself dates back to the early days of computer science. A `span` is an instance of a dope vector, which is a data structure that describes the shape of an array. Dope vectors were used in implementations of ALGOL60 [91].

In our proposal, a `span<T>` pointer would carry three values with it: the memory location that will be accessed by dereferencing the `span<T>`, a lower bound on the memory that can be accessed via the current pointer value, and an upper bound on accessible memory. Those values can be accessed using the `.` operator combined with the special field names `current`, `lower_bound`, and `upper_bound`. The resulting values have the type `array_ptr<T>`. The special field names can only be read and cannot be modified by assignments.

```
span<int> p = ...
array_ptr<int> low = p.lower_bound;
array_ptr<int> high = p.upper_bound;
array_ptr<int> current = p.current;
```

The operations on a `span` would be similar to those on `array_ptr`, except that the dynamic bounds values would be used:

- Indirection: the `*` operator could be applied also to a value of type `span<T>`. It would produce a value of type `T`
- Array reference: the `[]` operator could be applied also to a value of type `span<T>`. `e1[e2]` is equivalent to `*(e1 + e2)`.
- Pointer arithmetic: adding or subtracting a value of `span` pointer type and an integer would be allowed. Pointer arithmetic overflow would be considered a runtime error.

A `span<T>` value would be created by casting a value of another pointer type to the `span<T>` type. A value of another pointer type could be converted implicitly to an `span<T>` in situations where a `span<T>` value is expected, the referent type of the other pointer type is `T`, and the bounds of the value can be determined automatically.

For example, a variable of array type could be converted automatically to a `span`. First, the array type would be converted to a pointer type of either `T *` or `array_ptr<T>`, depending on whether the array type is checked or unchecked. This pointer type would then be converted to an `span<T>`. The bounds of a variable of array type are easily determined at compile time, so the pointer type would then be converted to an `span<T>`:

```
int x[10]
span<int> p = x;
// p.current = x; p.lower_bound = x; p.upper_bound = x + 10;
```

Similarly, an `array_ptr` value with declared bounds can be converted implicitly to a `span` value:

```
array_ptr<int> src = ...
span<int> p = src;
```

The operators for casting in Section 5.1 would be expanded to have rules that treat `span` values similarly to `array_ptr` values.

Having `span` values carry lower bounds is an important difference between our proposal and the C++ proposal. In the proposed C++ design, `span` values carry counts of elements. The C++ proposal does not support decrementing the `span`. For symmetry with `array_ptr`, we think it would be important in the Checked C extension that `span` values carry lower bounds.

11.3 Removing relative alignment

We considered removing the concept of relative alignment from the design in order to simplify the design. Relative alignment is described in Sections 2.9 and 3.9. If relative alignment is removed, however, compilers have to assume that bounds and pointers are not relatively aligned. This would result in more costly bounds checks and more bounds checks in optimized code.

Checks against upper bounds would take several more instructions. Given a pointer p to type T , $*p$ accesses the memory from p to $p + \text{sizeof}(T) - 1$. Given an upper bound ub , the upper bounds check for p becomes $p + \text{sizeof}(T) - 1 < ub$, not $p < ub$. The computation of $p + \text{sizeof}(T) - 1$ would need an overflow check also, so several extra instructions would be added to an upper bounds check, not just an extra addition.

There would also be more bounds checks because it would be harder for compiler optimizers to eliminate upper bounds checks in loops. Most programmers would write code that strides through an array using a comparison that $p < ub$. The comparison $p < ub$ does not imply $p + \text{sizeof}(T) - 1 < ub$, so the comparison is not sufficient for a compiler to optimize away the upper bounds check. A compiler would have to know that a pointer and bounds are relatively aligned in order to eliminate the upper bounds check. It would be hard for a compiler to prove this because it would require interprocedural or whole-program analysis.

11.4 Address-of operations and array-to-pointer conversions always produce checked pointer types

We considered a design where the address-of operator (`&`) and array-to-pointer type conversions always produce checked pointer types. To preserve compatibility with existing C code, we would introduce implicit conversions from checked pointers to unchecked pointers. We found that we were not able to preserve backwards compatibility for the address-of operator and that implicit array-to-pointer conversions required bounds checking.

11.4.1 Address-of operator rules

The address-of operator (`&`) applied to an lvalue expression of type T would produce a value of type `ptr<T>`.

Existing C code expects the address-of operator to produce a T^* . To allow most code to compile without changes, we add an implicit cast rule: `ptr<T>` can be cast implicitly to a T^* in those situations where a T^* type is expected, except for pointer arithmetic operators that add or subtract

a pointer and an integer. Those situations include pointer assignment, arguments to function calls, return statements, and conditional expressions. In all these situations a $T *$ type must have been declared explicitly in the code already, so this implicit cast does not introduce unchecked pointer types where none existed before.

Pointer arithmetic operators are excluded to avoid the silent introduction of unchecked pointer types and to preserve the value of having the `ptr<T>` type. If there were always an implicit cast from `ptr<T>` to $T *$, then any expression that uses pointer arithmetic could do pointer arithmetic on `ptr<T>` values.

Code takes the address of an array element and immediately does pointer arithmetic will still fail to type check, introducing a potential backward compatibility issue:

```
f(void)
{
    int a[10];
    int *x = &a[0] + 5; // &a[0] has type ptr<T>. Pointer arithmetic is
                        not allowed
    ...
}
```

We expect this kind of code to be rare because the succinct style is to use `a` instead of `&a[0]`, but it is nonetheless a possibility, so this proposal still violates the principle of not changing the meaning of existing C code.

```
f(void)
{
    int a[10];
    int *x = ((int *) &a[0]) + 5; // redundant but OK under old rule
    ...
}
```

11.4.2 Array-to-pointer conversion rules

Array types may be complete or incomplete. A complete array type specifies the number of elements in the array using a constant expression. In incomplete array type does not specify the number of elements in the array. Examples of complete array types are `int[10]` and `int[10][10]`. Examples of incomplete array types are `int[]` and `int[][10]`.

If the type of an expression or a subexpression is an “array of T ”, the following rules would apply. If the array is a complete type, the type of the expression is altered to `array_ptr<T>`. If it is an incomplete type, the type of the expression is altered to $T *$. This alteration does not happen if the expression is an operand of an address-of operator, `++`, `--`, `sizeof`, or the left operand of an assignment operator or the `.'` operator.

These rules would have an interesting effect for arrays of complete types: all array references involving those arrays would be bounds checked. Any address computations involving those arrays will be checked for overflow also. Because the existing C language definition leaves out-of-bounds access of arrays of complete type undefined, as well as the meaning of overflowing address computations undefined, this is compatible with the existing C language definition.

However, these rules by themselves are problematic for existing C code. It is common in C code to use array types interchangeably with pointer types. The rule that complete array types are converted to `array_ptr` types could cause problems for such code

```
f(int *arg, int len)
{
    ...
}

g(void) {
    int x[10];
    f(x, 10);
}

h(void) {
    int x[10];
    int *ptr = x;
    f(ptr, 10);
}
```

To allow existing code to continue to compile unchanged, we adopt the rule that an `array_ptr<T>` can be implicitly cast to a `T *` in situations where a `T *` type is expected. Those situations may include pointer assignment, arguments to function calls, return statements, and conditional expressions. For conditional, expressions of the form `exp1 ? exp2 : exp3`, the implicit coercion occurs when `exp2` or `exp3` has type `T *` and the other expression has type `array_ptr<T>`. These situations do not include array references and adding or subtracting a pointer type and an integer. `array_ptr<T>` is an acceptable type for those operations and a coercion to `T *` is not needed.

We allow `array_ptr` values to not be within bounds. Because of this, any implicit conversion of an `array_ptr` value with a bounds to an unchecked pointer type must be bounds checked. Otherwise, it is easy to write “checked” code that creates undetected buffer overruns:

```
// f looks like it is correct, but does something bad that is
// undetected before calling unchecked code
f(array_ptr<int> p where p : bounds(p, p + 10))
{
    // first argument implicitly converted to int *
    poke(p + random_large_value(), 31415);
}

void poke(int *p, int val)
{
    *p = val
}
```

The silent introduction of a bounds check at a call to a method violates the design principles of control and clarity. The implicit conversion introduces an invisible failure point in a program where one does not otherwise exist. Pointer arithmetic is not normally bounds checked, so it is not expected fail.

11.5 Alternate bounds for the address-of operator applied to a pointer dereference

The bounds for $\&*e$ are defined to be the bounds of e in Section 4.2.3. We considered using narrower bounds for $\&*e$ of `bounds(e , $e+1$)`, where the bounds describe memory containing only a single value. We rejected this choice for two reasons.

First, the narrower bounds use e . This is a problem because expressions used within bounds expressions must be non-modifying expressions. These are a subset of C expressions that do not modify variables or memory. The expression e might not be a valid non-modifying expression, in which case there would be no way to write the narrower bounds expression. We could try to restrict $\&*e$ so that e must be a non-modifying expression. We do not know the extent of changes that this could require in existing C programs.

Second, the meaning of $\&*e$ is ambiguous in C. This ambiguity often arises when programmers take the address of array elements: `& $e1$ [$e2$]` is a synonym for `&*($e1+e2$)`. It is not clear whether programmers mean to refer to single elements or multiple elements of arrays. In some cases, programmers mean to refer to only single elements:

```
void swap(int *p, int *q) {
    tmp = *p;
    *p = *q;
    *q = *tmp;
}

void f(void) {
    int arr[5] = {0, 1, 2, 3, 4};
    swap(&arr[0], &arr[5]);
}
```

In other cases, programmers mean to refer to a range of elements:

```
int sum(int *start, int count) {
    int total = 0;
    for (int i = 0; i < count; i++) {
        total += start[i];
    }
    return total;
}

void f(void) {
    int arr[5] = {0, 1, 2, 3, 4};
    sum(&arr[3], 3);
}
```

C provides no way to differentiate between the two cases. This leads us to choose the more general bounds (the wider bounds). A programmer can always narrow the bounds if desired. The converse is not true.

Some programming languages provide the notion of array slices and have syntax for slices. An array slice is a sub-section of an array with a designated beginning and ending. However, extending C with new syntax for array slices would violate the design principle of minimizing changes to C.

11.6 Alternate semantics for bounds declarations

There are a variety of possible semantics for bounds declarations. A bounds declaration has the form:

```
x : bounds-exp

bounds-exp:
    count(non-modifying-exp)
    bounds(non-modifying-exp, non-modifying-exp)
    bounds(unknown)
    bounds(any)
```

It may be attached to declarators, parameter declarations, or assignment statements:

```
init-declarator:
    declarator inline-bounds-specifieropt where-clauseopt
    declarator inline-bounds-specifieropt where-clauseopt = initializer where-clauseopt
    ...
```

```
parameter-declaration:
    declaration-specifiers declarator
    inline-bounds-specifieropt where-clauseopt
```

```
expression-statement:
    expressionopt where-clauseopt;
```

The information in the bounds declaration is used at pointer dereferences involving either (1) the variable or (2) pointers constructed from the value of the variable.

One design choice for bounds declarations is when bounds expressions are evaluated. In the design, evaluation of bounds expressions is *deferred* until bounds checks. The bounds expressions could be evaluated *eagerly* at the point of the bounds declarations.

If bounds expressions in a bounds declaration $v : e$ are evaluated eagerly, they must be evaluated only when v is non-null. If v is null, the bounds might not be meaningful. This keeps eager evaluation from causing accidental runtime failures when null values are encountered.

Consider the code for the use of `malloc`. With eager evaluation, the bounds expressions in `bounds(result, result + size)` would not be evaluated if `malloc` returns `null`:

```
array_ptr<int> result = malloc(size) where result : bounds (result, result
    + size);
if (result != NULL) {
    ... *result = ...
}
```

We considered eager evaluation, but rejected it because it would turn `array_ptr` types into `span` types. When bounds expressions are always eagerly evaluated, the results need to be stored somewhere so that they can be used when v is used. For local variables, hidden temporary variables could be introduced. This breaks the design principle of not introducing hidden costs, though. To avoid introducing hidden costs, the semantics of `array_ptr` types could be changed so that they carry their bounds with them. This just turns `array_ptr` types into `span` types. For structures, introducing

hidden state or converting `array_ptr` types to `span` types is especially problematic because it breaks data layout compatibility.

For these reasons, we think it is better to think of bounds declarations as being program invariants describing the bounds of variables. Normally, program invariants are not evaluated at runtime. However, in the case of pointers, the program invariants are used to provide bounds safety at runtime.

Deferred evaluation of bounds expressions has issues, too, though. First, there can be problems if a programmer modifies a variable used in a bounds expression within the extent of a bounds declaration. Static checking could fail if the bounds declaration no longer holds. These would be unexpected errors for C programmers. Second, it is a new concept for C programmers that could cause confusion. We recommend a study of programmers to evaluate the difficulty of learning the concept.

Because bounds declarations constrain assignments to variables within the scope of the bounds declarations, we considered several alternate definitions of bounds declarations. First, we considered not having lexically-scoped bounds declarations and just having flow-sensitive bounds declarations. Flow-sensitive bounds declarations are more subtle to understand, though, while lexically-scoped bounds declarations can be understood at a glance. We decided to keep lexically-scoped bounds declarations because they are simpler to understand and allow bounds invariants to be declared that always cover a set of statements. In contrast, with only flow-sensitive bounds declarations, a programmer might need to redeclare the bounds invariant at assignments to variables that occur in the bounds declaration. This could lead to verbose code, something C tries to avoid, and it could also be error-prone.

We considered the opposite approach of having only lexically-scoped bounds declarations. However, this introduces the opposite problem of redeclaring invariants. A pointer variable could not have different bounds declarations at different points in the program. This could make modifying existing C code to be bounds-safe more complex: an existing variable might need to be replaced with several new variables.

Finally, we considered several alternate definitions of the extent of a flow-sensitive bounds declaration for a pointer variable:

- Defining extent to be the set of statements up to the first assignment to any variable occurring in the bounds declaration. This is a “minimal” notion of extent. It removes the special case for pointer increment and decrement, so bounds declarations would be required at those statements. We believe the special case will lead to more succinct code, so we chose to keep it.
- Defining extent to be all the statements between the bounds declaration and the next bounds declaration for the pointer variable or the last use of the pointer variable. This is a “maximal” notion of extent. We thought this case might lead to surprising error messages when modifying existing code. In particular, with this definition, extending the lifetime of a pointer variable could lead to errors at assignments within the new part of the lifetime, specifically assignments to variables that occur in the bounds declaration. The current definition is more conservative. It could produce errors only at new uses of the pointer variable or assignments in the new part of the lifetime that increment or decrement the pointer variable.
- Adding special cases to the current definition beyond pointer increment and decrement.

We believe that we need experience using flow-sensitive bounds declarations to choose between these different possible definitions of extent.

11.7 Allowing pointer variables to be assigned values with no relationship to their bounds

We considered allowing pointer variables to be assigned pointer values not derived in some way from the object with which their bounds are associated. The idea would be to avoid unnecessary restrictions on operations involving pointers.

In this approach, the meaning of a bounds expression would be defined differently than that given in Section 3.1. The meaning would be the following. Given an expression e with a bounds expression `bounds(lb , ub)`, let the runtime values of e , lb , and ub be ev , lbv , and ubv , respectively. If ev is not null, there will always exist some object at runtime with the bounds (low , $high$) such that $low \leq lbv$ & $ubv \leq high$. In other words, the requirement is that expression bounds are always a subrange of the range of memory for some valid object. This is provided that the value of the expression with which those bounds are associated is non-null.

The problem with this approach is that it has unexpected consequences for the bounds that can be declared for pointer variables. Any valid pointer bounds could be declared for a variable because there is no longer a requirement that a pointer stored in the variable be derived from a pointer to the object associated with the bounds. The following example would be valid:

```
array_ptr<int> x : count(5) = malloc(sizeof(int) * 5);
array_ptr<int> y : bounds(x, x + 5) = malloc(sizeof(int) * 2);
```

This makes it more likely that programming errors involving bounds declarations are detected only at runtime. We did not pursue this approach further for this reason.

11.8 Function pointer casts

The rules in Section 5.1 for casting between function pointers require that the bounds declarations on parameters and return values be identical after conversions to canonical forms. It is possible to have more general rules around function pointer casts, at least from a checking perspective.

For example, a function that expects an `array_ptr` with 5 elements can always be used in place of one that expects an `array_ptr` with 10 elements. This implies that a function pointer that expects an `array_ptr` with 5 elements can be cast to a function pointer that expects an `array_ptr` with 10 elements. Similarly, a function that returns an `array_ptr` with 10 elements can always be used in place of a function that returns an `array_ptr` with 5 elements.

More generally, a function with weaker preconditions can be used in place of one with stronger preconditions. A function with stronger post-conditions can be used in place of a function with weaker post-conditions.

We chose not to generalize the rules for function pointer casts until we have evidence from real-world experience that the generalization is needed. It is likely that we will need to add support for weaker preconditions and stronger post-conditions for `where` clauses on casts to function pointer types, to avoid surprising programmers. It is unclear whether this would be useful in practice for bounds declarations on pointer types, or only of theoretical interest.

11.9 Null pointers and bounds expressions

The meaning of bounds expressions is conditional on values not being null. From Section 3.1:

At runtime, given an expression e with a bounds expression `bounds(lb, ub)`, let the runtime values of e , lb , and ub be ev , lbv , and ubv , respectively. The value ev will be 0 (null) or have been derived via a sequence of operations from a pointer to some object obj with `bounds(low, high)`. The following statement will be true at runtime: $ev == 0 \vee (low \leq lbv \wedge ubv \leq high)$.

If ev is null, the bounds may or may not be valid. This creates a problem. Pointer arithmetic cannot be allowed on null values. If it were allowed, then $e : \text{bounds}(lb, ub)$ would not imply $e + k : \text{bounds}(lb, ub)$, where k is a non-zero constant. Consider the counterexample where ev (the runtime value of e) is 0. For the first bounds expression, $ev == 0 \vee (low \leq lbv \wedge ubv \leq high)$ is true. For the second bounds expression $ev + k == 0 \vee (low \leq lbv \wedge ubv \leq high)$ must be true. We know that $ev + k == 0$ is false, so that means that the first bounds expression must imply that $low \leq lbv \wedge ubv \leq high$ is true. However, it does not: $A \vee B$ does not imply B .

This is handled in the design by using runtime checking to prevent pointer arithmetic involving null pointers. However, this produces an odd result. A pointer variable can have bounds that are always valid because they correspond to an actual object. The value for this pointer variable cannot be moved using pointer arithmetic to null and then to another value besides null.

There is no way in the current design to express that a variable has bounds that are always valid. This could be addressed with a new bounds expression:

bounds-exp:
`object_bounds(bounds-exp, bounds-exp)`

The meaning of this bounds expression would be defined as follows:

At runtime, given an expression e with a bounds expression `object_bounds(lb, ub)`, let the runtime values of e , lb , and ub be ev , lbv , and ubv , respectively. The value ev will have been derived via a sequence of operations from a pointer to some object obj with `object_bounds(low, high)`. The following statement will be true at runtime: $low \leq lbv \wedge ubv \leq high$.

In other words, the bounds are always valid. This implies that any access to memory where $lbv \leq ev \wedge ev < ubv$ will be within the bounds of obj .

The meaning of $e : \text{bounds}(lb, ub)$ could be defined as $e == 0 \vee \text{object_bounds}(lb, ub)$. `object_bounds(e1, e2)` would imply `bounds(e1, e2)`. Conversely, if some value v has `bounds(e1, e2)` and v is not null, this would imply `object_bounds(e1, e2)`.

For variables and expressions with an `object_bounds` bounds expression, runtime checks for null pointer arithmetic would not be necessary.

It would be problematic to use `object_bounds` widely for C function arguments. Implicit in many uses of `object_bounds` would be an assertion that the parameter to which it is being applied non-null pointer. Consider:

```
f(array_ptr<int> x : object_bounds(x, x + 5) {
    array_ptr<int> y = x + 1;
```

```
    ...  
}
```

This risks dividing C functions into those that can take null pointer arguments and those that only take non-null pointer arguments. In our experience, requirements that pointers not be null tend to propagate virally throughout code bases. If an entire code base can be converted, this can work well. Otherwise, it results in messy dynamic checks for non-nullness in code. Now, it is possible with lightweight invariants and `dynamic_check` that such checks would not be messy.

The existing practice in C is that null pointers are widely used interchangeably with non-null pointers. This introduces uncertainty about the usefulness of this feature for C code bases. The runtime benefit of eliminating non-null checks in pointer arithmetic is likely small. Following the principal of minimality, we have rejected the design choice of adding `object_bounds` for now.

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