Gemini

Designing and Implementing a Functional Hardware Description Language

Thesis Defense

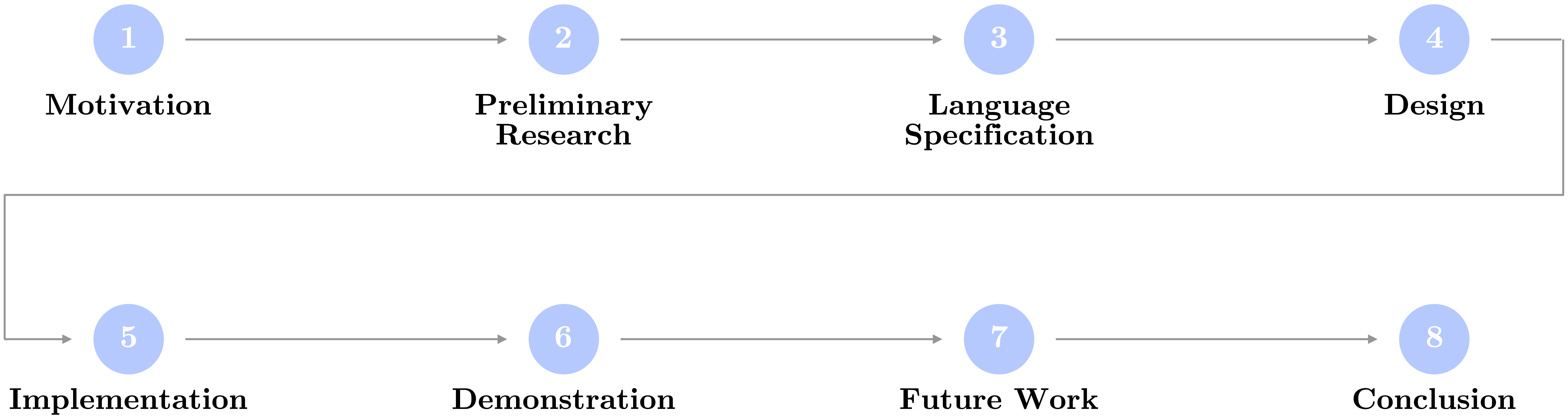
EDMUND T. PRATT, JR.
SCHOOL OF ENGINEERING

Aditya SRINIVASAN

Drew HILTON

APRIL 25, 2018

Roadmap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Preliminary Research
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Language Specification
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Design
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Implementation
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Demonstration
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Future Work
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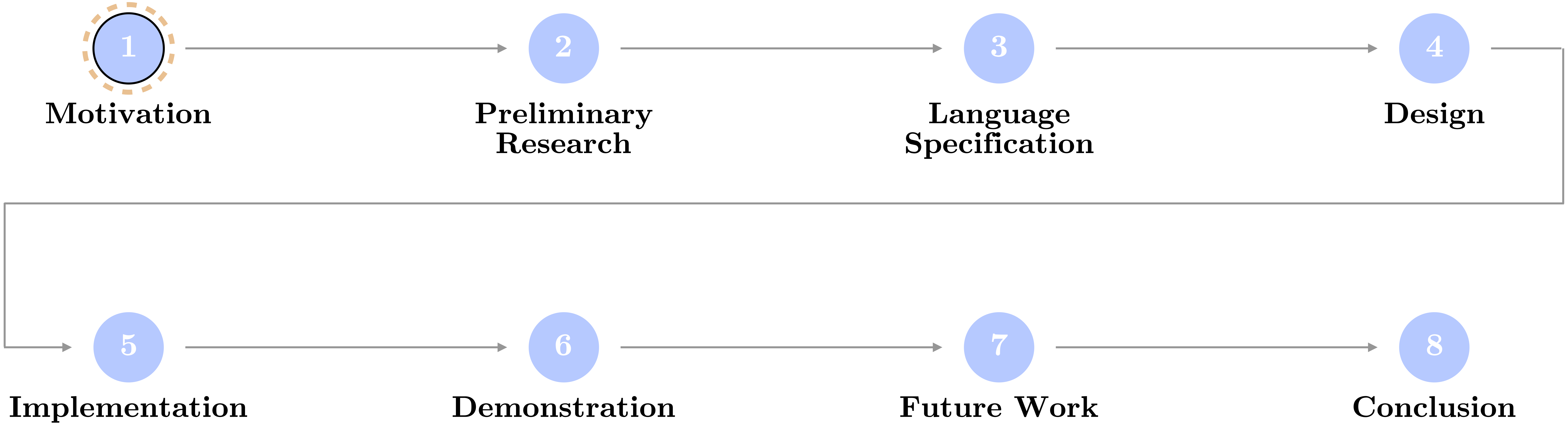
Conclusion

Roadmap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Motivation

The Problem: Verilog lacks the expressivity and modularity of software programming languages, due to a lack of features such as:

- Strong type system
- Recursion
- Pattern-matching
- …and more

Motivation

I spent the last year answering the following questions:

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Question 1
Can I design a programming language that combines the powerful features of software programming languages with the ability to describe electronic circuits?

Motivation

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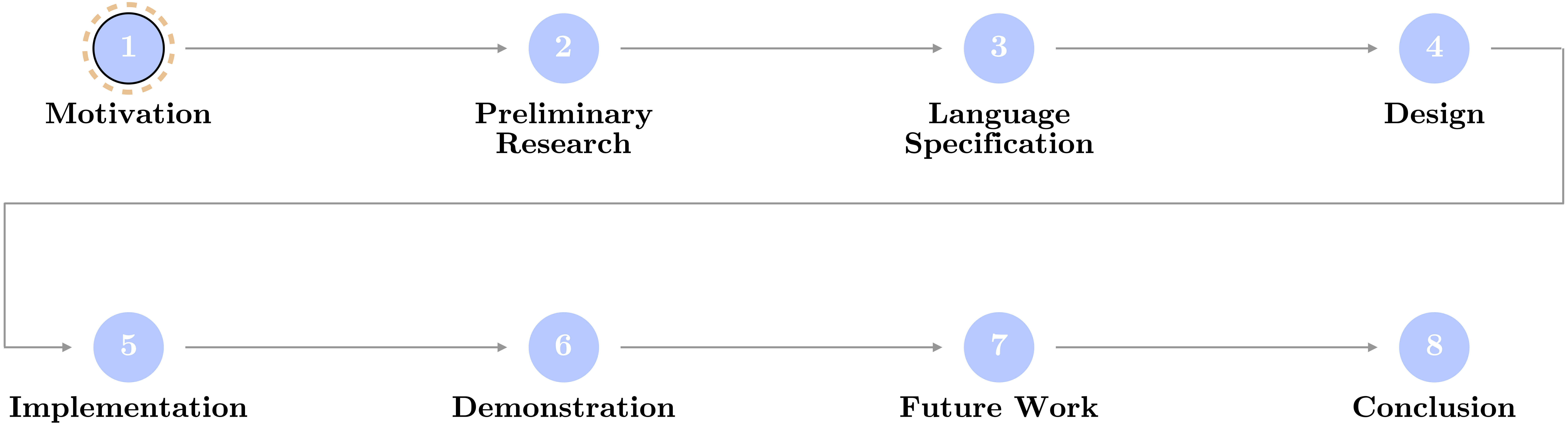
Question 1
Can I design a programming language that combines the powerful features of software programming languages with the ability to describe electronic circuits?

Question 2
Can I develop a compiler that accepts a program in this language and produces an optimized Verilog module?

Roadmap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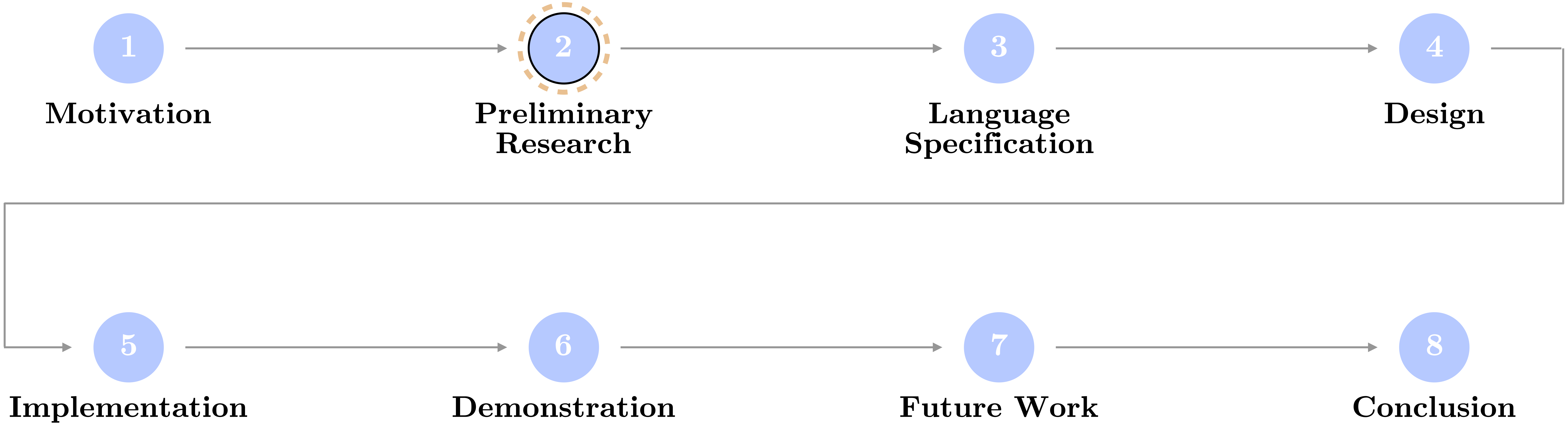
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Preliminary Research

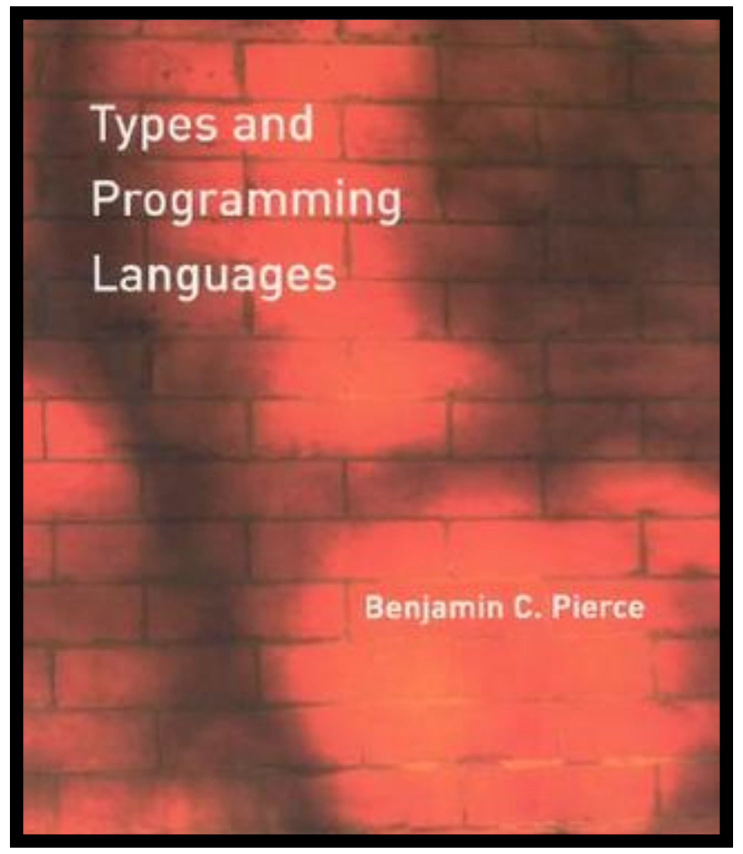
Possessed some prior knowledge through coursework

- ECE 350 (Digital Systems)
- ECE 553 (Compiler Construction)

Did not know enough about type theory to design a powerful language

Preliminary Research

Read the entirety of '<u>Types and Programming Languages</u>' by Benjamin Pierce, a textbook used in graduate-level type-theory seminars



Provided me with the theoretical tools I needed

Preliminary Research

Other languages exist that attempt to do the same thing

Haskell for Hardware (only software programmers can understand)

Lava (not high-level enough)

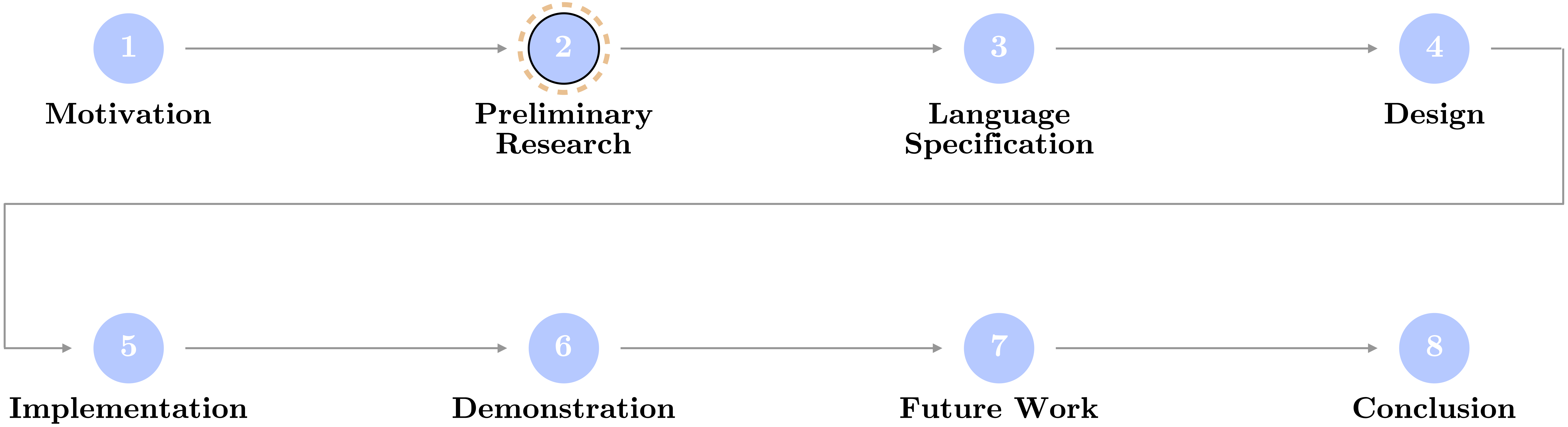
Preliminary Research

Other languages exist that attempt to do the same thing

Haskell for Hardware (only software programmers can understand)
Lava (not high-level enough)

Gemini needs to be accessible to both parties

Roadmap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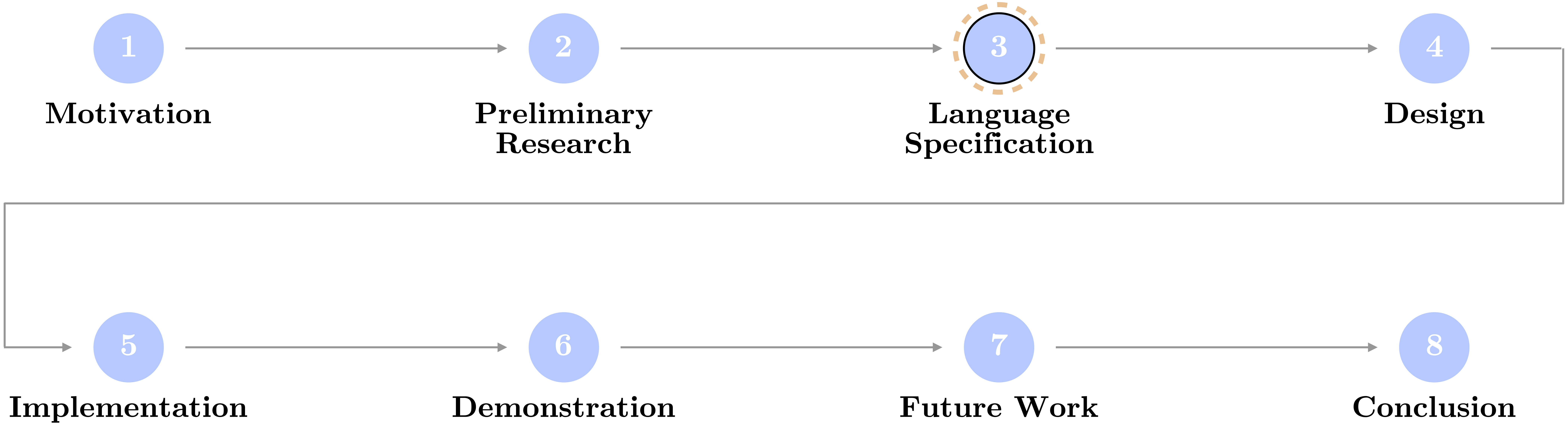
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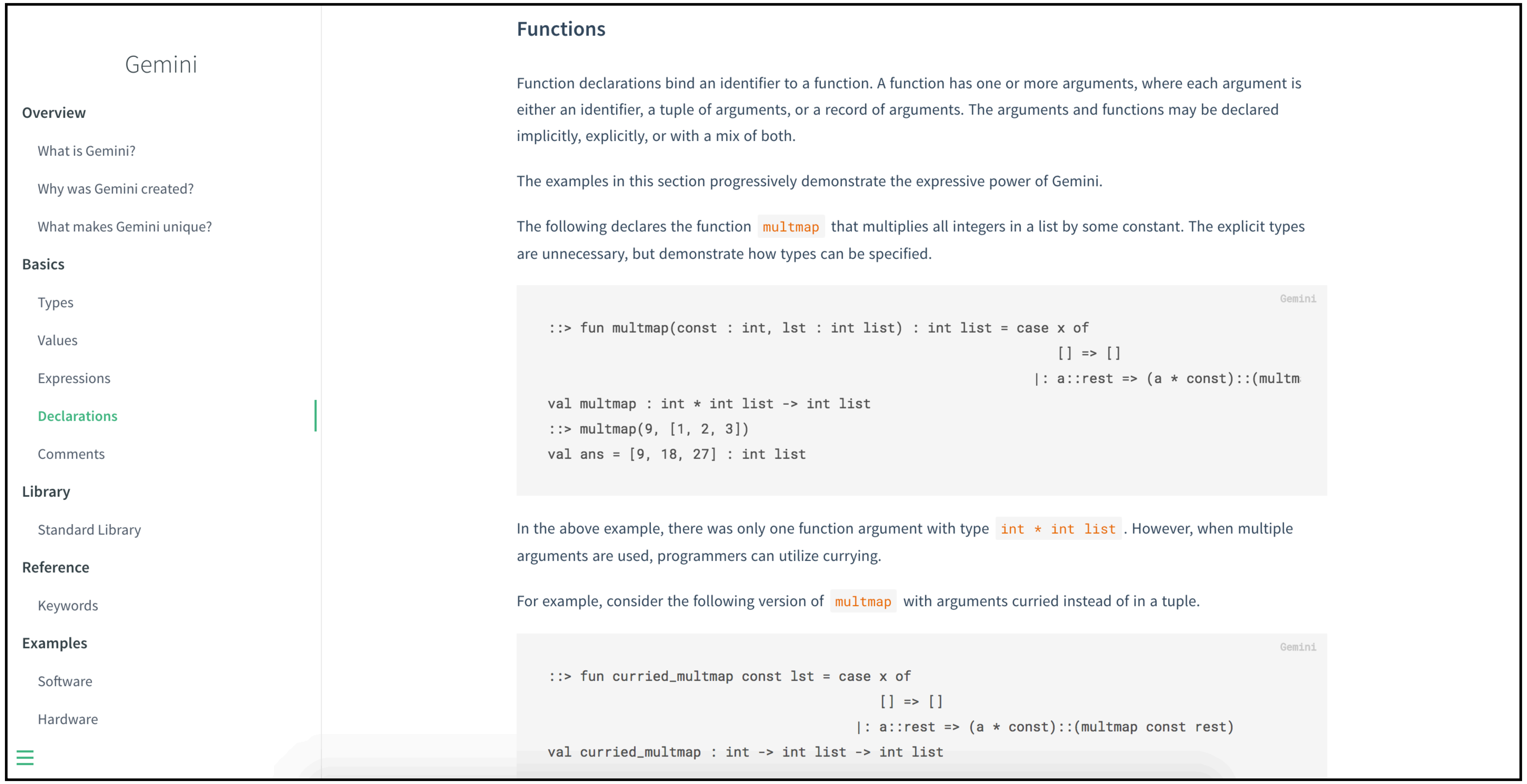
Language Specification

Complete documentation with examples can be found at bit.ly/gemini-docs



Gemini

Functions

Function declarations bind an identifier to a function. A function has one or more arguments, where each argument is either an identifier, a tuple of arguments, or a record of arguments. The arguments and functions may be declared implicitly, explicitly, or with a mix of both.

The examples in this section progressively demonstrate the expressive power of Gemini.

The following declares the function `multmap` that multiplies all integers in a list by some constant. The explicit types are unnecessary, but demonstrate how types can be specified.

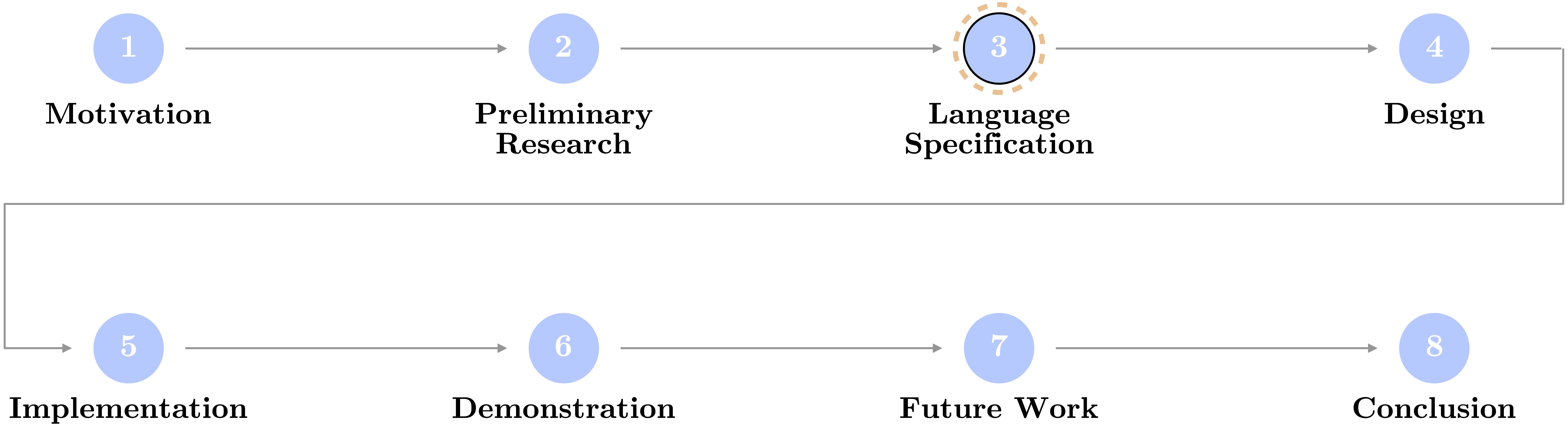
```
Gemini
::> fun multmap(const : int, lst : int list) : int list = case x of
                                                     [] => []
                                                   |: a::rest => (a * const)::(multm
val multmap : int * int list -> int list
::> multmap(9, [1, 2, 3])
val ans = [9, 18, 27] : int list
```

In the above example, there was only one function argument with type `int * int list`. However, when multiple arguments are used, programmers can utilize currying.

For example, consider the following version of `multmap` with arguments curried instead of in a tuple.

```
Gemini
::> fun curried_multmap const lst = case x of
                                      [] => []
                                    |: a::rest => (a * const)::(multmap const rest)
val curried_multmap : int -> int list -> int list
```

Roadmap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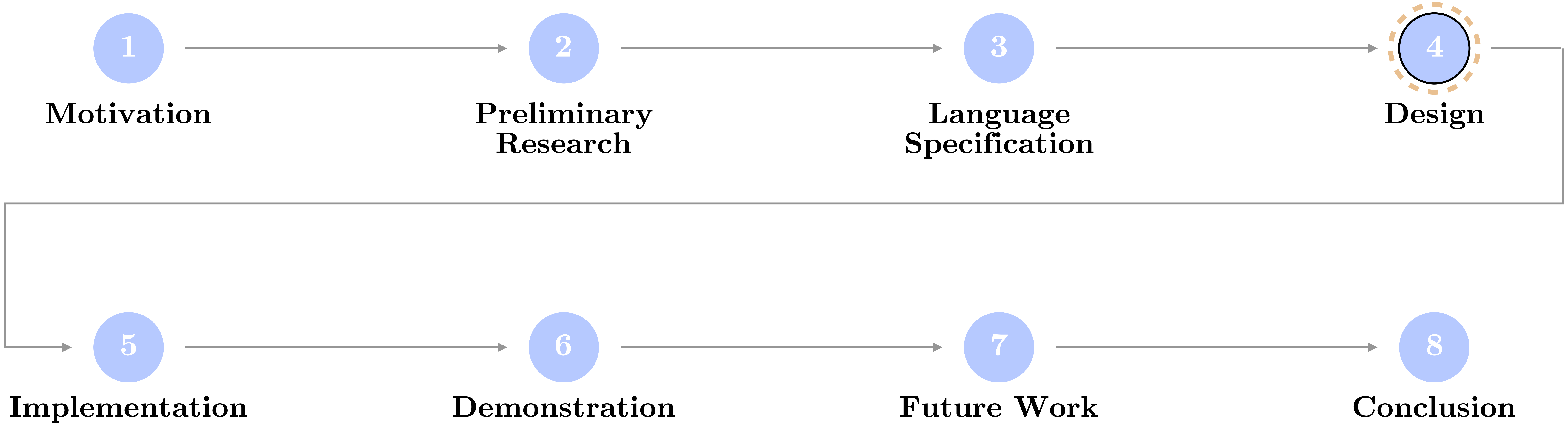
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Design

1. Kinding System
2. Grammar
3. Typing Relation
4. Evaluation Rules
5. Proof of Safety

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2. Grammar
3. Typing Relation
4. Evaluation Rules
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Design // KINDING SYSTEM

What is a type?

DESIGN // KINDING SYSTEM

What is a type?

A classification of a value (`int`, `string`, etc.)

DESIGN // KINDING SYSTEM

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What is a kind?

DESIGN // KINDING SYSTEM

What is a type?

A classification of a value (`int`, `string`, etc.)

What is a kind?

A classification of a type; “the type of types”

DESIGN // KINDING SYSTEM

In conventional programming languages…

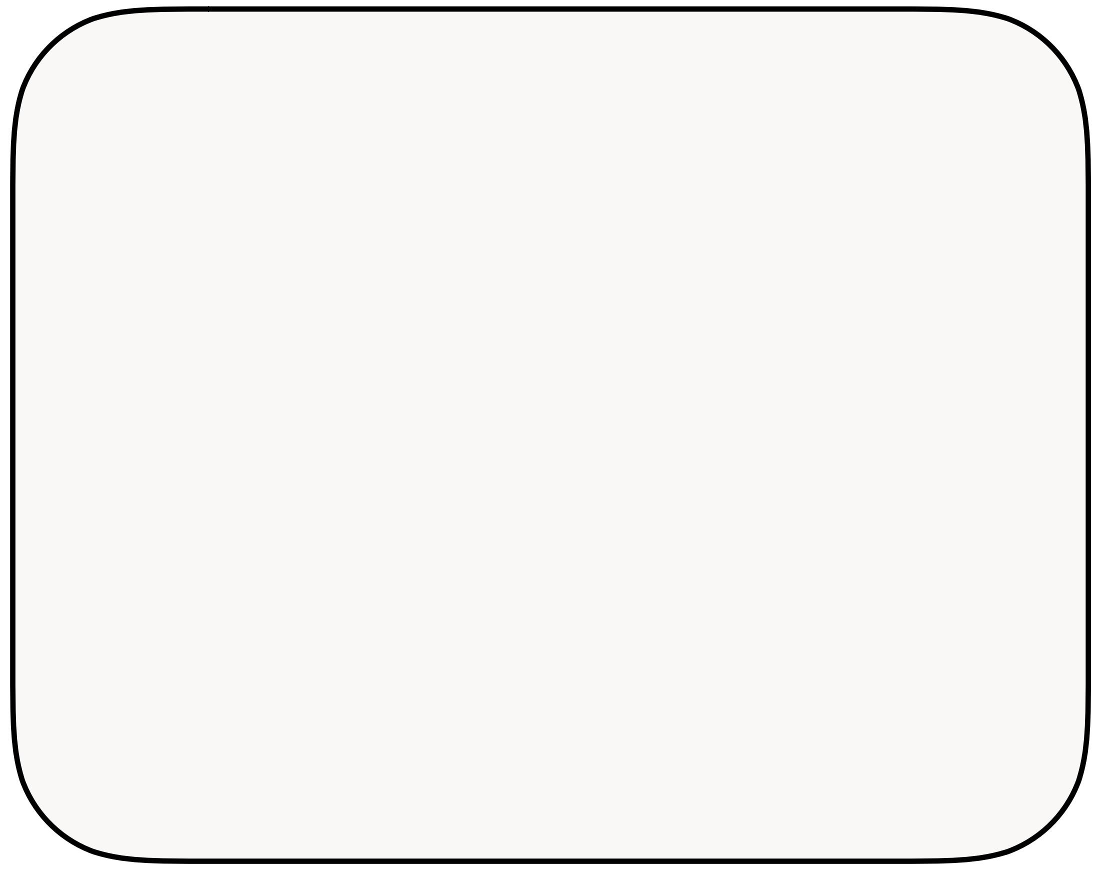
Single atomic kind $*$ (“type”) and the constructor $\Rightarrow$ (“to”)

DESIGN // KINDING SYSTEM

In conventional programming languages…

Single atomic kind $*$ (“type”) and the constructor $\Rightarrow$ (“to”)

$*$



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$*$

$* \Rightarrow *$

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$*$

$* \Rightarrow *$

$* \Rightarrow * \Rightarrow *$

Design // KINDING SYSTEM

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Single atomic kind $*$ (“type”) and the constructor $\Rightarrow$ (“to”)

$*$

`int`

`string`

$* \Rightarrow *$

$* \Rightarrow * \Rightarrow *$

DESIGN // KINDING SYSTEM

In conventional programming languages…

Single atomic kind $*$ (“type”) and the constructor $\Rightarrow$ (“to”)

Design // kinding system

In conventional programming languages…

Single atomic kind $*$ (“type”) and the constructor $\Rightarrow$ (“to”)

`list`

$* \Rightarrow *$

DESIGN // KINDING SYSTEM

In conventional programming languages...

Single atomic kind $*$ ("type") and the constructor $\Rightarrow$ ("to")

`int list`

$* \Rightarrow *$

DESIGN // KINDING SYSTEM

In conventional programming languages…

Single atomic kind $*$ (“type”) and the constructor $\Rightarrow$ (“to”)

$*$

`int`

`string`

$* \Rightarrow *$

`list`

$* \Rightarrow * \Rightarrow *$

`int list`

$*$

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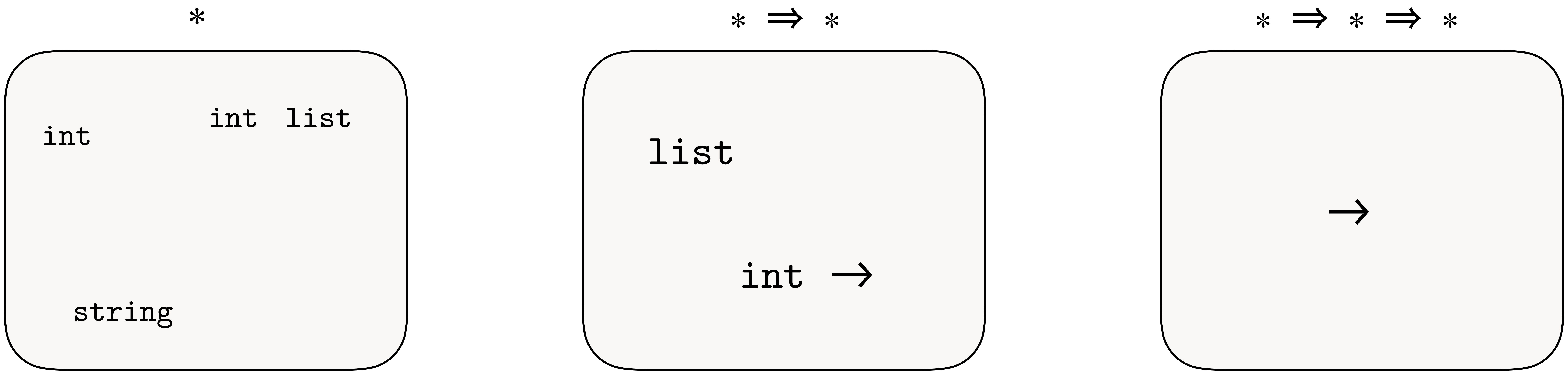

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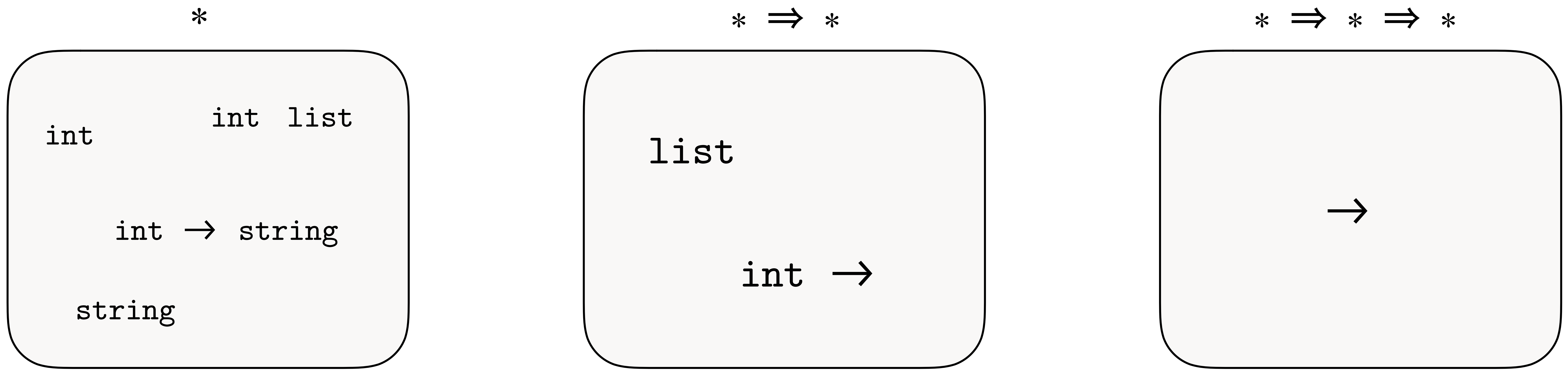

DESIGN // KINDING SYSTEM

In Gemini…

Three atomic kinds `S`, `H`, and `M` and the constructor $\Rightarrow$

Design // KINDING SYSTEM

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Three atomic kinds `S`, `H`, and `M` and the constructor $\Rightarrow$

$$
\begin{array}{lll}
S & ::= & \texttt{int} \\
 & | & \texttt{real} \\
 & | & \texttt{string} \\
 & | & T_S\ \texttt{list} \\
 & | & \{\texttt{l}_1\texttt{:}\ T_S\texttt{, ..., l}_n\texttt{:}\ T_S\} \\
 & | & T_S\ \texttt{ref} \\
 & | & T_H\ \texttt{sw} \\
 & | & \texttt{C}_\texttt{i}\ T_S \\
 & | & T_S \rightarrow T_S \\
 & & \\
H & ::= & \texttt{bit} \\
 & | & T_H\ [n] \\
 & | & T_H\ \texttt{@}\ n \\
 & | & \texttt{\#}\{\texttt{l}_1\texttt{:}\ T_H\texttt{, ..., l}_n\texttt{:}\ T_H\} \\
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M & ::= & T_H \rightarrow T_H
\end{array}
$$

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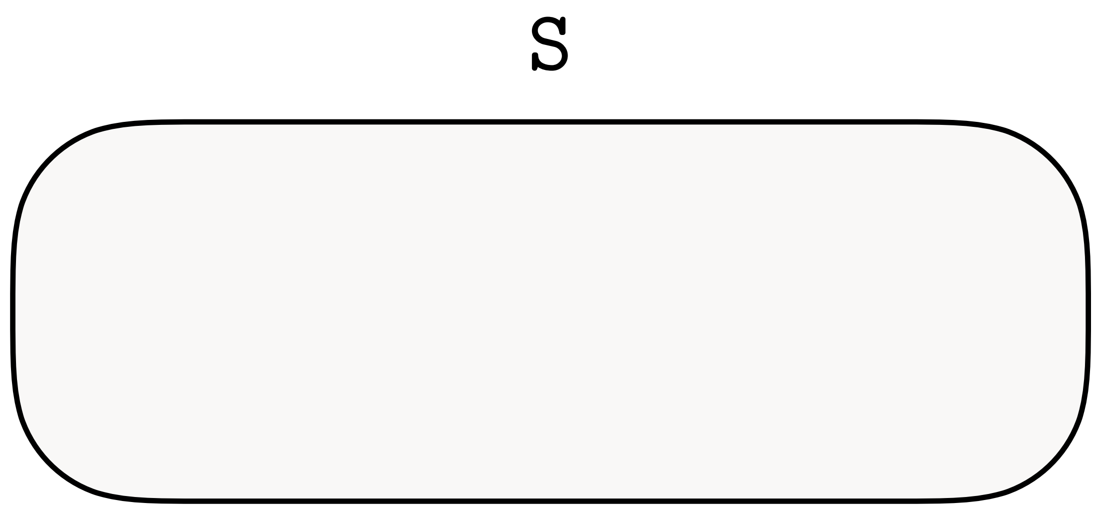
Three atomic kinds `S`, `H`, and `M` and the constructor ⇒



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      |  real
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      |  T_S list
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      |  T_S ref
      |  T_H sw
      |  C_i T_S
      |  T_S → T_S

H    ::= bit
      |  T_H [n]
      |  T_H @ n
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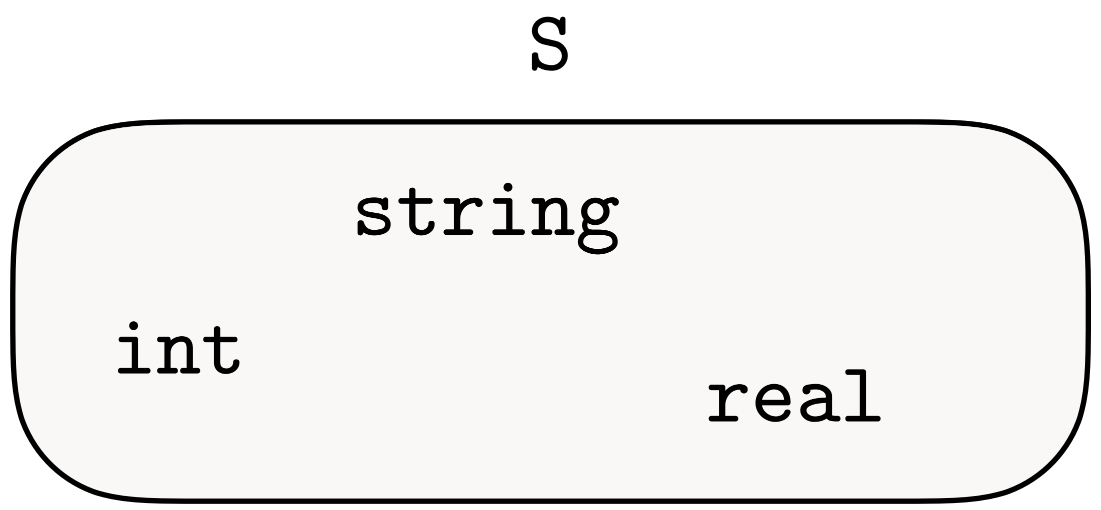

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S ::= int
| real
| string
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| {l_1: T_S, ..., l_n: T_S}
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| T_H sw
| C_i T_S
| $T_S \to T_S$

H ::= bit
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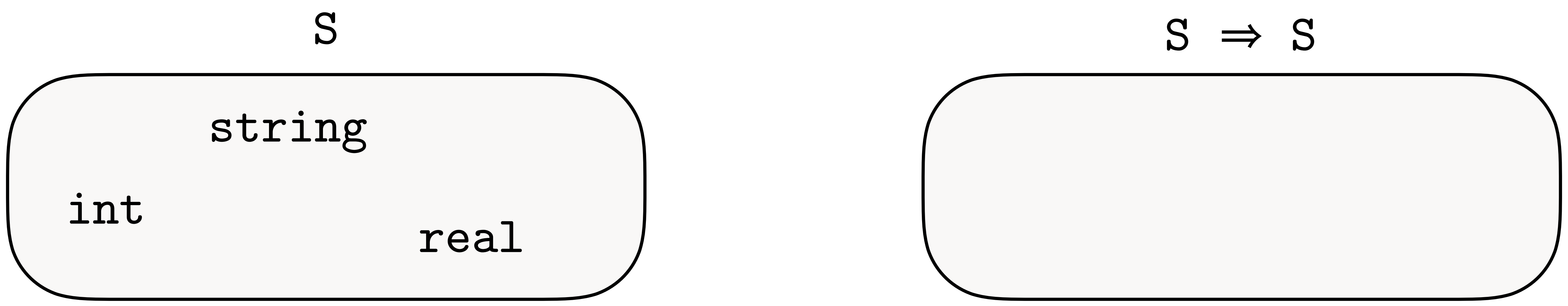

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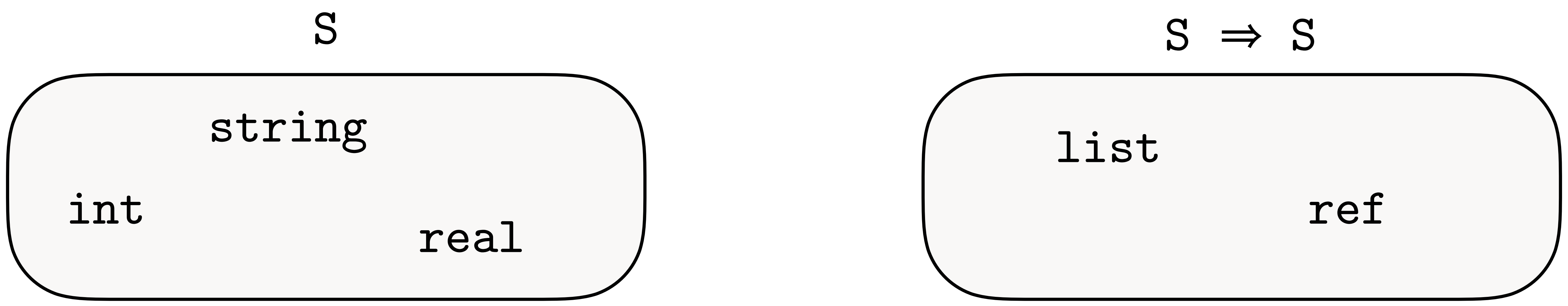

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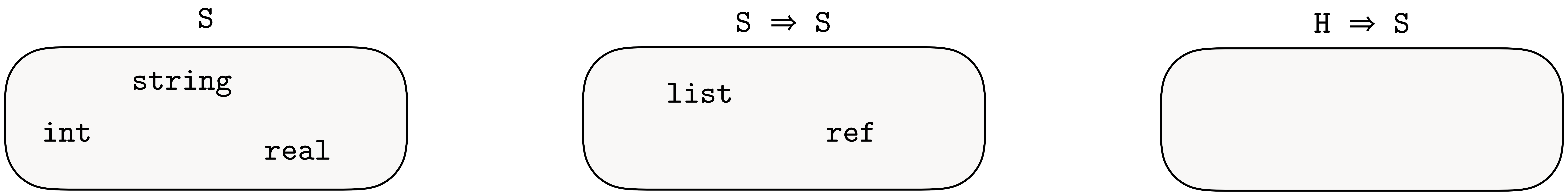

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M    ::= T_H → T_H
```

In Gemini...

Three atomic kinds `S`, `H`, and `M` and the constructor ⇒

`S`: string, int, real

`S ⇒ S`: list, ref

`H ⇒ S`: sw

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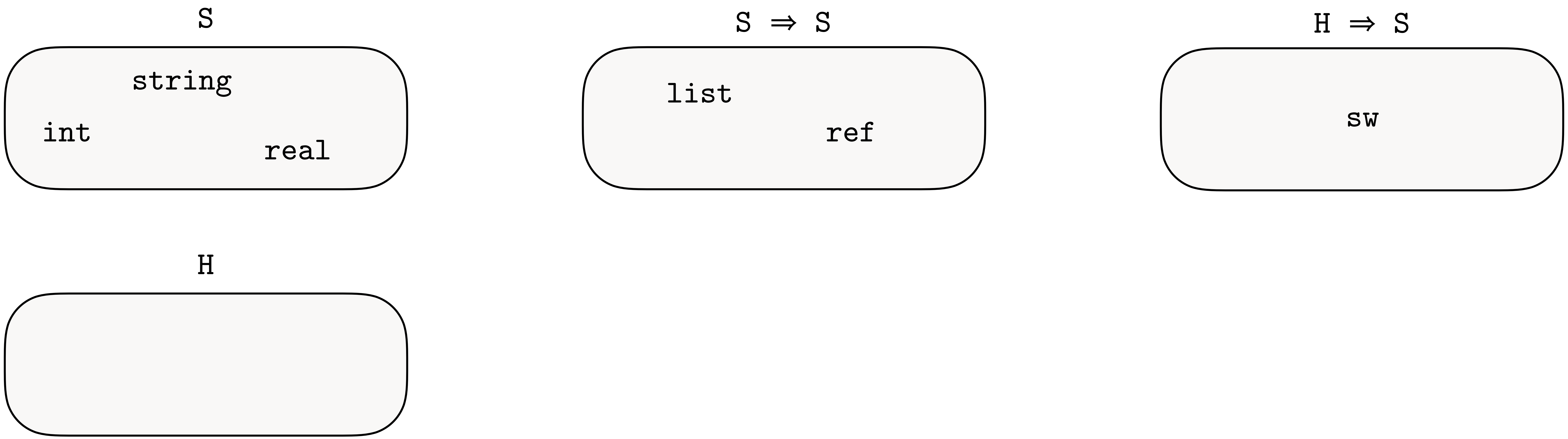

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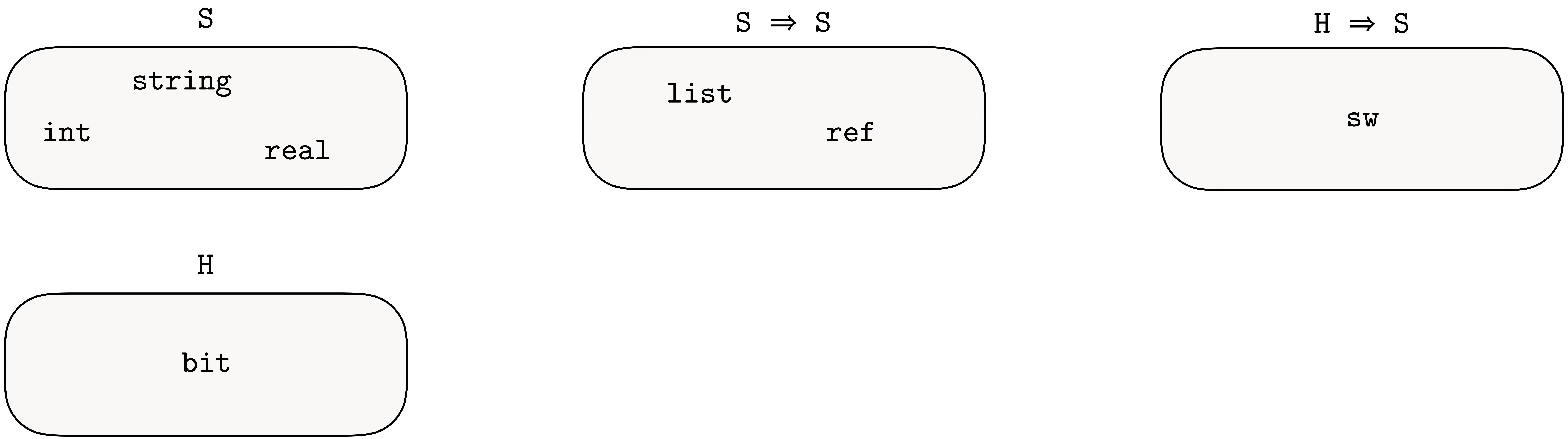

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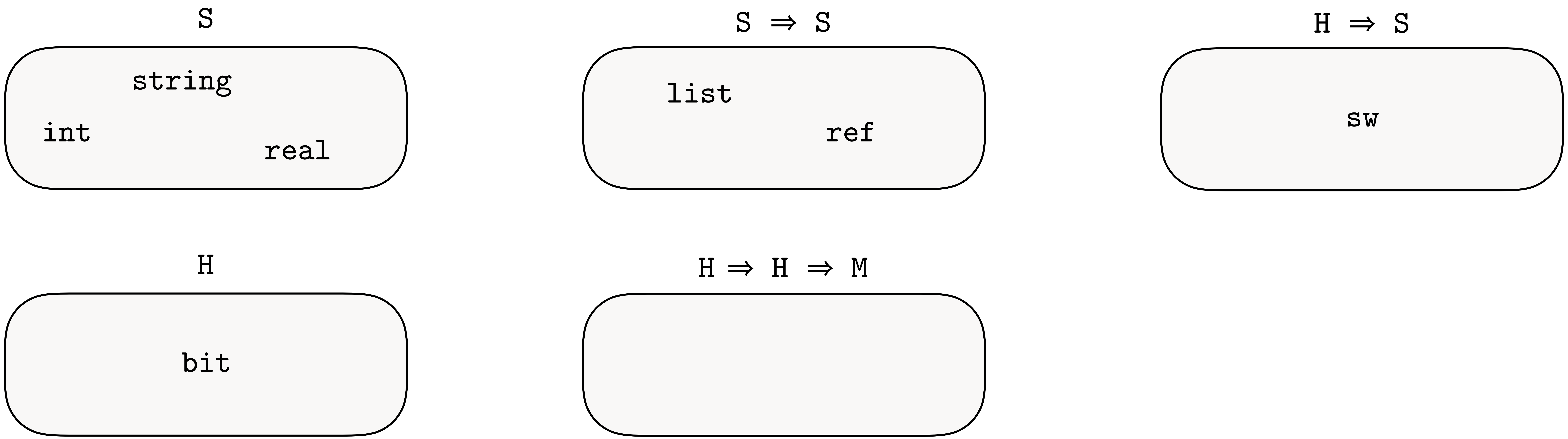

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M    ::= T_H → T_H
```

In Gemini...

Three atomic kinds `S`, `H`, and `M` and the constructor $\Rightarrow$

`S`

`string` `int` `real`

`S ⇒ S`

`list` `ref`

`H ⇒ S`

`sw`

`H`

`bit`

`H ⇒ H ⇒ M`

$\rightsquigarrow$

Design // KINDING SYSTEM

```
S    ::= int
       |  real
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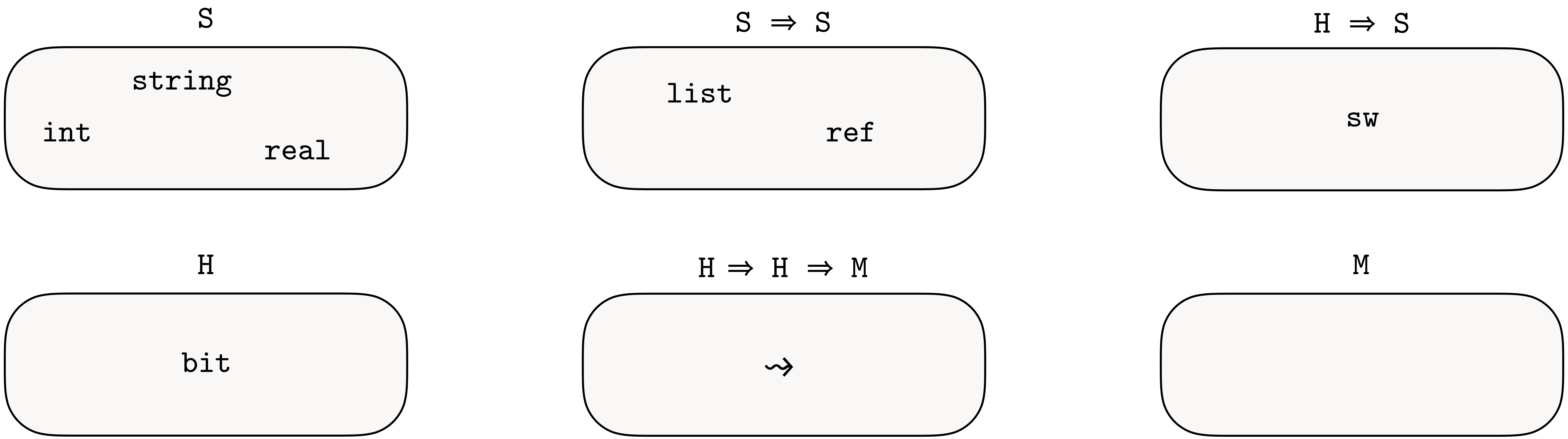
In Gemini…

Three atomic kinds `S`, `H`, and `M` and the constructor ⇒



Design // KINDING SYSTEM

```
S          ::= int
             |  real
             |  string
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H          ::= bit
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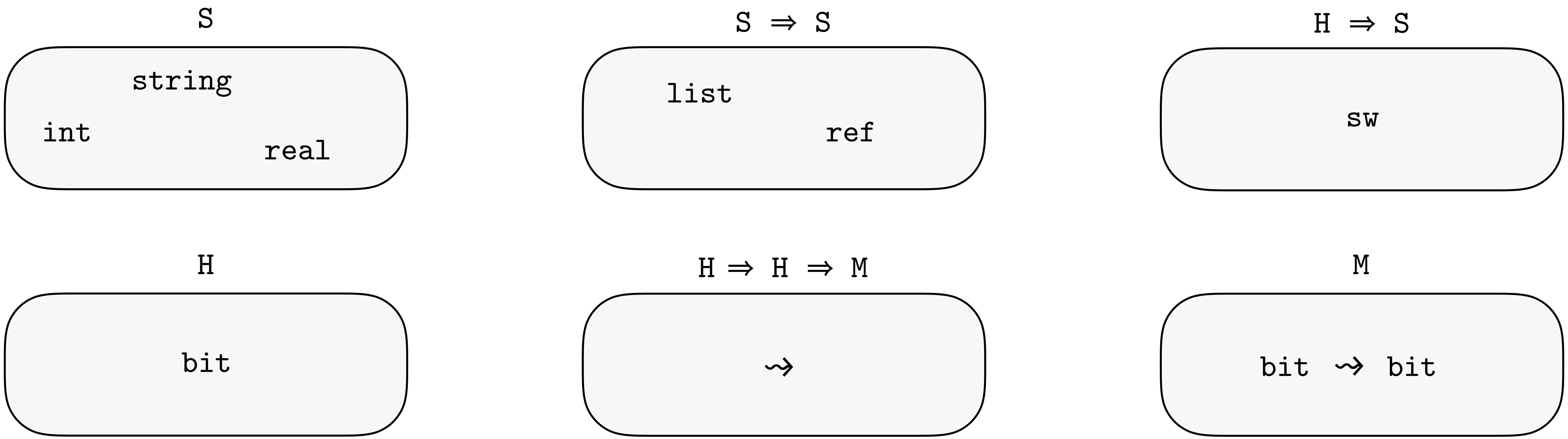
             |  #{l₁: T_H, ..., lₙ: T_H}

M          ::= T_H → T_H
```

In Gemini...

Three atomic kinds S, H, and M and the constructor $\Rightarrow$



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In Gemini…

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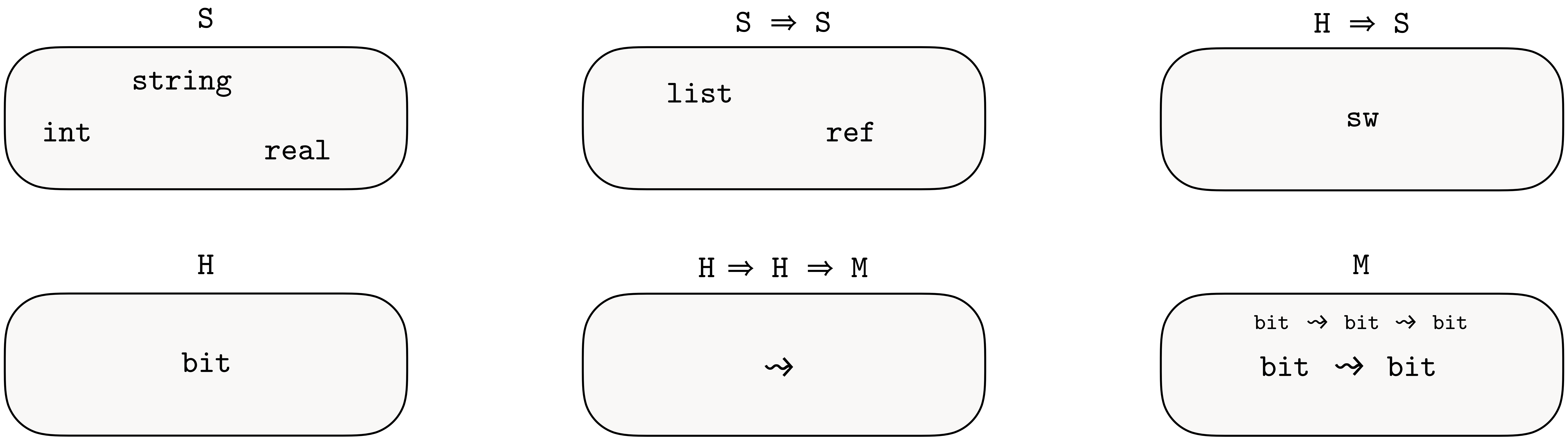

DESIGN // KINDING SYSTEM

S ::= int | real | string | T_S list | {l₁: T_S, ..., lₙ: T_S} | T_S ref | T_H sw | Cᵢ T_S | $T_S \to T_S$

H ::= bit | T_H [n] | T_H @ n | #{l₁: T_H, ..., lₙ: T_H}

M ::= $T_H \to T_H$

In Gemini…

Three atomic kinds `S`, `H`, and `M` and the constructor ⇒

S: string, int, real

S ⇒ S: list, ref

H ⇒ S: sw

H: bit

H ⇒ H ⇒ M: ⇝

M: ~~bit ⇝ bit ⇝ bit~~ bit ⇝ bit

DESIGN // KINDING SYSTEM

$$
\begin{array}{lll}
S & ::= & \texttt{int} \\
 & | & \texttt{real} \\
 & | & \texttt{string} \\
 & | & T_S\ \texttt{list} \\
 & | & \{\texttt{l}_1 : T_S, \ldots, \texttt{l}_n : T_S\} \\
 & | & T_S\ \texttt{ref} \\
 & | & T_H\ \texttt{sw} \\
 & | & \texttt{C}_i\ T_S \\
 & | & T_S \rightarrow T_S \\
 & & \\
H & ::= & \texttt{bit} \\
 & | & T_H\ [n] \\
 & | & T_H\ \texttt{@}\ n \\
 & | & \#\{\texttt{l}_1 : T_H, \ldots, \texttt{l}_n : T_H\} \\
 & & \\
M & ::= & T_H \rightarrow T_H
\end{array}
$$

In Gemini...

Three atomic kinds `S`, `H`, and `M` and the constructor $\Rightarrow$

S

`string` ~~`bit list`~~ `int` `real`

S ⇒ S

`list` `ref`

H ⇒ S

`sw`

H

`bit`

H ⇒ H ⇒ M

$\rightsquigarrow$

M

~~`bit` $\rightsquigarrow$ `bit` $\rightsquigarrow$ `bit`~~

`bit` $\rightsquigarrow$ `bit`

Design // KINDING SYSTEM

$$
\begin{array}{lll}
S & ::= & \texttt{int} \\
 & | & \texttt{real} \\
 & | & \texttt{string} \\
 & | & T_S\ \texttt{list} \\
 & | & \{\texttt{l}_1\texttt{:}\ T_S\texttt{,}\ \ldots\texttt{,}\ \texttt{l}_n\texttt{:}\ T_S\} \\
 & | & T_S\ \texttt{ref} \\
 & | & T_H\ \texttt{sw} \\
 & | & \texttt{C}_i\ T_S \\
 & | & T_S \rightarrow T_S \\
H & ::= & \texttt{bit} \\
 & | & T_H\ [n] \\
 & | & T_H\ \texttt{@}\ n \\
 & | & \texttt{\#}\{\texttt{l}_1\texttt{:}\ T_H\texttt{,}\ \ldots\texttt{,}\ \texttt{l}_n\texttt{:}\ T_H\} \\
M & ::= & T_H \rightarrow T_H
\end{array}
$$

In Gemini...

Three atomic kinds `S`, `H`, and `M` and the constructor ⇒

S

`string` ~~`bit list`~~ `int` `real`

S ⇒ S

`list` `ref`

H ⇒ S

`sw`

H

~~`string ref`~~

`bit`

H ⇒ H ⇒ M

⇝

M

~~`bit ⇝ bit ⇝ bit`~~

`bit ⇝ bit`

DESIGN // KINDING SYSTEM

In Gemini...

Three atomic kinds `S`, `H`, and `M` and the constructor $\Rightarrow$

$$
\begin{array}{lcl}
S & ::= & \texttt{int} \\
  & | & \texttt{real} \\
  & | & \texttt{string} \\
  & | & T_S \ \texttt{list} \\
  & | & \{\texttt{l}_1\texttt{:}\ T_S\texttt{, ..., l}_n\texttt{:}\ T_S\} \\
  & | & T_S \ \texttt{ref} \\
  & | & T_H \ \texttt{sw} \\
  & | & \texttt{C}_i \ T_S \\
  & | & T_S \rightarrow T_S \\
  & & \\
H & ::= & \texttt{bit} \\
  & | & T_H \ [n] \\
  & | & T_H \ \texttt{@} \ n \\
  & | & \#\{\texttt{l}_1\texttt{:}\ T_H\texttt{, ..., l}_n\texttt{:}\ T_H\} \\
  & & \\
M & ::= & T_H \rightarrow T_H
\end{array}
$$

DESIGN // KINDING SYSTEM

In Gemini…

Three atomic kinds `S`, `H`, and `M` and the constructor ⇒

Modeling time as a type

$$
\begin{array}{lll}
S & ::= & \texttt{int} \\
 & | & \texttt{real} \\
 & | & \texttt{string} \\
 & | & T_S\ \texttt{list} \\
 & | & \{\texttt{l}_1\texttt{:}\ T_S,\ \ldots,\ \texttt{l}_n\texttt{:}\ T_S\} \\
 & | & T_S\ \texttt{ref} \\
 & | & T_H\ \texttt{sw} \\
 & | & \texttt{C}_i\ T_S \\
 & | & T_S \rightarrow T_S \\
 & & \\
H & ::= & \texttt{bit} \\
 & | & T_H\ [n] \\
 & | & \boxed{T_H\ @\ n} \\
 & | & \#\{\texttt{l}_1\texttt{:}\ T_H,\ \ldots,\ \texttt{l}_n\texttt{:}\ T_H\} \\
 & & \\
M & ::= & T_H \rightarrow T_H
\end{array}
$$

DESIGN // KINDING SYSTEM

In Gemini...

Three atomic kinds `S`, `H`, and `M` and the constructor $\Rightarrow$

Value-parameterized types

$$
\begin{array}{lll}
S & ::= & \texttt{int} \\
 & | & \texttt{real} \\
 & | & \texttt{string} \\
 & | & T_S\ \texttt{list} \\
 & | & \{\texttt{l}_1\texttt{:}\ T_S\texttt{,}\ \ldots\texttt{,}\ \texttt{l}_n\texttt{:}\ T_S\} \\
 & | & T_S\ \texttt{ref} \\
 & | & T_H\ \texttt{sw} \\
 & | & \texttt{C}_\texttt{i}\ T_S \\
 & | & T_S \rightarrow T_S \\
 & & \\
H & ::= & \texttt{bit} \\
 & | & \boxed{T_H\ [n]} \\
 & | & T_H\ \texttt{@}\ n \\
 & | & \texttt{\#}\{\texttt{l}_1\texttt{:}\ T_H\texttt{,}\ \ldots\texttt{,}\ \texttt{l}_n\texttt{:}\ T_H\} \\
 & & \\
M & ::= & T_H \rightarrow T_H
\end{array}
$$

Design

1. Kinding System
2. Grammar
3. Typing Relation
4. Evaluation Rules
5. Proof of Safety

DESIGN // GRAMMAR

⟨*exp*⟩ ::= ⟨*literal*⟩
| ⟨*access*⟩
| ⟨*let binding*⟩
| ⟨*conditional*⟩
| ⟨*operation*⟩
| ⟨*assignment*⟩
| ⟨*pattern match*⟩
| ⟨*sequence*⟩
| ⟨*application*⟩

⟨*literal*⟩ ::= ⟨*identifier*⟩
| ⟨*integer literal*⟩
| ⟨*real literal*⟩
| ⟨*string literal*⟩
| ⟨*list literal*⟩
| ⟨*software record literal*⟩
| ⟨*ref literal*⟩
| ⟨*sw literal*⟩

⟨*identifier*⟩ ::= ⟨*id-start*⟩ ⟨*id-tail*⟩

⟨*id-start*⟩ ::= {any alphabetic character or underscore}

⟨*id-tail*⟩ ::= {any alphanumeric character or underscore} ⟨*id-tail*⟩
| ε

⟨*integer literal*⟩ ::= ⟨*binary-integer*⟩
| ⟨*octal-integer*⟩
| ⟨*decimal-integer*⟩
| ⟨*hex-integer*⟩

⟨*binary-integer*⟩ ::= `#'b:` ⟨*binary-digits*⟩

⟨*octal-integer*⟩ ::= `#'o:` ⟨*octal-digits*⟩

⟨*decimal-integer*⟩ ::= ⟨*decimal-digits*⟩
| ⟨*sign*⟩ ⟨*decimal-digits*⟩

⟨*hex-integer*⟩ ::= `#'x:` ⟨*hex-digits*⟩

Design // GRAMMAR

⟨*exp*⟩	::=	⟨*literal*⟩
	|	⟨*access*⟩
	|	⟨*let binding*⟩
	|	⟨*conditional*⟩
	|	⟨*operation*⟩
	|	⟨*assignment*⟩
	|	⟨*pattern match*⟩
	|	⟨*sequence*⟩
	|	⟨*application*⟩
⟨*literal*⟩	::=	⟨*identifier*⟩
	|	⟨*integer literal*⟩
	|	⟨*real literal*⟩
	|	⟨*string literal*⟩
	|	⟨*list literal*⟩
	|	⟨*software record literal*⟩
	|	⟨*ref literal*⟩
	|	⟨*sw literal*⟩

⟨*identifier*⟩	::=	⟨*id-start*⟩ ⟨*id-tail*⟩
⟨*id-start*⟩	::=	{any alphabetic character or underscore}
⟨*id-tail*⟩	::=	{any alphanumeric character or underscore} ⟨*id-tail*⟩
	|	ε
⟨*integer literal*⟩	::=	⟨*binary-integer*⟩
	|	⟨*octal-integer*⟩
	|	⟨*decimal-integer*⟩
	|	⟨*hex-integer*⟩
⟨*binary-integer*⟩	::=	`#'b:` ⟨*binary-digits*⟩
⟨*octal-integer*⟩	::=	`#'o:` ⟨*octal-digits*⟩
⟨*decimal-integer*⟩	::=	⟨*decimal-digits*⟩
	|	⟨*sign*⟩ ⟨*decimal-digits*⟩
⟨*hex-integer*⟩	::=	`#'x:` ⟨*hex-digits*⟩

Shown in full in Appendix B

DESIGN // GRAMMAR

```
⟨exp⟩                     ::= ⟨literal⟩
                            | ⟨access⟩
                            | ⟨let binding⟩
                            | ⟨operation⟩
                            | ⟨parameterization⟩

⟨literal⟩                 ::= ⟨bit literal⟩
                            | ⟨array literal⟩
                            | ⟨hardware record literal⟩

⟨bit literal⟩             ::= 'b: ⟨binary-digit⟩

⟨array literal⟩           ::= #[ ⟨list-body⟩ ]
                            | ⟨gen-array⟩
                            | ⟨bit-array⟩

⟨gen-array⟩               ::= #[ ⟨exp⟩ ; gen ⟨identifier⟩ => ⟨exp⟩ ]

⟨bit-array⟩               ::= ⟨exp⟩ 's: ⟨exp⟩
                            | ⟨exp⟩ 'u: ⟨exp⟩
                            | ⟨exp⟩ 'r: ⟨exp⟩

⟨hardware record literal⟩ ::= #{ ⟨record-body⟩ }
```

Design // GRAMMAR

⟨*exp*⟩	::=	⟨*literal*⟩
	|	⟨*access*⟩
	|	⟨*let binding*⟩
	|	⟨*operation*⟩
	|	⟨*parameterization*⟩
⟨*literal*⟩	::=	⟨*bit literal*⟩
	|	⟨*array literal*⟩
	|	⟨*hardware record literal*⟩
⟨*bit literal*⟩	::=	`'b:` ⟨*binary-digit*⟩
⟨*array literal*⟩	::=	`#[` ⟨*list-body*⟩ `]`
	|	⟨*gen-array*⟩
	|	⟨*bit-array*⟩
⟨*gen-array*⟩	::=	`#[` ⟨*exp*⟩ `; gen` ⟨*identifier*⟩ `=>` ⟨*exp*⟩ `]`
⟨*bit-array*⟩	::=	⟨*exp*⟩ `'s:` ⟨*exp*⟩
	|	⟨*exp*⟩ `'u:` ⟨*exp*⟩
	|	⟨*exp*⟩ `'r:` ⟨*exp*⟩
⟨*hardware record literal*⟩	::=	`#{` ⟨*record-body*⟩ `}`

Shown in full in Appendix B

Design

1. Kinding System
2. Grammar
3. Typing Relation
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5. Proof of Safety

DESIGN // TYPING RELATION

Each typing rule is a theorem

DESIGN // TYPING RELATION

Each typing rule is a theorem

$$\frac{\text{hypothesis}}{\text{conclusion}}\ (\text{T-NAME})$$

Design // typing relation

Examples of typing rules

$$\frac{\texttt{t}_1\texttt{:int} \quad \texttt{t}_2\texttt{:int}}{\texttt{t}_1 \texttt{ + } \texttt{t}_2 \texttt{ : int}} \ (\textsc{T-Int-Add})$$

DESIGN // TYPING RELATION

Examples of typing rules

$$\frac{\texttt{t}_1 : \texttt{T}_\texttt{H} \qquad \texttt{t}_2 : \texttt{T}_\texttt{H}}{\texttt{t}_1 \ \& \ \texttt{t}_2 : \texttt{T}_\texttt{H}} \quad \text{(T-AND)}$$

DESIGN // TYPING RELATION

Examples of typing rules

$$\frac{\texttt{t}_1 : \texttt{T}_\texttt{H} \qquad \texttt{t}_2 : \texttt{T}_\texttt{H}}{\texttt{t}_1 \ \& \ \texttt{t}_2 : \texttt{T}_\texttt{H}} \quad \text{(T-AND)}$$

51 rules in total, shown in full in Appendix B

Design

1. Kinding System
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5. Proof of Safety

DESIGN // EVALUATION RULES

Defining the semantics of the language

DESIGN // EVALUATION RULES

Defining the semantics of the language

1. Operational semantics
2. Denotational semantics
3. Axiomatic semantics

Design // evaluation rules

Defining the semantics of the language

1. Operational semantics
2. ~~Denotational semantics~~
3. ~~Axiomatic semantics~~

DESIGN // EVALUATION RULES

Operational semantics define an abstract state machine

Design // EVALUATION RULES

Operational semantics define an abstract state machine

$$f\left(\boxed{\texttt{exp}}\right) = \boxed{\texttt{exp'}}$$

DESIGN // EVALUATION RULES

Operational semantics define an abstract state machine

$$f\left(\boxed{\texttt{exp}}\right) = \boxed{\texttt{exp'}}$$

$$f\left(\boxed{\texttt{val}}\right) = \texttt{terminal}$$

DESIGN // EVALUATION RULES

Operational semantics can be further partitioned

1. Structural (small-step)
2. Natural (big-step)

DESIGN // EVALUATION RULES

Operational semantics can be further partitioned

1. Structural (small-step)
2. ~~Natural (big-step)~~

Design // evaluation rules

Each evaluation rule is a theorem

$$\frac{\text{hypothesis}}{\text{conclusion}}\ \text{(E-NAME)}$$

DESIGN // EVALUATION RULES

Examples of evaluation rules

$$\frac{\mathtt{t_1} \longrightarrow \mathtt{t_1'}}{\mathtt{if}\ \mathtt{t_1}\ \mathtt{then}\ \mathtt{t_2}\ \mathtt{else}\ \mathtt{t_3} \longrightarrow \mathtt{if}\ \mathtt{t_1'}\ \mathtt{then}\ \mathtt{t_2}\ \mathtt{else}\ \mathtt{t_3}} \quad \text{(E-IFELSE)}$$

Design // EVALUATION RULES

Examples of evaluation rules

$$\texttt{if 0 then } \mathtt{t}_2 \texttt{ else } \mathtt{t}_3 \longrightarrow \mathtt{t}_3 \qquad \text{(E-IfElse-F)}$$

DESIGN // EVALUATION RULES

Examples of evaluation rules

$$\texttt{if 0 then } \texttt{t}_2 \texttt{ else } \texttt{t}_3 \longrightarrow \texttt{t}_3 \qquad \text{(E-IFELSE-F)}$$

97 rules in total, shown in full in Appendix B

DESIGN

1. Kinding System
2. Grammar
3. Typing Relation
4. Evaluation Rules
5. Proof of Safety

DESIGN // PROOF OF SAFETY

We first prove two supporting theorems

DESIGN // PROOF OF SAFETY

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Theorem of Progress

Suppose `t` is a closed, well-typed term ($\vdash$ `t : T` for some `T`). Then either `t` is a value or else there is some `t'` with `t` $\longrightarrow$ `t'`.

DESIGN // PROOF OF SAFETY

We first prove two supporting theorems

Theorem of Progress

Suppose `t` is a closed, well-typed term ($\vdash$ `t : T` for some `T`). Then either `t` is a value or else there is some `t'` with `t` $\longrightarrow$ `t'`.

Theorem of Preservation

If `t : R` and `t` $\longrightarrow$ `t'`, then `t' : R`.

DESIGN // PROOF OF SAFETY

Proof by structural induction

Proof: By structural induction on a derivation of $\mathtt{t} : \mathtt{T}$.

Case T-INT, T-REAL, T-STRING, T-BIT, T-NIL:
Immediate since t is a value.

Case T-APP:

$\mathtt{t} = \mathtt{t}_1\ \mathtt{t}_2$
$\vdash \mathtt{t}_1 : \mathtt{T}_{11} \to \mathtt{T}_{12}$
$\vdash \mathtt{t}_2 : \mathtt{T}_{12}$

By the induction hypothesis, either $\mathtt{t}_1$ is a value or else there is some other $\mathtt{t}_1'$ for which $\mathtt{t}_1 \longrightarrow \mathtt{t}_1'$, and likewise for $\mathtt{t}_2$. If $\mathtt{t}_1 \longrightarrow \mathtt{t}_1'$ then by E-APP1, $\mathtt{t} \longrightarrow \mathtt{t}_1'\ \mathtt{t}_2$. On the other hand, if $\mathtt{t}_1$ is a value and $\mathtt{t}_2 \longrightarrow \mathtt{t}_2'$, then by E-APP2, $\mathtt{t} \longrightarrow \mathtt{t}_1\ \mathtt{t}_2'$. Finally, if both $\mathtt{t}_1$ and $\mathtt{t}_2$ are values, then case 5 of the canonical forms lemma tells us that $\mathtt{t}_1$ has the form $\lambda x : \mathtt{T}_{11}.\mathtt{t}_{12}$ and so by E-APPABS, $\mathtt{t} \longrightarrow [\mathtt{x} \mapsto \mathtt{t}_2]\mathtt{t}_{12}$ which is a value.

Proof: By structural induction on a derivation of $\mathtt{t} : \mathtt{T}$. At each step of the induction, we assume that the desired property holds for all subderivations (i.e. that if $\mathtt{s} : \mathtt{S}$ and $\mathtt{s} \longrightarrow \mathtt{s}'$, then $\mathtt{s}' : \mathtt{S}$, whenever $\mathtt{s} : \mathtt{S}$ is proved by a subderivation of the present one) and proceed by case analysis on the final rule in the derivation.

Case T-VAR:

$\mathtt{t} = \mathtt{x}$
$\mathtt{x} : \mathtt{T} \in \Gamma$

If the last rule in the derivation is T-VAR, then we know from the form of this rule that t must be a variable of type T. Thus t is a value, so it cannot be the case that $\mathtt{t} \longrightarrow \mathtt{t}'$ for any $\mathtt{t}'$, and the requirements of the theorem are vacuously satisfied.

Case T-APP:

$\mathtt{t} = \mathtt{t}_1\ \mathtt{t}_2$
$\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_{11} \to \mathtt{T}_{12}$
$\Gamma \vdash \mathtt{t}_2 : \mathtt{T}_{11}$
$\mathtt{T} = \mathtt{T}_{12}$

Looking at the evaluation rules with application on the left-hand side, we find that there are three rules by which $\mathtt{t} \longrightarrow \mathtt{t}'$ can be derived: E-APP1, E-APP2, and E-APPABS. We consider each case separately.

Subcase E-APP1:

$\mathtt{t}_1 \longrightarrow \mathtt{t}_1'$
$\mathtt{t}' = \mathtt{t}_1'\ \mathtt{t}_2$

From the assumptions of the T-APP case, we have a subderivation of the original typing derivation whose conclusion is $\Gamma \vdash \mathtt{t}_1 : \mathtt{T}_{11} \to \mathtt{T}_{12}$. We can apply the induction hypothesis to this subderivation obtaining $\Gamma \vdash \mathtt{t}_1' : \mathtt{T}_{11} \to \mathtt{T}_{12}$. Combining this with the fact that $\Gamma \vdash \mathtt{t}_2 : \mathtt{T}_{11}$, we can apply rule T-APP to conclude that $\Gamma \vdash \mathtt{t}' : \mathtt{T}$.

Subcase E-APP2:
Similar to E-APP1.

Subcase E-APPABS:

$\mathtt{t}_1 = \lambda x : \mathtt{T}_{11}.\mathtt{t}_{12}$
$\mathtt{t}_2 = \mathtt{v}_2$
$\mathtt{t}' = [\mathtt{x} \mapsto \mathtt{v}_2]\mathtt{t}_{12}$

DESIGN // PROOF OF SAFETY

Proof by structural induction

Proof: By structural induction on a derivation of t : T.

Case T-INT, T-REAL, T-STRING, T-BIT, T-NIL:
Immediate since t is a value.

Case T-APP:
$t = t_1\ t_2$
$\vdash t_1 : T_{11} \to T_{12}$
$\vdash t_2 : T_{12}$

By the induction hypothesis, either t_1 is a value or else there is some other t_1' for which $t_1 \longrightarrow t_1'$, and likewise for t_2. If $t_1 \longrightarrow t_1'$ then by E-APP1, $t \longrightarrow t_1'\ t_2$. On the other hand, if t_1 is a value and $t_2 \longrightarrow t_2'$, then by E-APP2, $t \longrightarrow t_1\ t_2'$. Finally, if both t_1 and t_2 are values, then case 5 of the canonical forms lemma tells us that t_1 has the form $\lambda x : T_{11}.t_{12}$ and so by E-APPABS, $t \longrightarrow [x \mapsto t_2]t_{12}$ which is a value.

Shown in full in Appendix B

Proof: By structural induction on a derivation of t : T. At each step of the induction, we assume that the desired property holds for all subderivations (i.e. that if s : S and $s \longrightarrow s'$, then s' : S, whenever s : S is proved by a subderivation of the present one) and proceed by case analysis on the final rule in the derivation.

Case T-VAR:
$t = x$
$x : T \in \Gamma$

If the last rule in the derivation is T-VAR, then we know from the form of this rule that t must be a variable of type T. Thus t is a value, so it cannot be the case that $t \longrightarrow t'$ for any t', and the requirements of the theorem are vacuously satisfied.

Case T-APP:
$t = t_1\ t_2$
$\Gamma \vdash t_1 : T_{11} \to T_{12}$
$\Gamma \vdash t_2 : T_{11}$
$T = T_{12}$

Looking at the evaluation rules with application on the left-hand side, we find that there are three rules by which $t \longrightarrow t'$ can be derived: E-APP1, E-APP2, and E-APPABS. We consider each case separately.

Subcase E-APP1:
$t_1 \longrightarrow t_1'$
$t' = t_1'\ t_2$

From the assumptions of the T-APP case, we have a subderivation of the original typing derivation whose conclusion is $\Gamma \vdash t_1 : T_{11} \to T_{12}$. We can apply the induction hypothesis to this subderivation obtaining $\Gamma \vdash t_1' : T_{11} \to T_{12}$. Combining this with the fact that $\Gamma \vdash t_2 : T_{11}$, we can apply rule T-APP to conclude that $\Gamma \vdash t' : T$.

Subcase E-APP2:
Similar to E-APP1.

Subcase E-APPABS:
$t_1 = \lambda x : T_{11}.t_{12}$
$t_2 = v_2$
$t' = [x \mapsto v_2]t_{12}$

// PROOF OF SAFETY

Definition

A term is in a stuck state if no evaluation rules apply to it but it is not a value.

DESIGN // PROOF OF SAFETY

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A term is in a stuck state if no evaluation rules apply to it but it is not a value.

Theorem of Safety

A well-typed term can never reach a stuck state during evaluation.

Design // PROOF OF SAFETY

Definition

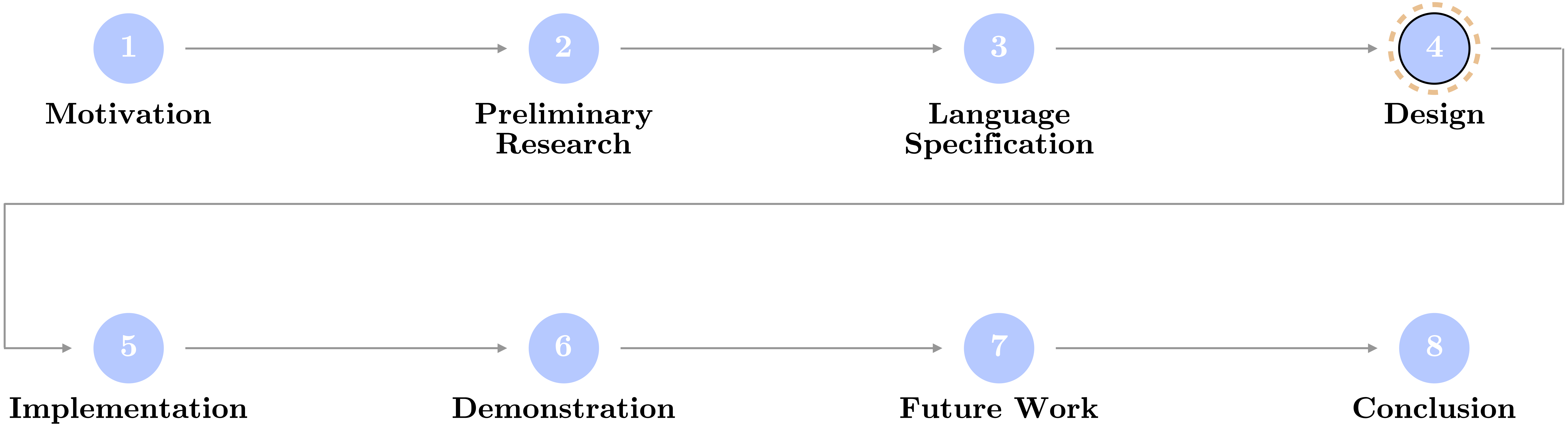
A term is in a stuck state if no evaluation rules apply to it but it is not a value.

Theorem of Safety

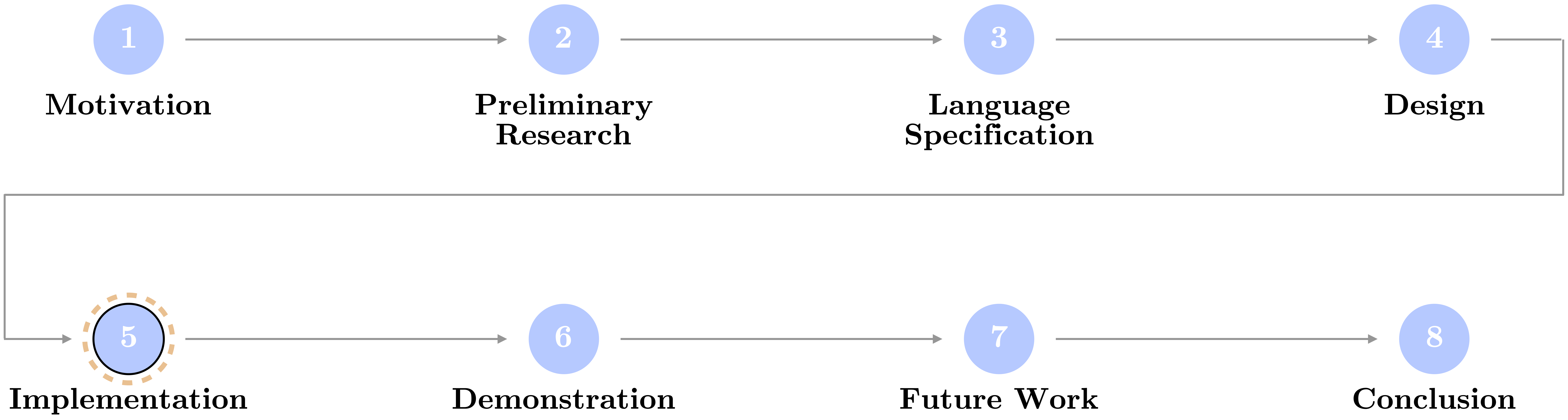
A well-typed term can never reach a stuck state during evaluation.

Proof: Progress tells us a well-typed term can either always take a step of evaluation or it is already a value. Preservation tells us if a well-typed term takes a step of evaluation, the resulting term is also well-typed. In combination and inductively, these guarantee safety. $\square$

Roadmap


1
Motivation
2
Preliminary Research
3
Language Specification
4
Design
5
Implementation
6
Demonstration
7
Future Work
8
Conclusion

Roadmap


1
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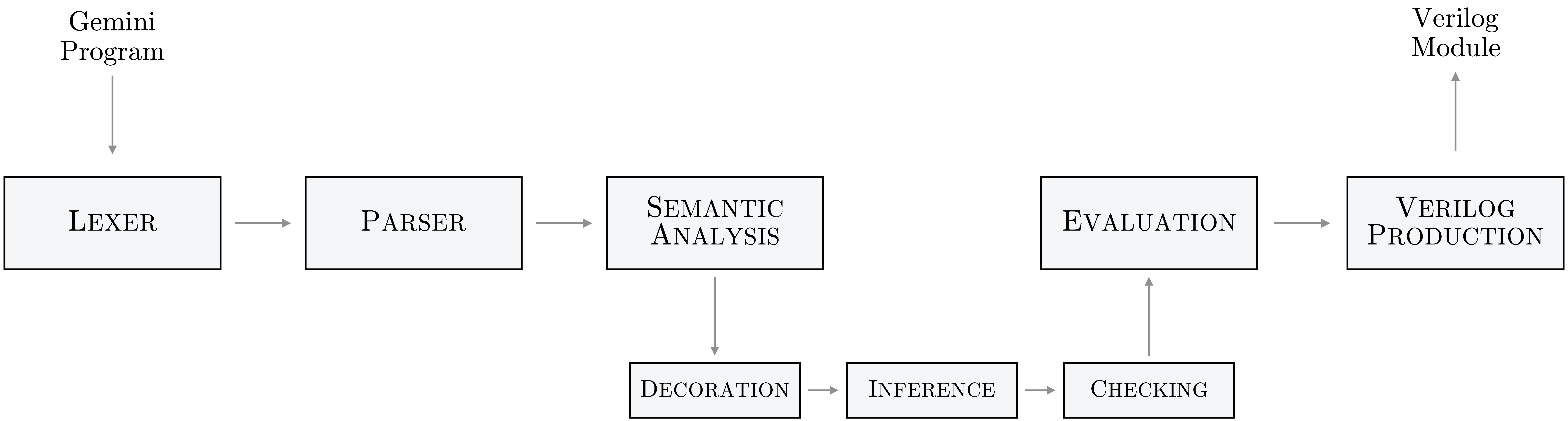
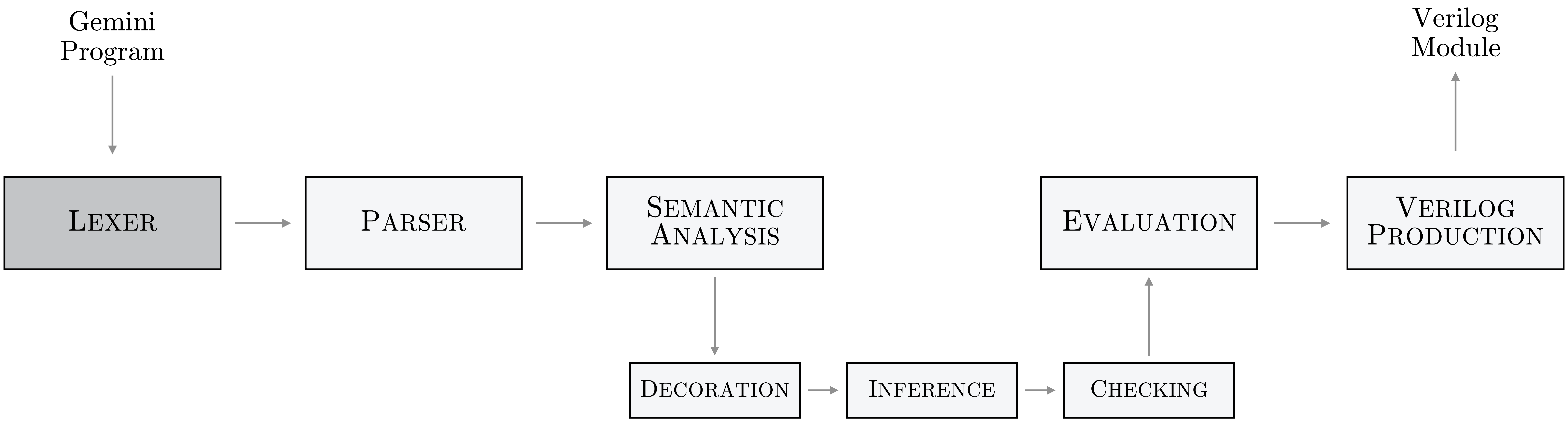
Implementation

Implementation



Implementation



Implementation // **Lexer**

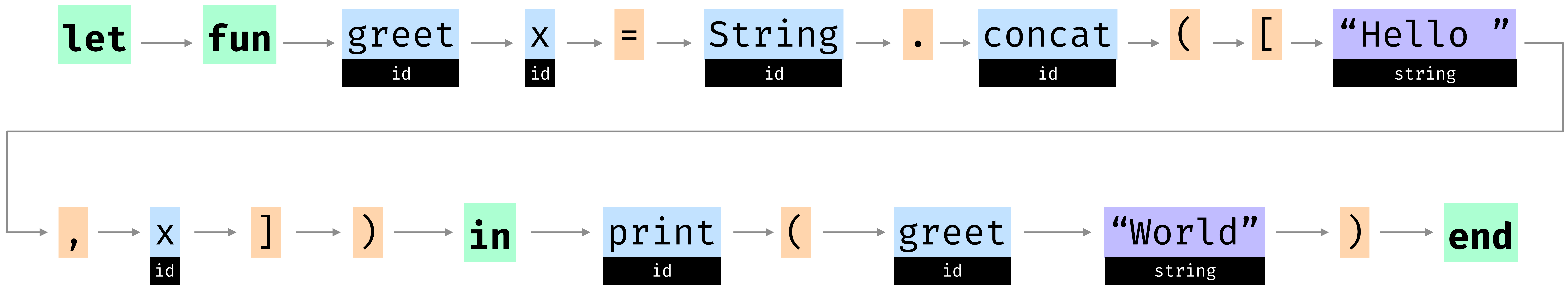
Scans program and produces lexemes, classified into token classes

Scans program and produces lexemes, classified into token classes

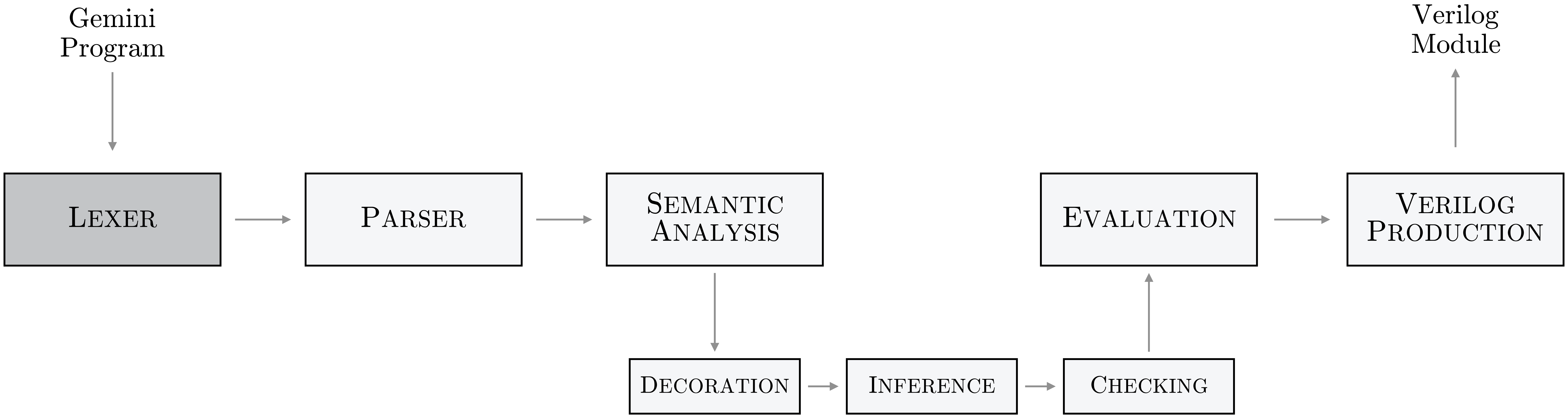
```
let
    fun greet x = String.concat([“Hello ”,  x])
in
    print(greet “World”)
end
```

Implementation // Lexer

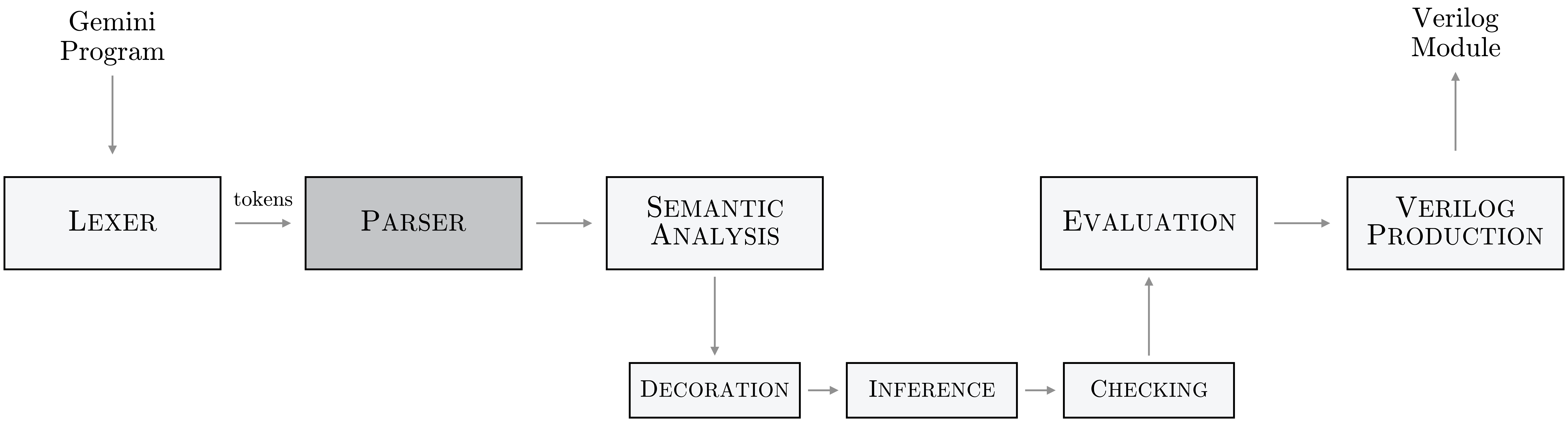
Scans program and produces lexemes, classified into token classes



Implementation



Implementation



Implementation // Parser

At this point, we know program is syntactically correct

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It may not be grammatically correct (Ex: `42 +`)

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We must verify the grammar

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Problem

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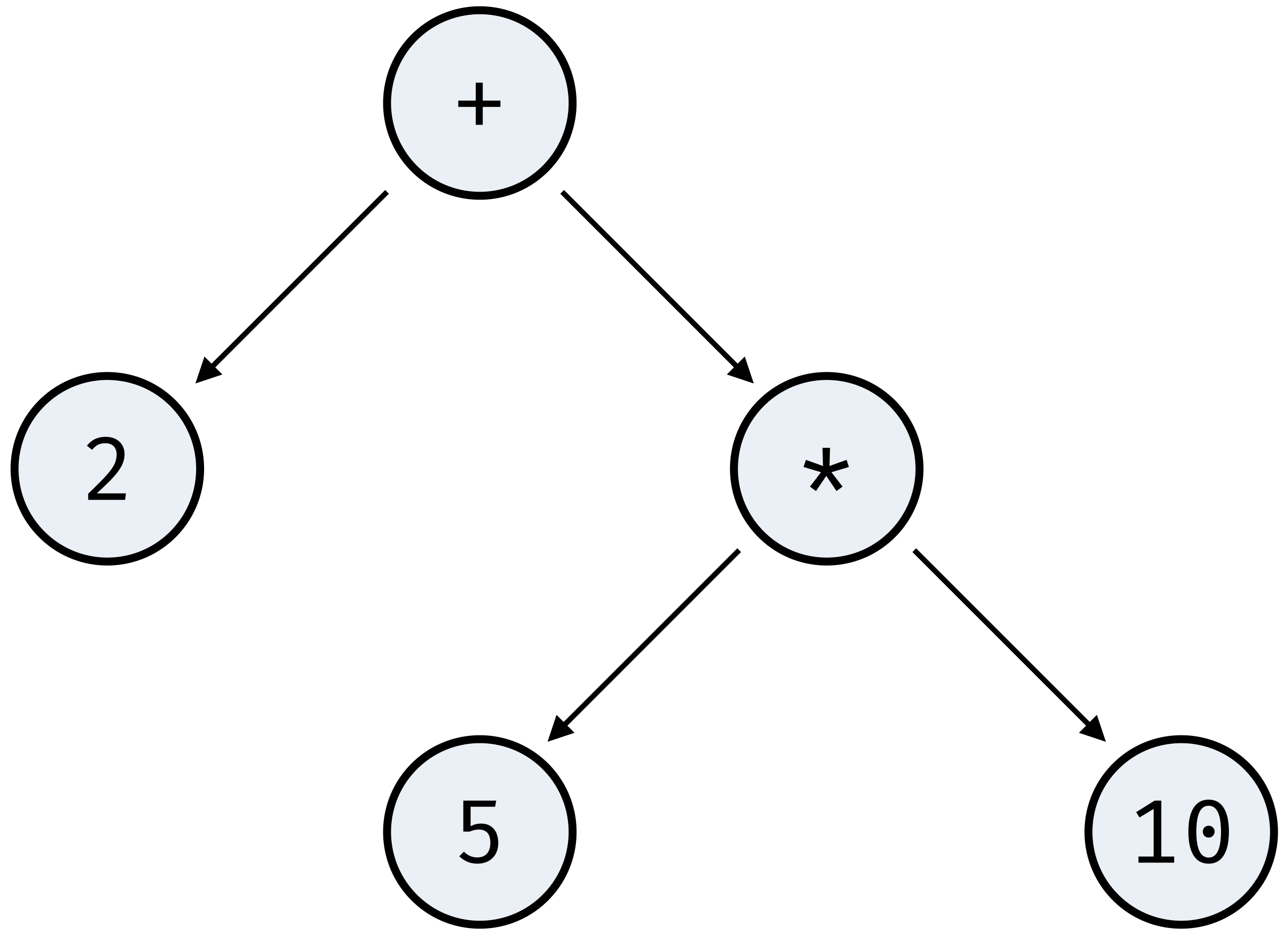
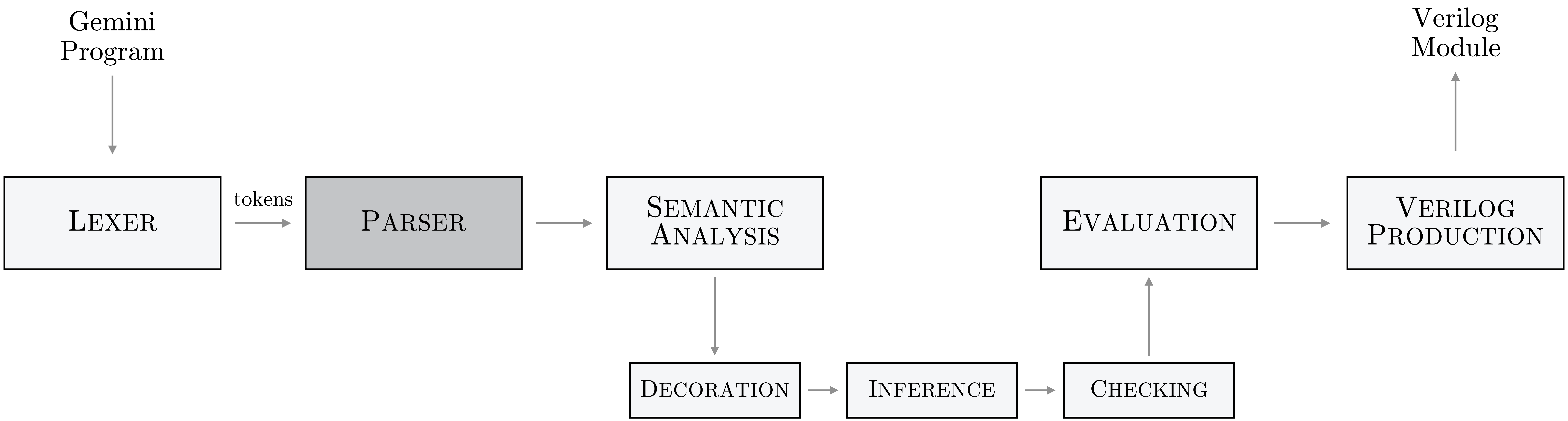
`2 + 5 * 10`



IMPLEMENTATION



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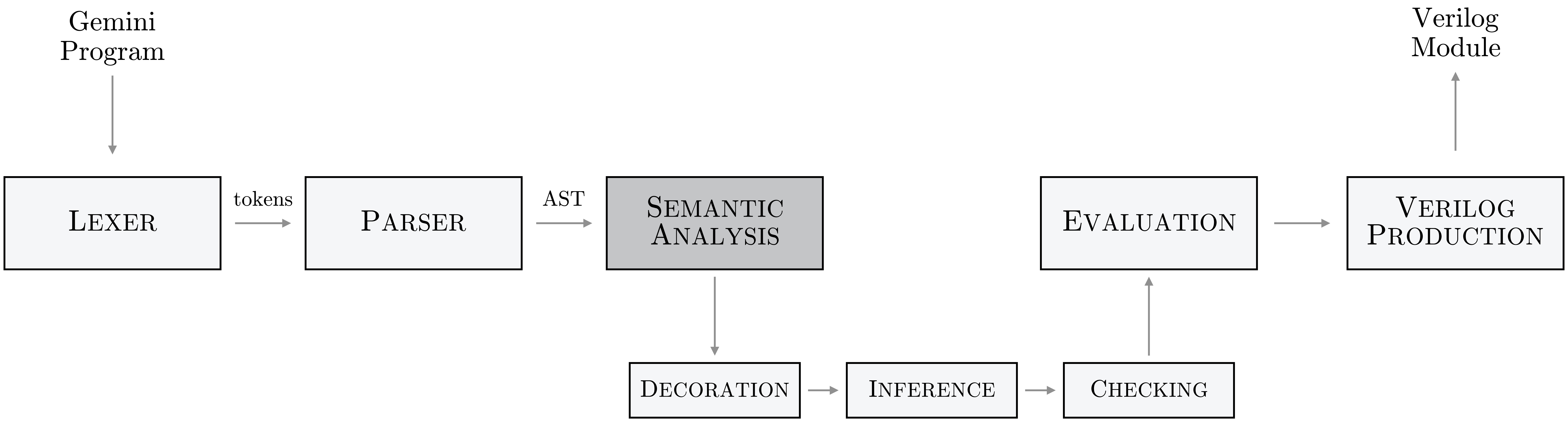

At this point, we know program is syntactically and grammatically correct

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Problem

It may not be semantically correct (Ex: `“hello” + 42`)

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Problem

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Solution

We must verify the type semantics

Preventative Issue

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fun add(x, y) = x + y
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It is the responsibility of the compiler to infer the actual types

Semantic Analysis

1. Decoration
2. Inference
3. Checking

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We translate from Gemini to a fictional intermediate language called ExplicitGemini

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fun print_and_mult(x    , y    , s : string)     = (print(s); x * y)
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fun print_and_mult(x :'a, y :'b, s : string) :'c = (print(s); x * y)
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```
fun print_and_mult(x :'a, y :'b, s : string) :'c = (print(s); x * y)
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`'a` represents a type variable, which we try to infer based on how it is used

1. Decoration
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3. Checking

With all variables decorated, we infer all types as generally as possible

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Two underlying algorithms

1. Unification
2. Substitution

Algorithm: Unification computes the smallest possible substitution mapping from type variables to types

```
fun doubleList (mylist : ‘a) : ‘b = case mylist of
                                      [] : ‘c ⇒ [] : ‘d
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```

```
{‘c ↦ int list}        {‘g ↦ int list}        doubleList : int list → int list
{‘d ↦ int list}        {‘a ↦ int list}
{‘e ↦ int}             {‘b ↦ int list}
{‘f ↦ int list}
```

Algorithm: Substitution applies the mappings to the variable and type environments

In some cases, type variables do not get substituted

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```
fun concat e mylist = e::mylist
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The type of `concat` is `‘a → ‘a list → ‘a list`

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The type of `concat` is `‘a → ‘a list → ‘a list`

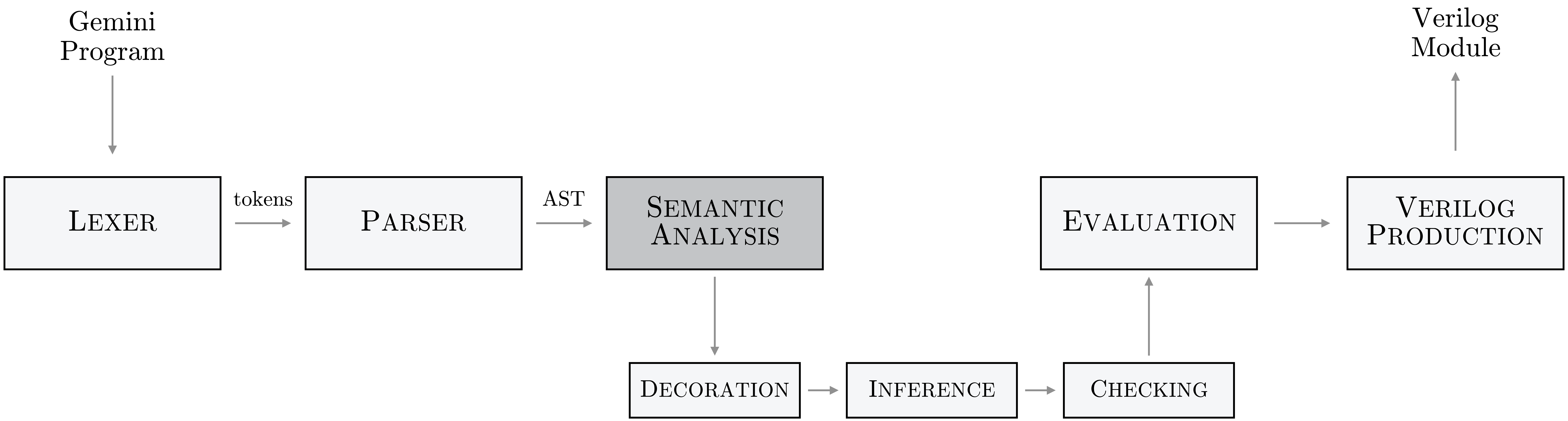
In type theoretical terms, $\forall \mathrm{a}.\lambda \mathrm{x} : \mathrm{a}.\lambda \mathrm{y} : \mathrm{a}\ \mathrm{list}.\mathrm{x}::\mathrm{y}$

Implementation // Semantic Analysis

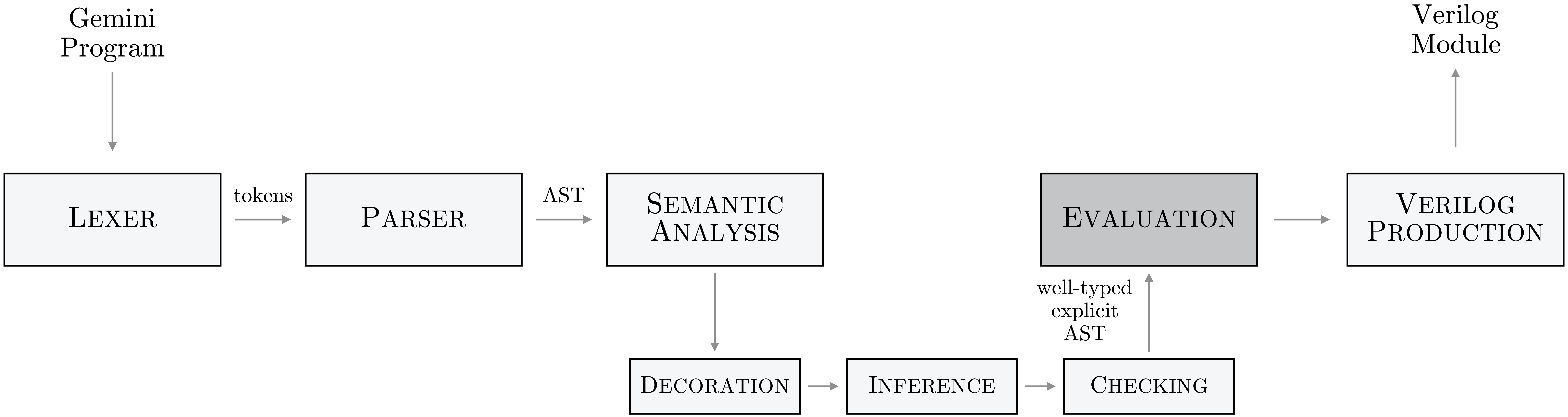
1. Decoration
2. Inference
3. Checking

Now that all types are inferred, we can enforce typing rules that we formalized earlier

IMPLEMENTATION



Implementation



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Verilog only supports hardware values

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Problem
Verilog only supports hardware values

Solution
Execute all software expressions to generate a hardware-only tree

Implementation // Evaluation

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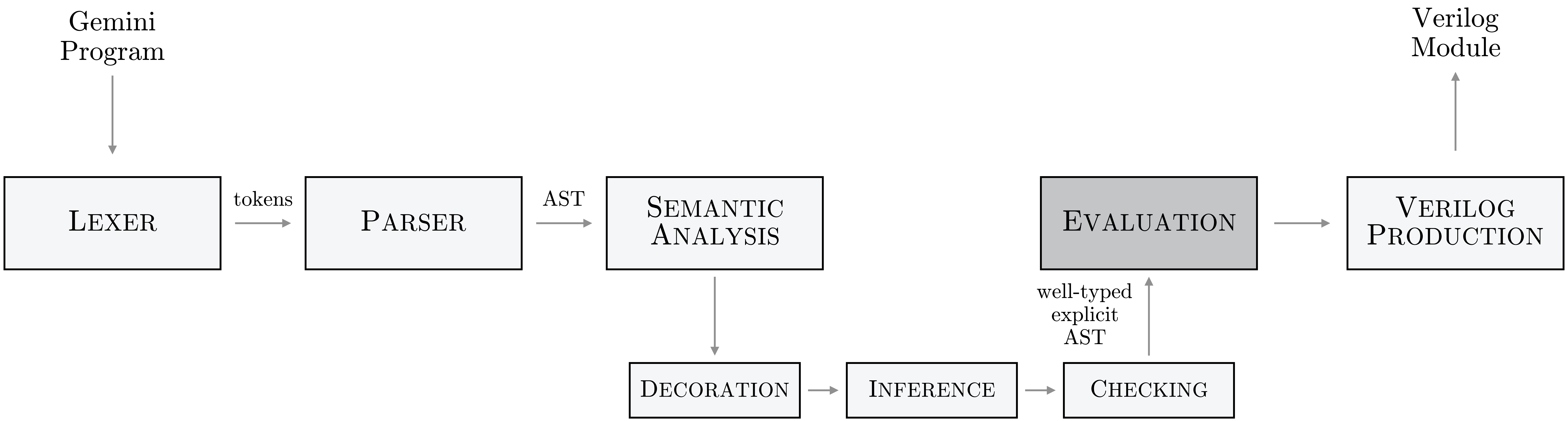
4. For each declaration, the value store is augmented to map from the variable name to its value

Implementation



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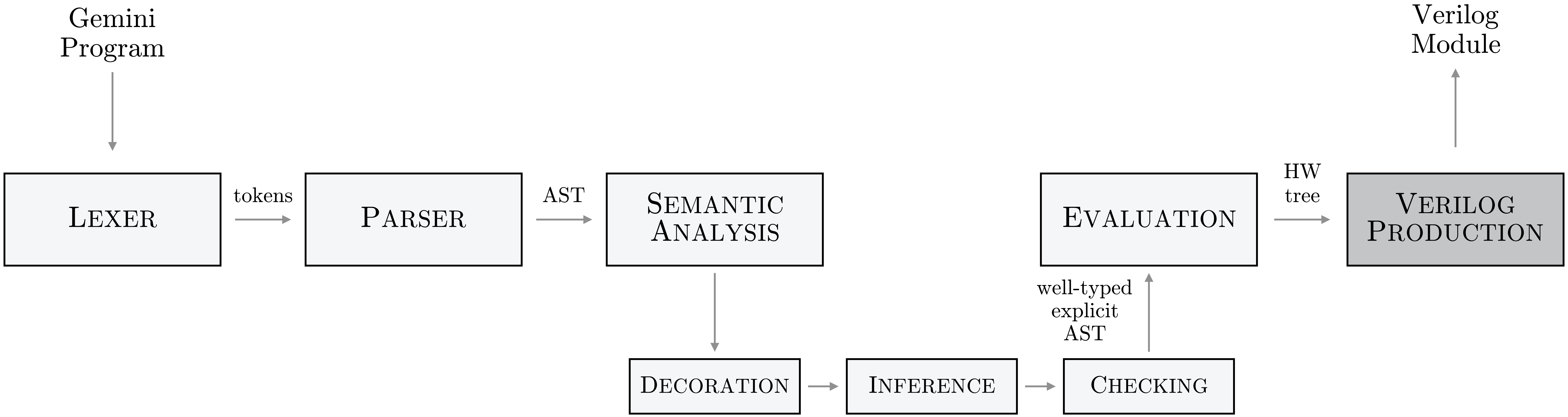

Implementation // Verilog Production

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Solution
We must output Verilog that represents the tree

Verilog Production

Verilog production is similar to algorithms in the past

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Implementation // Verilog Production

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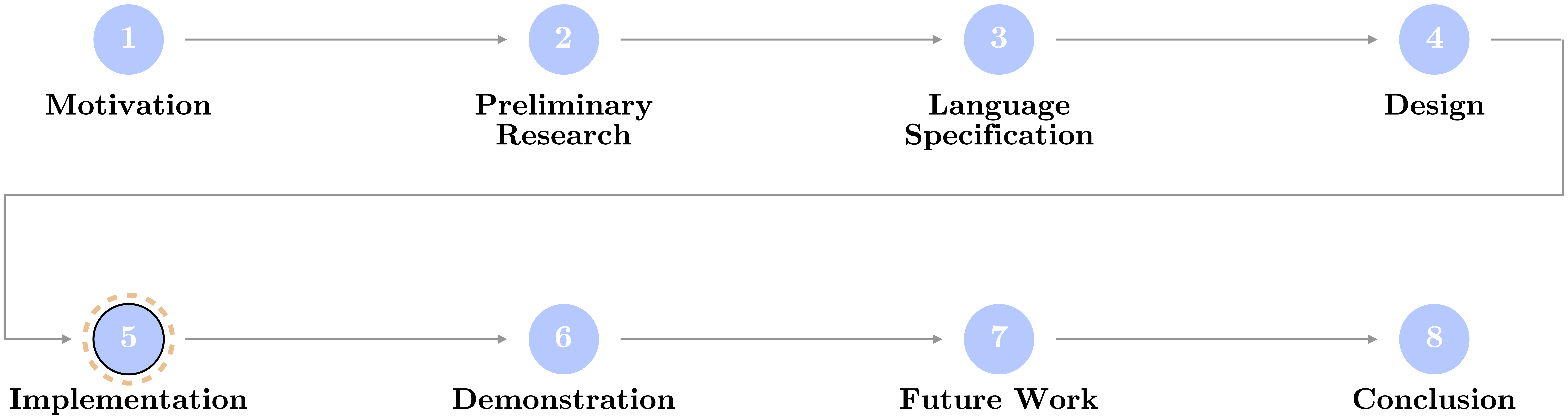
4. For each node, fresh wire is generated and returned for superexpressions to use

Roadmap


1
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Preliminary Research
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Language Specification
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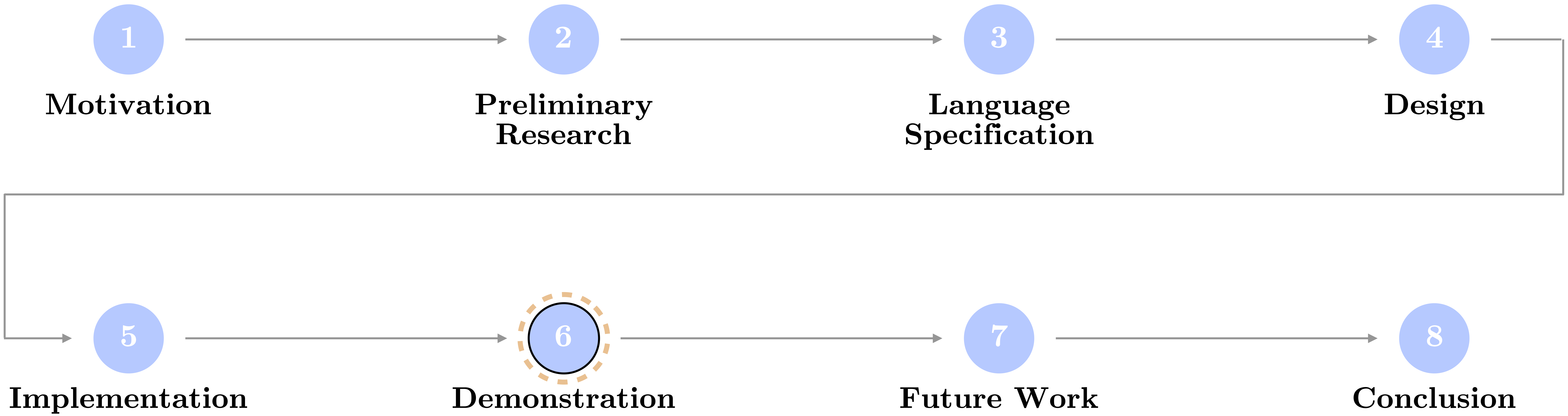
Future Work
8
Conclusion

Roadmap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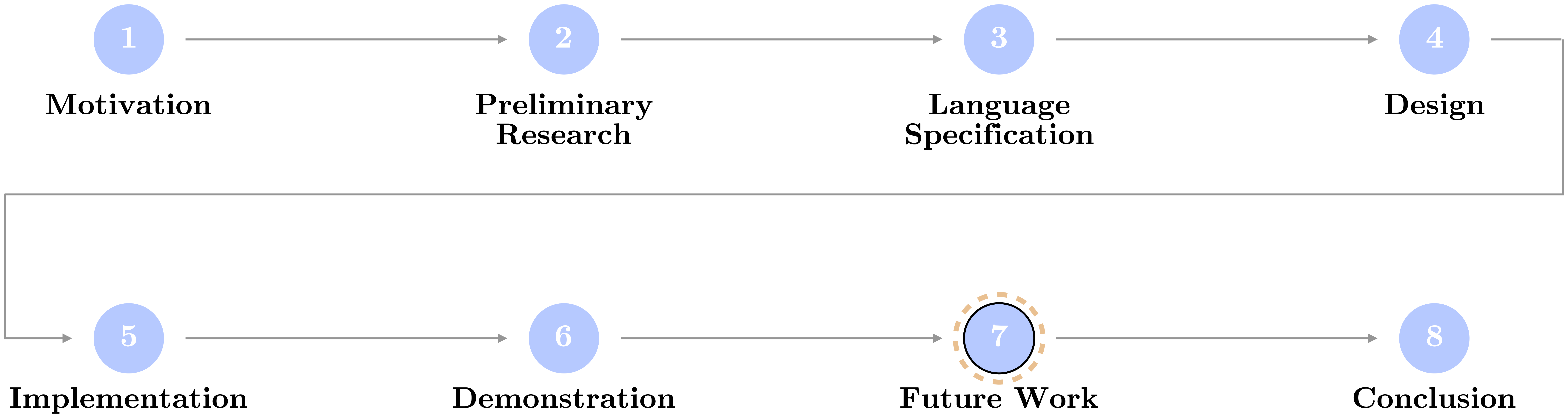
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Optimizations

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- Simulation/waveform backend
- Testbench generation

Optimizations

Future Work

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Optimizations

- Dataflow analysis to reuse wires
- Constant propagation
- Constraining resources finitely

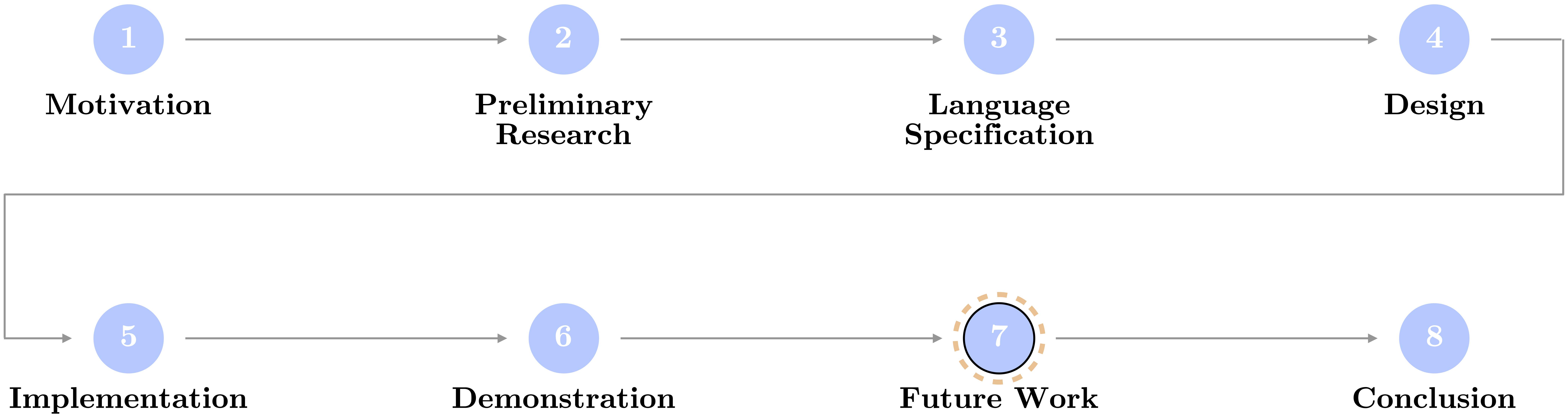
Future Work

Plan to Open-Source

All code is hosted on GitHub

Extensive documentation at bit.ly/gemini-docs

Roadmap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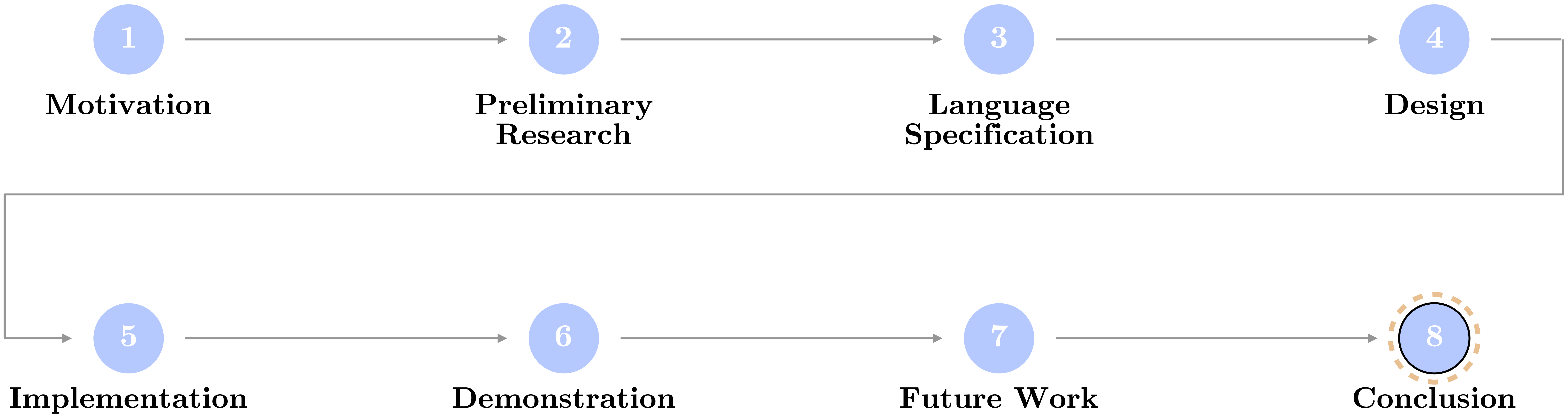
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Answer
Yes, and Gemini is proof that unconventional features like multiple kinds, value-parameterized types, and the manifestation of time are possible to implement.

References

[1] Barbacci, M. ”A comparison of register transfer languages for describing computers and digital systems,” Carnegie-Mellon Univ., Dept. of Computer Science, March 1973

[2] ”Verilog's inventor nabs EDA's Kaufman award”. EE Times. November 7, 2005

[3] Department of Defense (1992). Military Standard, Standard general requirements for electronic equipment. Retrieved November 15, 2017

[4] Barbacci, M., Grout S., Lindstrom, G., Maloney, M.P. ”Ada as a hardware description language : an initial report,” Carnegie-Mellon Univ., Dept. of Computer Science, 1984

[5] Pierce, Benjamin C. Types and Programming Languages. MIT Press, 2002

[6] Appel, Andrew W., et al. “A Lexical Analyzer Generator for Standard ML.” A Lexical Analyzer Generator for Standard ML. Version 1.6.0, October 1994, Princeton University, Oct. 1994, www.smlnj.org/doc/ML- Lex/ manual.html.

[7] Tarditi, David R., and Andrew W. Appel. “ML-Yacc User's Manual Version 2.3.” Princeton University, The Trustees of Princeton University, 6 Oct. 1994, www.cs.princeton.edu/˜appel/modern/ml/ml-yacc/manual.html

Questions?