SafeStrings
Representing Strings as Structured Data

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Strings are ubiquitous in code. Not all strings are created equal, some contain structure that makes them incompatible with other strings. CSS units are an obvious example. Worse, type checkers cannot see this structure: this is the latent structure problem. We introduce SafeStrings to solve this problem and expose latent structure in strings. Once visible, operations can leverage this structure to efficiently manipulate it; further, SafeStrings permit the establishment of closure properties. SafeStrings harness the subtyping and inheritance mechanics of their host language to create a natural hierarchy of string subtypes. SafeStrings define an elegant programming model over strings: the front end use of a SafeString is clear and uncluttered, with complexity confined inside the definition of a particular SafeString. They are lightweight, language-agnostic and deployable, as we demonstrate by implementing SafeStrings in TypeScript. SafeStrings reduce the surface area for cross-site scripting, argument selection defects, and they can facilitate fuzzing and analysis.

1 Introduction

Strings are the great dumping ground of programming. Their meagre structural obligations mean that it is easy to pour information into them. Developers use them to store semi-structured, even structured, data. Thomas Edison (paraphrasing Reynolds) captured the reason: "There is no expedient to which a man will not resort to avoid the real labor of thinking." Take colour assignment in css. As flat strings they take the form ‘#XXX’ or ‘XXXXXX’, but they implicitly encode three integer values for rgb. Colour operations are naturally arithmetic, but as strings they are cumbersome and error prone for developers to use. Simple operations are difficult: logically correct equality ‘#000’ == ‘#000000’ is false. Incorrect assignments are common: x = ‘#F65T00’ can only be caught by the developer. We call this problem the latent structure problem. This is a widespread problem. Finding errors of this sort is extremely difficult, and programmers care about these errors.

The TypeScript community has seen a great deal of discussion about string literals (Rosenwasser 2015) and regex-validated strings (TypeScript 2016). Regex here refers to PCRE2 style expressions, which augment regular expression with backtracking, grouping, and lookahead. A quick internet search for “validated strings” returns over ten million hits discussing solutions to the problem1. The latent structure problem bedevils debugging; it also introduces security vulnerabilities: format string attacks and SQL injection attacks are well known examples (Gollmann 2011). Handling strings properly does not just give greater type safety, it gives greater safety.

Current type checkers cannot tackle the latent structure problem because they cannot reach past string to the underlying structure; many problems in string theory are undecidable, making many analyses either dependent on heuristics or very expensive. Strings seem an easy method for representing structured information: instead, they are a great way to de-structure information. Latent structure encoded in strings is stringly typed. The consequence is that programs pass around and manipulate richly-structured strings as if they had little or no structure.

1Google 29 March 2019.
Industry has been working to solve the latent structure problem. To date, the dominant approach is string validation by adding language support for checking that a string is what it claims to be. This is the tack taken in a recent pull request for regex-validated strings in TypeScript (TypeScript 2016). This request has been open since 22 January 2016 and has had over 50 detailed comments. It uses regular expressions to check that a string has the desired "shape". A raw string is checked for certain properties and this information is used to instantiate a string subtype. This catches the CSS colour error: `/ˆ#([0-9a-f]{3}|[0-9a-f]{6})/` does not accept `'#F65T00'`. The PCRE2 is lifted to the level of types, becoming part of the type declaration (Listing 1). This is clearly powerful, but it has not been added to the language, despite the enthusiasm for the idea evident in the request and despite the working code.

It is programming folklore that regular expressions add extra problems without resolving the old ones. In type declarations, this is even more true: a CSS colour has a reasonably simple structure, but a regular expression for an email address is not for the faint-hearted:

```typescript
type Email = /ˆ[-a-z0-9~!$%ˆ&* _ =+}{\?]+(@([a-z0-9_\-]+\.[a-z0-9]+)\.[a-z]{2,5})?$/i;
```

Listing 1. Email PCRE2 type as suggested in (TypeScript 2016).

Clearly, regular expression validated strings are difficult to write and difficult to maintain. They do not admit of any easy notion of subtyping, even though it is reasonable to say that a `gmail` address should be a subtype of `email`. Regex-validated strings are essentially immutable and the question of what type results when applying operations to them is not even addressed. Any change in a string necessitates rechecking the entire string, changing the red element of a CSS colour for instance. This is expensive and wasteful.

We introduce SafeStrings to solve the latent structure problem. Like the PCRE2 validation approaches, SafeStrings expose the latent structure of a string to the type checker. This is where the similarity ends. While regex-validated strings check, find structure, and then throw the memory of that structure away, SafeStrings retain and manipulate the structure, taking what is latent and making it manifest. SafeStrings allow operations closed over the type: an operation can be guaranteed to return the same type of SafeString (Section 3). As they store an image of the string’s structure, SafeStrings do not need to recheck the entire string when performing updates, unlike with regex-validated strings.

SafeStrings make the latent structure of the string available to the type checker (Section 2). SafeStrings represent CSS colour string (Section 5) internally as `(Hash (Red N) (Green N) (Blue N))`. A special operation `cast()` allows us to reconstruct the original string: `cast(): string = '#' + red.toHex() + green.toHex() + blue.toHex();`. Composable recognisers mediate habitation of the structure, e.g. each structural element has its own independent parser and the string is tested by putting them together in the correct order: `cssColour = parseHash.then(parseRed.then(parseGreen.then(parseBlue)));`. We reject `'#F65T00'` as malformed, but we can also correctly allow the equality `x : CssColour = '#000'; y : CssColour = '#000000'; x == y = true;` as the structure of both strings is the same (Section 3.2). Of course, raw string equality is still possible. SafeStrings model subtyping elegantly (Section 3.1). The internal representation of the string as a structure means subtyping comes naturally from overriding structural elements. In the case of email addresses, a generic recogniser for the domain part of the address is replaced with one especially tailored for `gmail`. There is no need to recheck the entire string (Section 3.3).

Capturing information in a type is familiar in functional programming, where it is common to define a monad or applicative functor over a structure, then define functions over it. This pattern
is ultimately derived from categorical thinking: the recognition that certain types of structure (functors) and functions (evaluation) define algebras. SafeStrings realise that the latent structure problem can be solved in strings by modelling them as functor algebras (section 2).

To evaluate SafeStrings we consider three case studies of useful string types: filepaths (Section 5.2) css strings (Section 5.3) and email strings (Section 5.1), in TypeScript. SafeStrings are a lightweight annotation system that exploits the structure available in string literals. SafeStrings support an elegant and natural programming model over strings by pushing the complexity away from the programmer. This is in contrast to regex-validated strings, where the complexity sits directly in the type signature, for limited gains. We demonstrate a possible concrete syntax for TypeScript which we implement via a simple preprocessing stage (Section 4.3). The preprocess stage adds only a sprinkle of syntactic sugar: SafeStrings are immediately deployable. SafeStrings do not require any special language mechanisms beyond the ability to represent structured data and to define recognisers over this data.

Exposing latent structure necessarily exposes complexity. Deciding who deals with that complexity and when is vital for the usability of any programming model. SafeStrings provide a simple and spare user-facing programming model; they move the intrinsic complexity away from front-end developers to library authors.

Our principle contributions are:

- We identify the latent structure problem, the gap between a language’s representation of data and the fine-grained way programs actually use and structure that data;
- To solve the latent structure problem, we introduce SafeStrings, a lightweight, language-agnostic, and immediately deployable programming model (Section 2);
- We show how SafeStrings facilitate the definition and verification of type safe operations over strings (Section 3.5); and
- We present a realisation of SafeStrings for TypeScript (Section 4).

The latent structure problem is not limited to strings. Lists, for example, are also likely to have additional latent structure. The prevalence of strings in programming means that the problem is often most acutely felt in that domain. SafeStrings are integratable with the notion of value literals, creating SafeLiterals, a uniform and easily extensible mechanism for introducing typed value literals. This extension provides a simple solution to the proliferation of ad-hoc object parsers and under-constrained JSON encodings to represent literal values in TypeScript and other programming languages. All artefacts are available at anonymised.repo.to.do.

## 2 SafeStrings

SafeStrings address the latent structure problem for strings. Strings used in programming, such as phone numbers, filepaths and zipcodes, tend to be highly structured. SafeStrings harness this latent structure and surface it as required. This surfacing brings greater type safety, greater control over mutability, and powerful subtyping capabilities.

In what follows, we use the term regular expression for expressions over the regular operators that capture only the regular languages. We use PCRE2 to mean string matching expressions now in widespread use in industrial programming languages. These have regular expression-like syntax, but are strictly more expressive, due to the presence of backtracking, grouping, and lookahead. The pull request for regex-validated strings (TypeScript 2016) uses JavaScript-style expressions. These are PCRE2. We use string to refer to the string type of a language and string or raw string
to mean a string in the sense of a list or array of characters, without reference to its exact representation (e.g. object or null-terminated list) in a given language. We assume that raw strings are finite to simplify the presentation\(^2\).

Informally, \textit{SafeStrings} combine a string, a grammar and a recogniser. A \textit{SafeString} is the set of all strings \(s\) such that they are in the language of the given grammar, i.e. \(\text{SafeString} = \{s \mid s \in L(G)\}\), where \(L(G)\) is the language of the grammar. One can readily see that a \textit{SafeString} expresses a subset of strings. The recogniser is a parser (Section 4). In essence, a \textit{SafeString} is a DSL (Domain Specific Language) embedded in the native \texttt{string} type of a language and specialising it in a principled fashion. A \textit{SafeString} recogniser mediates this embedding: only raw strings accepted by the parser are encoded into \textit{SafeStrings}.

Operations take place inside the DSL rather than in the less structured world of strings. The original, raw string can be recovered through a casting mechanism that has rules for recreating the original string from the structure.

This is a lot of additional work to make strings safe. It is necessary because it is difficult to extract structure from strings due to their form. They are just the free monoid over an alphabet, \(\sigma\), with concatenation as the binary operation, \(\cdot\), and the empty string, \(\epsilon\), as the unit. This provides the type checker with relatively little information. Any combination of characters makes a valid string. No other common data types are similarly unconstrained. Finding and encoding more structure enables the type checker to make stronger static guarantees about the dynamic behaviour of a program.

An email address \texttt{safe@mail.com} viewed solely as a \texttt{string} is uninteresting, but represented as a \textit{SafeString} provides a much greater amount of information available for analysis. An email string, for example, could be represented by a structure such as

\begin{verbatim}
(At '.Selenium' (Name string1) (InvariantDot '.') (Left string2) (Right string3))
\end{verbatim}

The structure is an abstract syntax tree (AST). Each substring needs to be checked. It is not sufficient for a string to merely have the scaffold (i.e. '@' and '.') of an email address to qualify as an email string. Each element of the structure has to have an associated recogniser.

Using a single PCRE2, the recogniser for an email address is, as we have seen (Section 1) formidable. Given the power to compose and order recognisers however, it is a much simpler proposition:

\begin{verbatim}
InvariantAt = /@/ Name = /[0-9a-zA-Z]+/ InvariantDot = /\./ Left = /[0-9-a-zA-Z-]+/ Right = /[0-9-a-zA-Z-.]+/
\end{verbatim}

This presentation risks losing the string itself, and a \textit{SafeString} should behave like a string when required: we therefore also require a cast() : \texttt{email} \rightarrow \texttt{string} function that 'reconstructs' a \texttt{string} from the representation. Its exact definition depends on the details of the representation.

\textit{Definition 2.1}. A \textit{SafeString} is a 4-tuple \(\langle G, R, \phi, \alpha \rangle\) where

\begin{align*}
G &: \text{Grammar} \quad \text{(1)} \\
R &: G \rightarrow \text{string} \rightarrow \text{AST}_\perp \quad \text{(2)} \\
\phi &: \text{AST} \rightarrow \text{AST}^{\text{PL}} \quad \text{(3)} \\
\alpha &: \text{AST}^{\text{PL}} \rightarrow \text{string} \quad \text{(4)}
\end{align*}

\(^2\text{A stream might be modelled as a SafeString if finite prefixes of the stream had an encodable structure. We leave this for future work.}\)
G is the grammar. R is a recogniser, a (partial) function that takes a grammar and an input string, and returns AST ⊥, lifted to include ⊥, capturing the possibility of failure. ϕ takes the AST and maps it to AST\(^{PL}\), a concrete realisation of the AST in the language PL. PL may be a programming language (i.e. target) or a family of languages (e.g. LLVM IR). α is the cast() operation, taking AST\(^{PL}\) back to a raw string.

The fundamental insight for SafeStrings comes with ϕ: previous work on validated string types performs the check R but does not convert and store the AST. The hard work of verification is discarded rather than kept and utilised. The handling of the error condition, ⊥, in R is implementation specific; one can just fail, or return information about the error (i.e. a parse error). AST\(^{PL}\) might take the form of an object or an abstract data type. We are assuming, of course, that a string has some structure. A string with no discernible grammar (i.e. a randomly generated string) is not a good candidate to be a SafeString. At its simplest, the grammar conforms to a regular language, but is not limited to such: SafeStrings easily embed context-free grammars and beyond. The CFGs (context-free grammars) of likely use cases for SafeStrings are, in general, uncomplicated.

At its most general, the structure of a SafeString is an F-algebra \((A, α)\). Let \(F\) be an endofunctor on a category \(C\), \(F : C → C\), then \(A\) is the carrier set and \(α\) a morphism of the form \(F(A) → A\). \(F\) corresponds to the Grammar, whereas \(A\) is the set of strings. The ’interpretation’ morphism \(F(A) → A\) can now be seen to be cast() of Section 1, specialised in that case to strings. In general, the habitation of a SafeString is conditioned solely on its syntactic well-formedness. Whether the resulting SafeString is meaningful depends on the sophistication of the recogniser: a syntactically correct email may identify no recipient.

An invariant in a SafeString is a sub-string of the raw string that always occupies the same position w.r.t the other elements of the string. Both the “@” symbol and the first dot “.” of an email address are invariants. They dictate the scaffold of the string around which the other elements (substrings) are disposed. Consider an ‘inner-r’ string. A suitable representing structure would be:

\[(\text{InnerR} \ (\text{InvariantR} \ 'r') \ (\text{Left} \ str_1) \ (\text{Right} \ str_2))\]

‘r’ is an invariant element in an inner-r string and need not be specifically encoded in the representation, i.e. the representation could be \((\text{InnerR} \ (\text{Left} \ str_1) \ (\text{Right} \ str_2))\). The ‘r’ is trivially recoverable by defining the cast() method as \(\text{cast} = \text{str}_1.\text{cast()} + \ 'r' + \text{str}_2.\text{cast()}\).

The space requirements of SafeStrings depends on the size of AST \(^{pl}\). In general, a SafeString requires more space than a raw string. A well designed encoding, however, can make the SafeString representation more space efficient than that of the raw string. Consider the archetypical context-free language of equal numbers of \(a\)s and \(b\)s, \(a^nb^n\). Such a string can be arbitrarily long, but the SafeString need only record the structure and the recogniser as a PCRE2 (Listing 2). A SafeString is not limited solely to PCRE2 for membership tests. We can write recognisers that also count string length or perform other operations that are not explicitly linked with membership. The SafeString EqualAandB also counts the number of inputs.

Methods for string safety, such as type aliasing or regex-validated strings (Section 6), are special, degenerate cases of SafeStrings. We call these special cases monolithic SafeStrings. Monolithic
SafeStrings invoke $R$ whenever they want to expose and access the internal structure. It does not store the AST. They only need the recogniser $R$, and do not define $\phi$ and $\alpha$. In effect, a monolithic SafeString matches the entire string and places that string inside a wrapper. This wrapper exposes the string to the type checker without exposing the latent structure of the string:

```cpp
class Monolithic {
    // recogniser check on input
    raw : 'no_recorded_structure'
}
```

A monolithic SafeString is the same as Fowler’s wrapper type (Section 6) and is isomorphic to regex-validated string literals. This can easily be seen by noting that the only salient different between regex validated types and monolithic SafeStrings is the method by which a new type is created, i.e. either by privileged keyword or via a native record. As we shall see in Section 3, monolithic SafeStrings, while easy to implement, lack much of the flexibility one gets from treating them with a more complex representation. We briefly explore the implementation of monolithic SafeStrings and SafeStrings over relatively simple structures as captured by PCRE2, showing how they subsume earlier work (Section 6). More interesting SafeStrings involve grammars with multiple constructors and recognisers that match elements to constructors as well as accepting the input string.

SafeStrings permit the efficient definition of function sensitive operators. Even a very simple regular language need not be treated as a monolithic SafeString. The regular expression `^*r.*` recognises structure and therefore can be made modular. For ‘inner-r’ strings, SafeStrings has isolated the Left and Right substrings without losing their relation to the main structural element. We now examine the benefits SafeStrings provide by exposing the latent structure of a string.

## 3 Subtyping and Operations over SafeStrings

Type systems, at their most general, capture program invariants and use this information to provide feedback to a user. This feedback is most often in the form of a *type error* which typically results in a compilation failure or cessation of interpretation. Type systems are usually classified by whether they are static or dynamic.

One of the main advantages of static type systems is they capture an abstraction of the program’s dynamic invariants at compile time. This comes at the necessary cost of over-approximation. Classical type systems especially only capture a relatively coarse image of the program’s behaviour. For example, most type systems capture the fact that a variable $i$ is an integer\(^3\). They cannot however model the fact that an integer is even, natural number. Dependent types (Martin-Löf 1985) are sufficiently expressive to capture this kind of invariant at the type level. Dependent types come with a large annotation and cognitive burden on the programmer (Section 6).

Liquid types are a decidable subset of dependent types so can strip away much of the associated annotation complexity. This decidability means that constraints can be inferred statically without proofs required from the user, in much the same manner that ‘normal’ types themselves can be inferred in a Hindley-Milner type system. Liquid types are necessarily less expressive than full dependent types, but the decidability makes them more useful for regular programming.

SafeStrings capture much of the expressive power of liquid types and apply it to strings. Given that much of string theory is undecidable (Ganesh et al. 2011), it is inherently difficult to have a decidable fragment of string theory suitable for instantiating liquid types. Many useful fragments of string theory are decidable however (Chen et al. 2017) and progress has been made on solvers

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\(^3\)An obvious counterexample is TypeScript, which has a general number type.
for string theory (Berzish et al. 2017). These approaches to string safety are complementary to our approach, and could be integrated into a language’s type checker.

The problem is compounded when we consider operations specialised over strings. As is well known, the concatenation of two strings is a string, but the concatenation of two email strings is very unlikely to be a well-formed email string. It is, however, still a string, so the operation is closed under its supertype (Section 3.5). Exposing this information to a type checker allows us to have liquid typing for specialised strings. Moreover, it provides the opportunity to specialise operations over SafeStrings. Thus SafeString concatenation can be written in two forms, one which can be checked to still be within its type, and one which automatically is upcast to string.

We discuss the relationship between SafeStrings and liquid types w.r.t operations over strings in the remainder of this section. We start by discussing subtyping for strings and SafeStrings.

### 3.1 Subtyping

Even though strings are often represented by objects in many languages, they do not easily admit of a principled subtype relation, especially if that subtype of string has validation conditions (Listing 3). An inheritance relation in most OOP languages is created by extending and altering the structure of an object. Treating the string as a structure, as in SafeStrings, allows the same subtyping and inheritance mechanisms to be brought into play. It also simplifies the problem of validation (Listing 4).

We may categorise subtyping broadly between nominal and structural: nominal subtyping means that one type is the subtype of another if so declared (i.e. a named relationship is sufficient), whereas structural subtyping considers two types compatible if they share corresponding elements, regardless of names. Java is a notable example of a language with nominal subtyping, whereas TypeScript has structural subtyping.

In languages that have subtyping, it is reasonable to ask how subtyping might work on SafeStrings. Using monolithic SafeStrings does not provide the necessary structure to satisfactorily answer this question. One method is to ask if one language is included within another. The inclusion problem for regular languages is PSPACE-complete (Meyer and Stockmeyer [n. d.])), although a subset of regular language inclusion problems can be decided in polynomial time (Hovland 2012). In particular, inclusion for \( RE^{\leq k} \) is in \( P \), where \( RE^{\leq k} \) is the class of regular expressions where each symbol appears at most \( k \) times. The complexity is still poor, on the order of \( n^k \), with \( n \) being the length of the regular expression. In general, however, the problem of language inclusion for simple regular expressions is intractable (Martens et al. 2004). Moreover, these bounds hold only for regular languages, they do not hold for the complexity of regexes.
export class Email {
    user : Parser = parseName ;
    dom : Parser = parseGenericDom ;

    email : Parser = parseName . then ( parseAt ) . then ( parseGenericDom )
}

Gmail extends Email {
    static dom : ParserGmailDom ;
}

MoreGmail extends Gmail {
    static extra : Parser = parseMore ;
    email = super . email . then ( extra )
}

Listing 4. Subtyping email SafeStrings in pseudocode similar to TypeScript. Subtyping can be done in the usual fashion, by overriding and extending.

There are various methods to simulate a subtype relation without resorting to language inclusion. Listing 3 shows one such solution as suggested in the pull request for regex string literals in TypeScript (TypeScript 2016).

let email : Email;
let gmail : Gmail;

type Gmail = Email & /"[-a-z0-9"$%\&*_+=]+@gmail\.[a-z0-9]+$/i;
gmail = email; // correct

Listing 3. A possible, but expensive, solution to the problem of subtyping for regex-defined string literals as found in the original pull request (Rosenwasser 2015). This method would also work for one-field SafeStrings. In addition to obvious efficiency problems due to redundancy, it suffers from readability and maintainability problems.

This solution is less than ideal: it does a complete check twice. First it ascertains whether the input string is of type Email and then looks again to assert membership in the second regex, which introduces the specialisation. This is clearly of limited extensibility and maintainability. Moreover, given the backtracking and lookahead abilities in regexes, this could be a very expensive operation.

SafeStrings address the problem of subtyping via manipulation of the structure (Figure 1). An email SafeString might have a generic structure similar to (name, at, domain) where 'at' is an invariant, a necessary requirement for string membership (Section 2). It is reasonable to accept a gmail string to be a specialisation of an email. This requires that the domain contain the substring 'gmail' in the appropriate position. Given a set of composable parsers, a gmail subtype of an email address is a specialisation of one, or more, of those sub-parsers. In Section 5, parser combinators are used. These are ideally suited for this role due to there composability. We note however that this is not an essential requirement (Section 6).

An inheritance relation can thus be formed naturally either by changing the rules for membership in structural elements, or by adding additional parts to the structure.
Listing 5. Blending two cssColour strings together in guaranteed to produce a well-formed cssColour string. This operation is closed over its type due to the fact that a cssColour string is structurally an integer, and addition has the required properties.

3.2 Equality

Equality, broadly speaking, carries the same dichotomy as subtyping: nominal or structural. The details are again language dependent. Structural equality for SafeStrings asserts that foo : string \(\Rightarrow\) = "foo" and foo : Foo = "foo" evaluate to true despite the fact that they have different types. This is reasonable behaviour, as Foo is presumably a subtype of string. A purely nominal approach however would evaluate to false, as the annotated types of the two declarations differ.

Ideally one would want to have access to both behaviours. The former reflects the intuition that one is dealing only with strings unless otherwise required, the latter when we require the string to have a checked structure.

TypeScript already has access to two forms of equality, inherited from JavaScript ‘==’ and ‘===’. This gives us an easy way to model the two desired behaviours. Each SafeString therefore requires a definition of a method, eq, in two flavours, strict and weak. Weak performs a cast of a SafeString to its string representation, and then performs the equality test. strict checks the type instance first before progressing to checking the contents. Section 5 gives more detail about defining these important functions.

3.3 Typesafe Operations

One of the main advantages of liquid types is that they can confirm pre and post conditions overs primitive types under operations. For example, an integer refined to be even only can be shown to be even after an operation such as multiply by two. Perhaps more importantly, it can also show when an assertion fails. SafeStrings bring some of this discriminatory power into strings.

A SafeString, as we have seen, has an internal representation. This representation is sequence or tree-like. Operations over a SafeString are best viewed as tree surgery over one or more nodes. It is not usually necessary to operate on the entire tree. We have already seen this idea in Section 1 in the discussion of cssColour strings an example where it is necessary to operate over the entire tree, but doing so results in a rational, type safe function (Listing 5).

In general however, one need only edit one or two nodes. This means that, in the event that we do not have guaranteed closure, we need only recheck the substring that has been altered, without having to recheck the entire string. To return to one of our running examples, email strings, we might want to generate pseudo-random addresses via string concatenation. This procedure could be useful in, e.g. test cases generation or fuzzing. Naturally, we want this concatenation function “+” to behave in as safe a manner as possible, and providing as such information to the type checker as is possible.

Depending on the precise recogniser associated with name, the “+” can be checked either statically or dynamically for closure. Given a name recogniser of /[a-zA-Z0-9]+/ for example, it can be
Fig. 2. Editing individual nodes in the tree representation of a syntactically valid email address. Email addresses concatenation defined only over the name field. Depending on the regex, this can be resolved purely statically (i.e. the concatenation of the regex is isomorphic to the original) or with a runtime check.

```typescript
let email1 : Email = 'foo@bar.com'
let email2 : Email = 'bax@bar.com'

// overload + to perform safe email concatenation over names
'foo@bar.com' + 'bax@bar.com' // constrained to Email.
=> 'foobax@bar.com'

// raw string concatenation with return type string. Not a valid email address
'foo@bar.com' + 'bax@bar.com' => 'foo@bar.combax@bar.com'
```

Listing 6. Typesafe email concatenation and normal string concatenation in TypeScript. The user can overload the operation by choosing to constrain the return type.

```typescript
"someone@email.com".split('@')\[0\] // OK: returns 'someone'
"someoneemail.com".split('@')\[0\] // Bad: returns 'someoneemail.com' without warning
```

Listing 7. Slicing in TypeScript

readily seen that concatenating two strings matching this pattern are still within the pattern. A real email address name field is more complicated of course. Regular string concatenation can still be had via cast() (Listing 6).

Another common operation over a string is slicing, i.e. extracting a substring. The key to recognising the power of slicing in SafeStrings is that we normally are looking to extract a particular substring from a string, and not just a random slice. These particular substrings are likely to be represented in the structure as individual elements or the composition of individual elements. Slicing then becomes merely projection. Listing 7 shows one way to perform this in TypeScript. Given a regex-validated string, one still needs to write email.split('@')[0]. With a SafeString however, one simply extracts the named field, i.e. email.name(), an action that has no additional runtime cost of extra function calls or string manipulation. Moreover, it cannot fail silently as in the manner of Listing 7. A user desiring free slicing over a SafeString need only manipulate the raw strings as opposed to its representation, i.e. take a slice from the cast() of the SafeString. We say about type safe string mutation when discussing various SafeStrings in Section 5.
private User getUser(String companyId, String userId) {
    // ...
}

public void doSomethingWithUser(String companyId, String userId) {
    User user = getUser(userId, companyId);
}

Listing 8. Argument selection defects are compounded when the parameters are all typed as string. SafeStrings reduce the instance of such defects by giving meaningful type information, rather than relying on bi-modal information channels.

Finally, we note a use of SafeStrings that is not directly related to their form or mutability. The problem of argument selection defects is well known. This is concerned with function parameters of the same type being used in the incorrect order. (Rice et al. 2017) give the motivating example found in Listing 8. A developer has mistakenly swapped the parameters in getUser. Appropriately typing these strings as SafeStrings would prevent this error from having occurred, meaning that the much more expensive testing process as detailed in Rice et al. is not required in this instance. While SafeStrings do not eliminate the problem (two SafeStrings of the same type could still be swapped), the surface area for such errors is now much smaller.

3.4 SafeStrings, Solvers, and their Applications

The question of the decidability of string theory, i.e. the problem of automatically solving string constraints, has seen a recent renewal of interest in the research community (Abdulla et al. 2017, 2014). This is doubtless due to the recognition of the importance of analysing string manipulating programs. A large amount of recent work has focused on the development of practical string solvers. The list of solvers that now handle at least a part of string theory includes, but is not limited to, Z3-str (Zheng et al. 2013), CVC4 (Liang et al. 2014) and Stranger (Yu et al. 2014). The primary use case for these solvers is in symbolic analysis (King (King 1976), Cadar et al. (Cadar et al. 2006)). A symbolic analysis systematically explores executions in a program and collects symbolic path constraints. A symbolic executor passes these constraints to a solver to determine which program locations to continue exploring. For this to be a practical approach with strings, the constraint language must precisely model strings in the language of the program under test.

Solvers are frequently used as the back end when implementing liquid types. Perhaps the most well known implementation is that of Liquid Haskell (Vazou et al. (Vazou et al. 2014)), but other targeted languages are ML (Xi and Pfenning (Xi and Pfenning 1999) and F# (Swamy et al. (Swamy et al. 2011)). The observant will notice that these are all statically typed, functional languages. Attempts to bring refinement types to so-called ‘scripting’ languages (such as TypeScript) have proven difficult (Chugh et al. (Chugh et al. 2012)). This difficulty is largely due to the interaction between higher-order functions and imperative updates. Vekris et al. (Vekris et al. 2016) develop a refinement type system for TypeScript that is primarily concerned with addressing these issues.

SafeStrings are complementary to this SMT-based approach. SafeStrings hold much interesting promise for symbolic execution in that they can reduce the constraint space over a program. The encoding of the SafeString can be passed to the SMT-solver allowing it to form constraints over a much more detailed representation that just string. SafeStrings also reduce the complexity of fuzzing string based programs. As the structure of a SafeString is explicit, and a program has type checked, then, at any particular program point, it is known that a SafeString has the structure specified. A fuzzer or test generator can use this information to ease the problem of finding malformed inputs and writing unit tests.
3.5 Closure Properties in SafeStrings.

Under SafeStrings, a even simple expression language has some surprising and enviable properties.

\[
\text{<expression> ::=}
\quad \text{<const> -> number}
\quad \text{<op> -> expression expression}
\]

As a SafeStrings grammar, any projection from this structure is a well-formed expression. Consider the encoding of the string "3 * 4 + 5" as \((\text{Add} (\text{Mult} (\text{Const} 3)(\text{Const} 4))(\text{Const} 5))\). The available projections from this algebra are the string itself and \((\text{Mult} (\text{Const} 3)(\text{Const} 4))\), or "3 * 4". We say a SafeString for this expression language is closed under projection. Such a useful state of affairs does not obtain in general. The projection of the name from a email SafeString is not itself an email address.

Going in the other direction, some SafeStrings support injections freely, consider the simple example of the inner-r string from Section 2. Admittedly this is a rather extreme example, but it serves to highlight the following important point: in general it is not possible to know what actions over a SafeString are necessarily closed over that SafeString. This means that the design of every SafeString needs to be bespoke and will support a different subset of possible operations.

This leads naturally to the question of error handling. There will be times when an operation over a SafeString does not result in a well-formed SafeString. Depending on requirements, there are two obvious ways to address this situation. One is to throw an exception and fail eagerly. The other is to use an Either type, familiar from functional programming. Either is the commonly accepted name for the coproduct, or disjoint union, of types in most functional languages.

4 Realisation of SafeStrings in TypeScript

To evaluate SafeStrings, we implemented them in TypeScript, because of its powerful and flexible type system and support for both object-oriented and function programming. Moreover, strongly typed data is extremely common in TypeScript and JavaScript code. TypeScript already offers ways to use literals, both string and number, as types (Section 6). Combined with type guards, union types and other features of the type system, they give ample scope for demonstrating the potential of SafeStrings.

A SafeString requires some way to model a structure and a way to have a recogniser over that structure. One needs only to find an image of these constructs in the language to have SafeStrings. To model the structure in TypeScript we chose to use objects in which the fields of the object corresponded with grammar productions. For the recognisers, we relied on parser combinators.

4.1 Parser Combinators

We use parser combinators for our evaluation due to their easy compositability. TypeScript has native support for regexes, and indeed, at the lowest level, parser combinators also make use of regular expressions. It is not clear what the full expressive power of regexes is in the language hierarchy, though they do have limited ability to recognise context-free languages. Monadic parser combinators are at least as expressive as this.

Regular expressions accept strings, but SafeStrings require more than this. Parser combinators do strictly more than accept; they can also process their input. For SafeStrings, this processing is the creation of an AST. We present a brief overview of parser combinators in the remainder of this subsection.

Parser combinators are familiar tools in functional programming, having been first introduced in 1975 by Burge (Burge 1975) and popularised by many others, such as Hutton and Meijer (Hutton and Meijer
spaces = some (oneOf " \t\n\r")

Listing 9. Parsing with combinator composition.

xml = do 
    name <- openTag
    content <- many xml
    endTag name
    return (Node name content )

Listing 10. XML parsing in Haskell’s Parsec library.

They provide an elegant and declarative methods for implementing parsers. In contrast to traditional parser generators, parser combinators are first class values which can be combined and manipulated to define new combinators. They elide the difference between lexers and parsers. They do not require a separate tool-chain, thus avoiding any integration issues. A SafeString library for TypeScript therefore can be entirely self-contained. It does not require any other tools to work apart from the TypeScript compiler itself.

A parser combinator is a self-contained unit. For example, one can write a combinator oneOf that succeeds if the input character is an element in its accepting list. Suppose the list is "\t\n\r", then oneOf "\t\n\r" defines a parser that accepts exactly one whitespace. To parse multiple whitespace, as in Listing 9, we combine, or compose, two combinators, some, which accepts one or more instances of another parser, and oneOf. Monadic parser-combinators are able to parse context sensitive grammars. This allows parser combinators to handle XML documents in a single pass as in Listing 10 (Leijen and Meijer (Leijen and Meijer 2001)). This guarantees well-formedness in a single pass over the source.

There are some drawbacks to parser combinators. Parser generators give static termination guarantees that most parser combinators cannot give. Work on total parser combinators, which provably terminate is an area of active research (Danielsson (Danielsson 2010)). So far at least, these have suffered from poor performance. Parser combinators are unable to deal directly with left-recursion. Most parser combinator libraries provide a chain combinator (Fokker (Fokker 1995)) that captures the left-recursive design pattern without obliging the user to rewrite a left recursive grammar to be right recursive (Aho et al. (Aho et al. 1986)). There is a risk of inefficiency with parser combinators. However, this is not a necessary feature of parser combinator libraries and many efficient implementations exist. TypeScript has at least one industrial strength library available\(^4\).

To model the grammar of a SafeString we chose TypeScript objects. This is primarily for familiarity of programming model. Complex grammars might benefit from a more abstract representation (i.e. the visitor pattern used for an AST), with purely functional references in the form of lenses. Finally, we also need a way to handle errors, as discussed in Section 3.5. TypeScript has good mechanisms for exception handling.

4.2 Preprocessing for Natural Assignment

We mention a preprocessing stage in section 1. This processing stage is very simple. Its sole function is to allow for declarations that are more string-like without needing to make changes to the TypeScript itself. This preprocessing is not required for SafeStrings to function properly. The

\(^4\)https://github.com/jneen/parsimmon
most common usage is to desugar assignments (listing 11). Preprocessing is also required to allow for the usual TypeScript operators on strings to work as expected, if $x$ and $y$ are both SafeStrings, then $x == y$ is rewritten as $x.doubleEq(y)$.

The preprocess stage has one other important function. A statically declared SafeString (i.e. one that is hard-coded) is converted into an object. Unfortunately, TypeScript does not statically check an object’s constructor. As all of the required information is present to check this declaration, for simplicity we pass those declarations through node in order to evaluate the constructors. It would be easy, though unnecessary for demonstration purposes, to incorporate the parse check directly into the compiler without having to evaluate the file.

4.3 Alternatives to Parser Combinators

Parser combinators are not a strict requirement of SafeStrings. The expressive powers of pcre2 regular expressions is sufficient to capture most of the likely use cases for type safe strings. The chief advantages of using parser combinators are readability and compositionality. JavaScript and TypeScript, as of 2018, have named capture groups for regular expressions (TypeScript 2018) (Listing 12). These can be made to correspond with simple instances of SafeStrings. Note that they do not create a new type, but can work within an object wrapper when users wish to create an uncomplicated SafeString.

The code in listing 12 is very close to what we want from a simple SafeString. Indeed, it automatic maps named capture groups to fields in a new SafeString object, with the associated sub-membership tests the (sub) regular expressions. However, compose these named groups is difficult and any change requires rechecking the entire string, unlike with a fully-fledged SafeString.

Declaring new SafeStrings of greater complexity than this is clearly a greater burden on the programmer. One needs to identify an appropriate grammar, write recognisers for that grammar, write methods over the structure, and write a class which encapsulates everything. Even for a string like an email, this is a non-trivial effort. For complex structures, the code is likewise more complex. To aid deployability, the most common SafeString types should be supplied in the form of a library. This might include email strings, css fragments, address formats and other forms of structured data. Library writers with unique string types could write the necessary code themselves if they require that level of type safety.
5 SafeStrings in Action

Now that we have detailed the formation of SafeStrings and discussed the mechanics of instantiating them in TypeScript, we look in more detail some concrete examples of SafeStrings, why they are a suitable target for making safe and how they are constructed. In turn we consider filepaths, css elements and finally email addresses.

5.1 SafeString Email Addresses

Email addresses are a common type of string in web programming. Ensuring that email strings are well formed is a standard procedure. Extracting information from an email string is also common, especially slicing out the name part of an email address. Email strings as string literals (Section 6) are too inflexible: they have far too much variety of form to capture in a simple literal type. Indeed, in the regex-validated strings pull request (TypeScript 2016), safety for email strings consumes much of the discussion. Representing them as monolithic or regex-validated strings goes some way to solving the problem, but fails to allow for operations and subtyping (Listing 3).

Intuitively, a subtype relation over email strings would be flat, with each provider (i.e. gmail or hotmail) being a subtype of a generic email string. This generic email should capture the ‘essence’ (i.e. the free structure) of an email string, without being tied to specific detail.

Subtyping of email addresses is now the action of overriding the parser for one of the declared fields. This produces a natural, intuitive, notion of type hierarchy. Turning an Email into a Gmail means changing the domain parser to accept ‘gmail’ specifically. Unlike with regular expressions, there is no decidability issue here either.

Operations over email strings can now be defined in such a way that they behave in a rational, type safe way. Normal string concatenation for example will produce a new string of type string, i.e. perform an upcast to string by default. For email addresses however, string concatenation could be defined solely over the name field of the SafeString. Now only the parser combinator associated with that field need be called. If this succeeds then the string is still an email string. It is not necessary to re-parse the entire string, as would be required by a PCRE2 approach. “foo@gmail.com” \append("bar") produces a string foobar@gmail.com : gmail. In languages which support operator overloading, one could overload ‘+’ so that the correct definition is chosen automatically. Types can then be checked with the typechecker.

This approach allows for a much more fine-grained handling of type safety. For example, rather than having user : string as a projection from a gmail string, the projection can be tagged with its origin by wrapping it in an object of its own (Listing 13).

Now the different fields of an email address can signal their origin even when detached from the original object. They signal the provenance of a string and reveal that it has been detached from another structure. This can be exposed to the typechecker, or treated as a simple type alias (Section 6). This latter serves as useful documentation to the user. With the former, it is possible to define operations over these projections in much the same manner as for strings of type Gmail. Such levels of type safety are not perhaps required for many simple programming tests, but the approach allows for it when required, rather than insisting on it.

5.2 SafeString FilePaths

Filepaths are a common feature in many programs and are usually typed as string. Some languages (e.g. Haskell) introduce a FilePath type that is, in fact, merely a type alias of string. Filepaths have different formats on different architectures, some using \, some /, or even a mixture of the two. Manipulating filepaths in the shell is a well known problem, relying on basename and realpath \to extract information. The shell is a unityped environment: everything is a string. While
class GmailName {
    gmailName : string;
    constructor(n:string) {
        this.gmailName = parse(n);
    }
}

class Gmail {
    name : GmailName
    domain : Domain
}

/* etc */

Listing 13. Provenance tracking in SafeStrings. While projections from the structure can be typed as string, they can also have their own newtype wrapper. A name extracted from an Gmail SafeString can signal its provenance by having the type GmailName.

type WindowsPath = `(\((\w|([\w]+\.\d?\w))*\)*)?(\w|([\w]+\.\d?\w))*(`\w\d\w`)*(`\w\d\w`)+)`

Listing 14. A regex-validated WindowsPath, where \w is any alphanumeric character.

shells could benefit from the versatility of SafeStrings, the problem exists equally in strongly typed programming languages.

A monolithic SafeString is the simplest way to gain increased type safety for filepaths. Listing 14 contains a regex-validated Windows pathfiles. It is immediately clear that this is not a useful constraint in a type. It is completely unmodular. Worse, it does not accept "/" as a directory separator, though this is valid for MicroSoft Windows. Closer inspection reveals that the regex contains a great deal of repetition. This repetition can be factored out when using parser combinators, and opens up the possibility of overriding one or more of the substrings to create specialised parsers (Section 3.1). Using a monadic parser combinator also solves the problem of consistent directory separators. The monadic state can be updated to accept whichever separator comes first and then propagate that constraint over the rest of the string.

Assuming that we do not want to use a 'simple' monolithic SafeString, one possible representation of a filepath might be:

(FilePath (Path array<Directory>) (File (Name string) (Ext string)))

where we do not need to represent the separator nor the "." in the filename proper as they are invariants. This representation assumes that we wish to normalise the separator over the entire program, i.e. cast() would be:

    cast() : string = dirs.join('n') + name.cast();

but there is no reason why we cannot also record the direction of the file separator. This could be used, amongst other aspects of the string, to induce a subtype relation for Filepaths based on separator direction, making a FilePath SafeString generic over Unix and Windows style paths. UnixPath
class UnixPath extends FilePath {
    separator = '/';
}

Listing 15. Subtyping for filenames via the use of the separator.

# HomeDotFile is a SafeString where the file must be located in the home # directory and be hidden.
HomedotFile = {
    dirs : [home],
    filename = /\.[chars]/
}  # temporarily overload rm so that it cannot delete HomeDotFile strings.
rm ~/.bashrc # fails as ~/.bashrc : HomeDotFile

Listing 16. Scripting in a SafeString-aware shell environment could be made much safer. A type safe rm would make it impossible to delete files in a sensitive directory or of a particular type, but the shell itself could remain essentially unityped with everything being considered a string.

and WindowsPath are now subtypes of FilePath, which in turn is still fully interoperable with string (Listing 15). This is conditioned solely on the granularity of the recogniser and representation.

The internal representation of a FilePath contains a traversable structure, the array of directories. Directories can be represented by raw strings (i.e. without associated recognisers, though further type safety could be had by providing checks). Extracting filename, extension and path are just named projections from the structure. Type safety can be taken further still by putting constraints over the length and contents of array<Directory> (Listing 16). The location of a file can be encoded in the type information and checked dynamically.

Suppose a shell with support for SafeStrings with method overloading. This is not unreasonable, as SafeStrings can function as simple strings when required. In it, the shell would allow you to define a SafeString HomePath. A string of type HomePath points to a file in the home directory. overload mv temporarily to mv so that it only functions from HomePath to one of its descendants. One can then call mv safe in the knowledge that in incorrect assignment is now impossible.

5.3 SafeStrings in CSS and Web-forms

Web-based programming is especially rich in strings. Cascading Style sheets (css) is an almost ubiquitous style sheet language that is fundamentally stringly-typed. This makes it very easy to incorrectly assign data with little that either a type checker or static analyser can do to prevent it. Here we show how SafeStrings solve this problem using four examples: css colours, phone numbers, units, and cross-site scripting.

CSS Colours We have already see in Section 1 some of the problems caused by representing colours as strings. Analysing a cssColour string reveals an underlying structure despite the superficial differences in presentation. Both ```#000``' and ```#000000``' encode the same information, but unimportant differences restrict their interoperability. Even simple equality fails: ```#000``' does not equal ```#000000``' even though they represent the same colour. Abstracting a cssColour string, however, gives the structure (Colour (Red N) (Green N) (Blue N)) which elides these superficial differences. Regular expressions can instantiate this structure for a particular string, but it is accomplished even more easily with a parser:

```cssColour = parseHash.then(parseRed.then(parseGreen.then(parseBlue)))```
can, of course, still be compared as *strings*, using *SafeStrings*’ *cast()* operation. For a *cssColour* the definition is shown in Listing 18. The ’#’ symbol is *invariant*, so it does not need to be stored.

*This *cssColour* representation, and the fact that it contains only valid hexadecimal colour strings, is much easier to manipulate than raw strings. Changing elements in the structure leaves the structure itself, notably its type, unaltered. For example, say we wanted to blend two colours together. This is not easily done when dealing with raw strings:

```
"#123" + "#332111" // naive: "#123#332111", an obviously invalid cssColour
```

### Phone Numbers

Phone numbers entered on websites make excellent *SafeStrings*. Unfortunately, there is no universal model for phone number construction to act as a supertype from which other formats can be derived ((Wikipedia contributors 2019)). Obtaining a regex to correctly match US phone numbers is difficult. Consider Listing 19, which shows a regex taken from a *stackoverflow* answer (fatcat1111 2017). One can readily see that this is inappropriate for a type constraint, and highly inflexible. Underlying this surface complexity, there is the *NANP*: North American Numbering Plan (NANPA 2019). This gives a formatting convention of *NPA*-NXX-XXXX where *NPA* is a three digit area code and the remaining seven digits are the subscriber number. This maps neatly into the structure in *(NPA N (Central N) (Ident N))* where *N* is a digit from 2–9. Whitespace, dots, dashes, or some combination may separate the groups. Parser combinators easily parse a number string into this structure, even when a mix of separators is used. Appropriately defining *cast()* cleanly normalises the format, without resorting to functions such as *replaceAll()*.

*Parsers expect structured data:* the code in listing 20 is reasonably generous in what it accepts. It recognises as a phone number 555-211 1234 with mixed separators, and 5552111234 as valid phone numbers. It does not accept other groupings such as 55 52111 234. The well-known *Robustness Principle or Postel’s Law* (Postel 1980) states “Be liberal in what you accept, and conservative in what you send” but it is also well-known that this maxim has harmful consequences (Thompson 2018). It is a difficult design decision to know how flexible to be when accepting input: in this case, we require that the input have at least the structural grouping of a phone number.

```
\d+\s*\d{2}\d{3}\s*\d{4} \d+\s*\d{2}\d{3}\s*\d{4} $```

```
"#123" + "#3322111" // naive: "#123#3322111", an obviously invalid cssColour
```
import * as P from 'parsimmon'

let separator = P.oneOf(' 
.').fallback('');

let areacode = P.regexp(/\[2-9\][0-9]\{2\}/).map(Number).desc('a valid area code');
let nxx = P.regexp(/\[2-9\][0-9]\{2\}/).map(Number).desc('a valid office code');
let xxxx = P.regexp(/\[0-9\]{4}/).map(Number).desc('a valid identifier');

let phoneParser = P.seqMap(areacode, separator, nxx, separator, xxxx, function(a, s1, n, s2, x) {
  return [a, n, x]
});

class USPhone {
  area : number;
  office : number;
  uniq : number;

  constructor(phone : string) {
    let pn : number[] = phoneParser.tryParse(phone);
    this.area = pn[0];
    this.office = pn[1];
    this. uniq = pn[2];
  }

  cast() : string {
    return this.area.toString() + '-' + this.office.toString() + '-' + this. uniq.toString();
  }
}

Listing 20. A part of the realisation of a US phone number SafeString in TypeScript, using the 'parsimmon' parser combinator library. This code fails with a parse error if the string is not accepted.

Listing 21. An easy typing error leads to a difficult to find mistake in css. Linting tools may find the problem, but as a SafeString this unit error would be caught automatically.

Units Units in css, such as pixels, points and picas, are all stringly typed. This makes it extremely easy to assign the wrong unit to the wrong variable. It also makes it very difficult to a static analysis to identify these errors. Yet, the latent structure of these strings is scarcely latent at all. Fortunately, SafeStrings easily solve the latent structure problem for these strings.

A string "1cm" has the simple representation (CM 1). It is trivial to catch the incorrect assignment let font-size : Point = '1cm'. It may seem that modelling these strings as SafeStrings is excessive.
// overloading + for a pixel string
add(operand : Pixel | Picas | Points) {
    if (operand instanceof Pixel) { return cm self.value + operand.value; }
    else if (operand instanceof Picas) { return cm self.value + operand.toCm();
        → }
    // ... etc
}

Listing 22. The complexity of adding incompatible units can be abstracted away from the front-end user.

<! -- unsafe html --!>
<h1>User <span onMouseOver="popupText('{{ bio }}')">{{ userName }}</span></h1>
<! -- the same code, with \safes for added safety --!>
<h1>User <span onMouseOver="popupText('{{ bio : Sanitised }}')">{{ userName : UserName }}</span></h1>

Listing 23. A simple example of XSS scripting in HTML as found in (Chen et al. 2017). Typing user input with SafeStrings significantly reduces the surface area for XSS attacks. Moreover, the structure of the user input is now known and can be used elsewhere in the code without having to recheck it. The SafeString Sanitised acts as a certificate for the contents of the input string; UserName does the same.

// a typical SQL query with a vulnerability
statement = ``` SELECT * FROM users WHERE name = ' ' + userName `''```;
// if userName = ' OR '1'='1' -- (bad: a SQL injection)
// an appropriate UserName sanitises the string, but also passes the
// information to the type checker
statement = ``` SELECT * FROM users WHERE name = ' ' + userName : UserName `''```;

Listing 24. SafeStrings for SQL queries can substantially reduce the surface for an injection attack.

This is not the case. Listing 21 has a simple mistake, c was typed instead of x in the unit for margin; spotting this error in a dense page of css is difficult and time-consuming. A linter may not detect this as an error. A declaration that margin takes the union type (PX | AUTO) catches the error without programmer effort.

Stripping the unit information and normalising the numerical representation also makes it much easier to define conversion functions that do not expose their complexity to the front-end user. This can be achieved by, for example, operator overloading. If operator overloading is not desired (TypeScript for example does not encourage it), then TypeScript’s union types can be used to overload a function to choose the correct transformation (listing 22).

Cross-site Scripting Poor control of strings can result in bugs that are merely irritating, i.e. layout and colour problems, or bugs that are dangerous. XSS (cross-site scripting) falls into the latter category. The replaceAll function is often used to sanitise user input in an attempt to mitigate the danger of XSS attacks (Chen et al. 2017). They take as a running example the code fragment in Listing 23. A SafeString for sanitised data could be a monolithic SafeString, habitation of the type being a proof that the input string does not contain a code injection. Now the string is Sanitised SafeString. Such a string can be used elsewhere without being reexamined, amortising the initial cost of checking. Such a check would be performed anyway in conscientious code, but knowledge of the sanitisation would not be passed to the type checker, leaving the programmer to check the string again and again.
record SString : Set where
  constructor mkString
    field
      s : String -- the raw string
      re : RegEx -- the recogniser
      p : SubString re (unpackString s) // this is a proof of membership

makeSafe : String → RegEx → Maybe SString
makeSafe s re with s ∈? re
  makeSafe s re | yes pr = just $ record {s = s; re = re; p = pr }
  makeSafe s re | no x = nothing

helloString : SString
helloString = fromJust $ makeSafe /quotedbl.Var hello/quotedbl.Var hello

Listing 25. What price safety? Dependent types allow a SafeString to carry with it its own proof of correctness. The programming burden for this style is non-trivial.

SQL injection attacks can also be reduced via SafeStrings. Listing 24 contains a simple SQL injection. Defining a UserName SafeString can effectively sanitise the user input. Escaping via e.g. replaceAll() is error prone, but abstracting dangerous elements of the input string into an AST and then using a cast() operation that cannot produce malformed input is a much safer approach.

6 Related Work
As there is little theoretical that corresponds directly to our approach with SafeStrings, we first focus on work that we believe is compatible, such as the use of constraint solvers, symbolic execution, the use of dependent and liquid types, and regex-validated string types. We go on to compare SafeStrings with various, mostly informal, approaches to the string latent structure problem such as type aliasing, the use of new types, object wrappers, and string literal types.

6.1 Liquid Types and Dependent Types
Type systems of differing levels of granularity and expressiveness abound both in the literal and in practice. SafeStrings solution to the latent structure problem has a strong overlap with dependent and liquid types. SafeStrings are programmable in a dependently typed language and offer very strong guarantees: under the Curry-Howard correspondence (Sørensen and Urzyczyn 2006), types are propositions and functions proofs. Making proofs out of functions is powerful, but requires much from a programmer intent on delivering a product. The code in Listing 25 allows the user to pass around not merely the structure itself, but a computer verified proof that the string is in the given language. Most languages do not offer this possibility, but not having a proof to consult does not mean that safety is compromised.

The goal of both dependent types and liquid types is to make the type level abstraction of program behaviour more expressive and less coarse. Strings have seen little research in this area, perhaps due to the problems of decidability in string theory (Ganesh et al. 2011).

6.2 Regular Expression Validation
Regex-validated string types of (TypeScript 2016) allow for a high degree of type safety w.r.t to strings. SafeStrings are strictly more expressive in that they are not tied to one form of membership test (i.e. PCRE2). Arbitrary logic can be included in the recogniser for a SafeString. SafeStrings also support subtyping, and operations over SafeStrings. These operations can be overloaded to
support *ad hoc* polymorphism. The maintenance burden of *SafeStrings* is not much more that *regex*-validated types. For simple declarations, the newly introduced *named capture groups* can stand in the stead of parser combinators (Section 4.3). Indeed, there is no theoretical necessity for parser combinators in the *TypeScript* implementation except for the noted provisos in Section 4.3 of subtyping and readability.

### 6.3 Industrial Approaches

There are a number of informal approaches to increased string type safety which make for reasonably usable design patterns.

The simplest is *type aliasing* (Team 2019). This is supported in many languages, but its primary use case is often for documentation purposes rather than type safety. In *TypeScript*, for example, one writes `type Name = string`. From the perspective of enforcing invariants however, the utility of aliasing is limited because it cannot enforce type (in-)equality (Listing 26). It cannot prevent static type errors of the kind

```typescript
gmail : Gmail = "not a gmail address"
```

where *Gmail* is some previously declared type alias for *string*.

If a language has *newtypes*, greater type safety can be achieved. These are a wrapper around an already existing type. A *newtype* is different from an alias in that it is exposed to the type checker and can be used to enforce inequality. Object-orientated languages support these by wrapping a primitive type in an object or using an interface (Team 2019). Listing 27 shows the syntax in *TypeScript*. This object wrapper pattern can be validated with a recogniser (Listing 30). A simple instance of this pattern is explored in (Fowler 1999). The constructor is augmented with a regex check for string membership. The constructor fails with an error if the string is not in the language expressed by the regex. This pattern is captured by *monolithic SafeStrings*.

Since version 1.8, *TypeScript* has had *string* and *number* literal types (Team 2019). The original pull request for string literals (Rosenwasser 2015) summarises them as: “A string literal type is a type whose expected value is a string with textual contents equal to that of the string literal type.” A string literal type can only be assigned the exact value specified in that type (Listing 28). String literal types can be used with other features of the type system, most notably *union types*, to create (finite) enumerable sets of strings. This allows them to act as type guards in pattern-matching in a similar way to type constructors in pattern-matching within the ML family (Listing 29). *Regex*-extended string literals relax the need for exact matching, making string literal types even more expressive.

---

**Listing 26.** Type aliasing in *TypeScript*

```typescript
type Name = string;
foo : Name = 'hello';
bar : string = 'hello';
foo == bar -> True // we probably want this to be false
```

**Listing 27.** *TypeScript* Interfaces can be used to create new types by wrapping other types.

```typescript
interface Name { name : string }
let foo : Name = { name : 'hello' }
foo == 'hello' // results in a 'no overlap' error, rather than just false
```
const good : "click" = "click"; // this is OK
const bad : "click" = "notAClick" // this assignment fails

Listing 28. A simple example of string literals in TypeScript to increase type safety for functions which take strings as parameters.

type Direction = "North" | "South" | "East" | "West"

function move(direction : Direction) {
    if (direction == "North") {
        // move north
    } .... // enumerate the options
}
move("SouthWest") // error: not one of our directions

Listing 29. A suggested use for string literals, as proposed in the original pull request (Rosenwasser 2015). This gives considerable expressive power and safety to functions that take strings. SafeStrings make this even more expressive.

class Name {
    name : string;
    /* optional regex check for membership */
    constructor(name : string) {
        this.name = name
    }
}

Listing 30. An object wrapper with a membership check. This pattern corresponds to monolithic SafeStrings.

The approach in Listing 30 is a design pattern which can be implemented in any language with records and access to regular expressions (Fowler 1999). This gives the pattern a distinct advantage over regex-validated strings and string literals. It does not require any changes to the target language to introduce these features. It uses only what the language already has. This is useful from the point of view of safety, but is problematic in some respects. Most obviously, it lacks the flexibility of SafeStrings; making operations more difficult to define, and limiting subtyping to the nominal system.

7 Conclusion

We have presented SafeStrings, a language-agnostic approach to type safety for strings. SafeStrings introduce many of the benefits associated with liquid types into an area previously little explored. SafeStrings require no special language mechanisms, requiring only an ability to encode structures and recognisers. One need only find the image of these concepts within the language to encode a SafeString. SafeStrings are applicable either statically or dynamically. Indeed, SafeStrings squeeze more invariants out of simple type systems by treating strings as algebraic structures. The complexity of advanced language features, such as dependent types and GADTs, are thus not required. A simple type system can go further by putting the burden of representation on the producer of library code, rather than the consumer.

We have also presented an instantiation of SafeStrings in TypeScript, showing the relative ease with which they can be encoded and used. Such strings represent a fragment of what can be achieved with dependent types in a non-dependently typed system. We do this by translating a
structure over which we have no particular control (i.e. string) into a form that exposes rich latent structure to the type checker. All artefacts are available at anonymised.repo.to.do.

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