Code Generation for High-Assurance Java Card Applets

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Summary

- Java Card
- Kestrel's work
- Applet generator
- Code generator
  - approach
  - details
  - checking correctness
  - accomplishments
- Current and future work

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What Is Java Card?

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A version of Java for smart cards

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plastic
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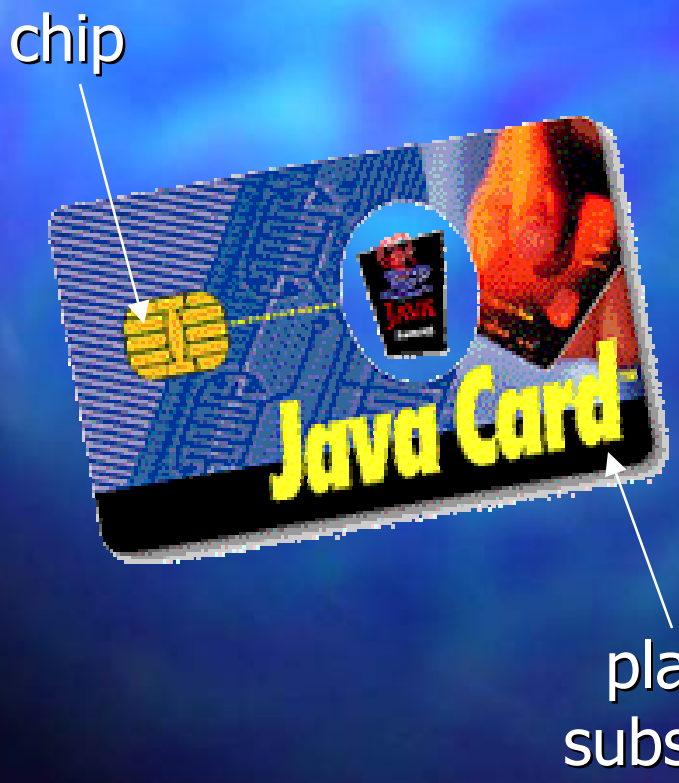

What Is Java Card?

A version of Java for smart cards

chip

plastic substrate

authentication,
banking,
telephony,
health care,
…

Java Card Technology

Java Card Technology

Java Card program

Java Card Technology

Java Card program

1) subset of Java

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2) different libraries

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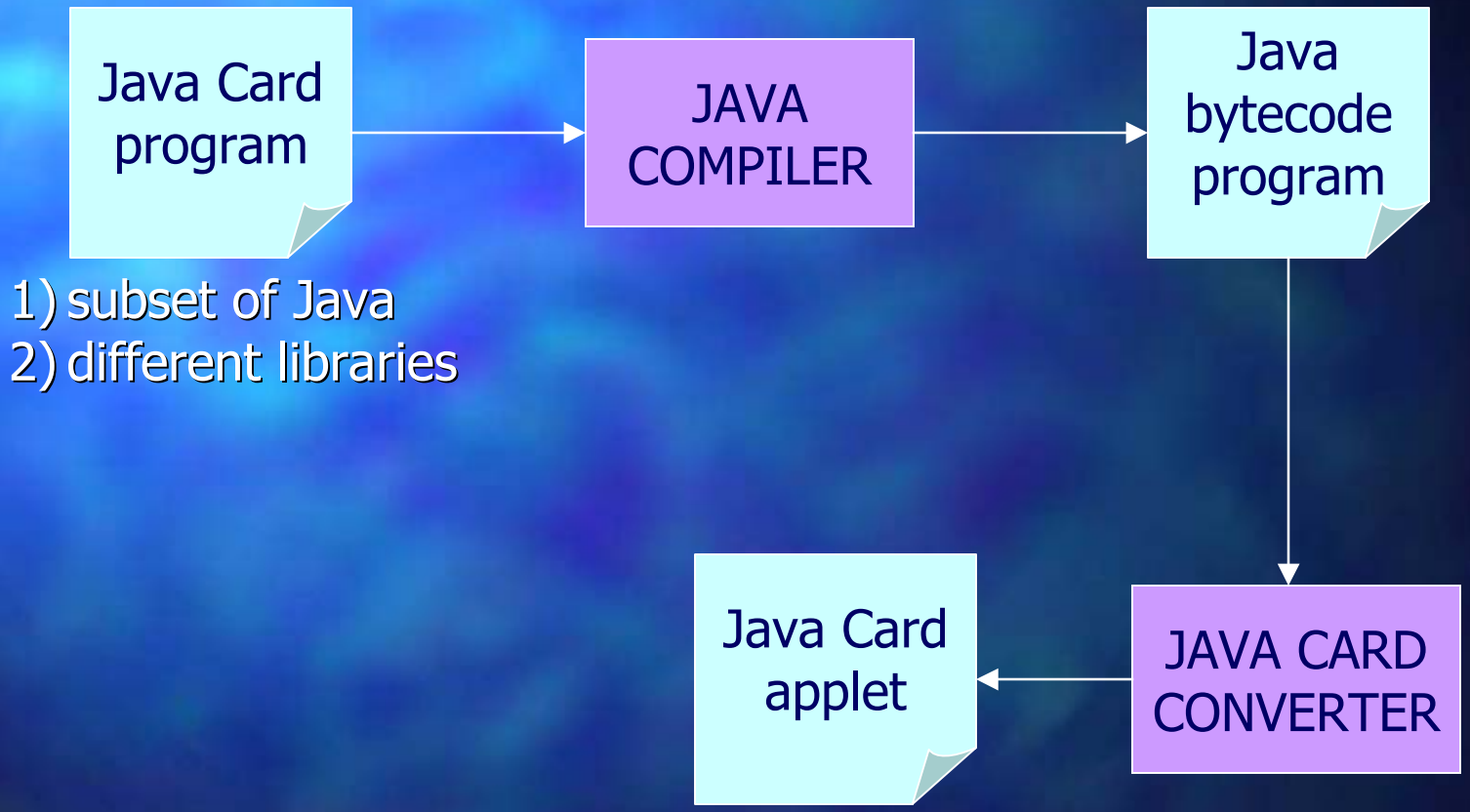
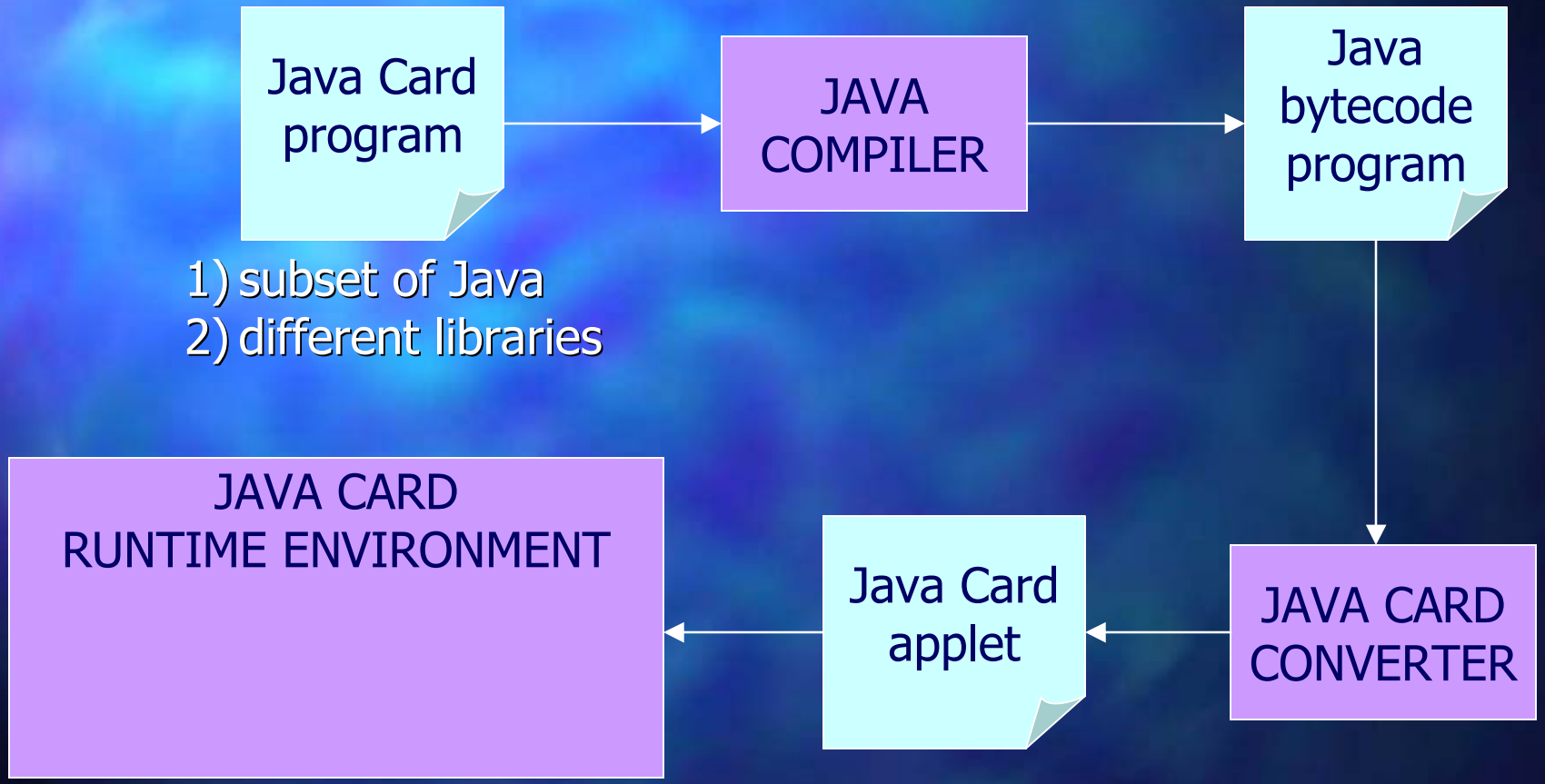


1) subset of Java
2) different libraries

Java Card Technology



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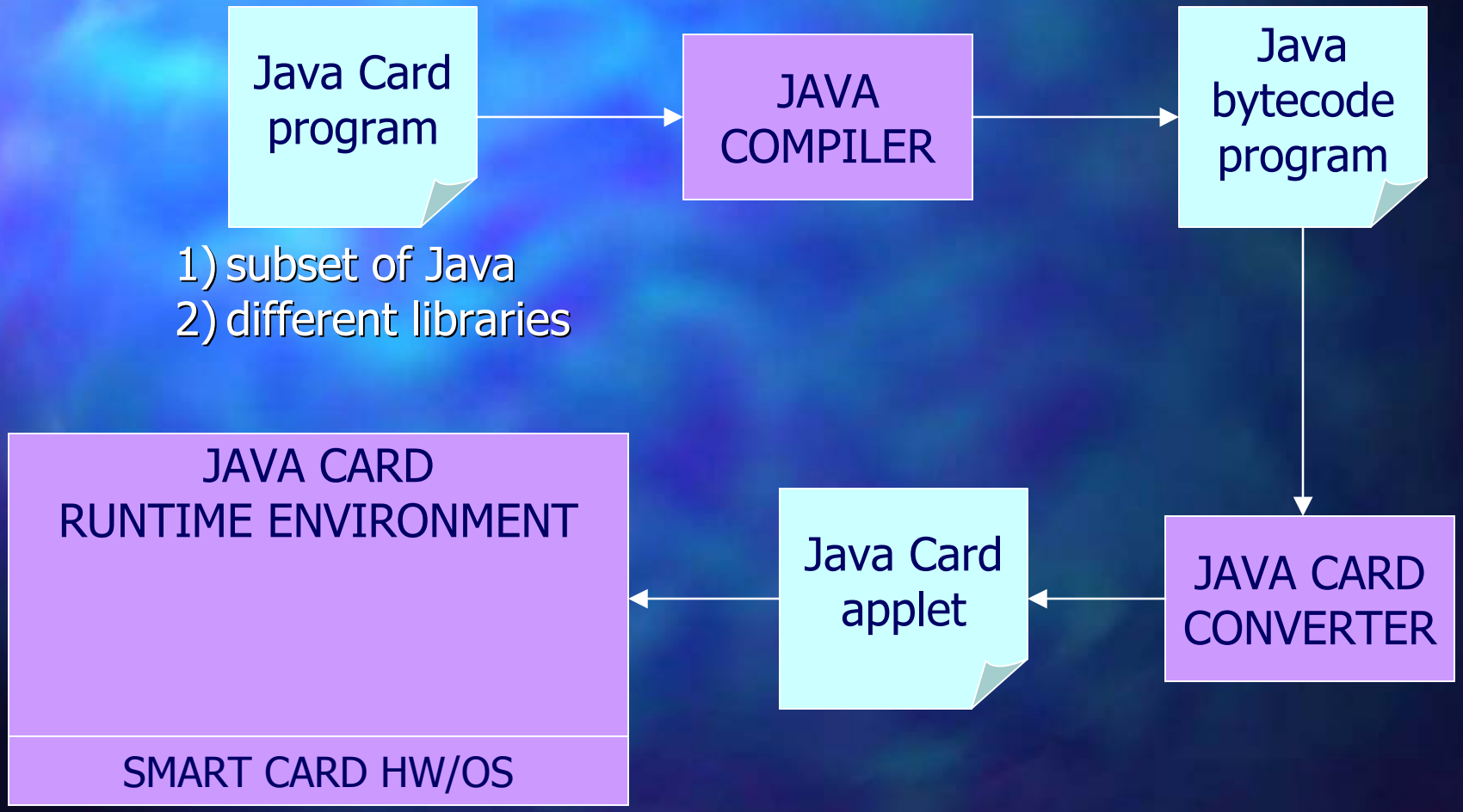

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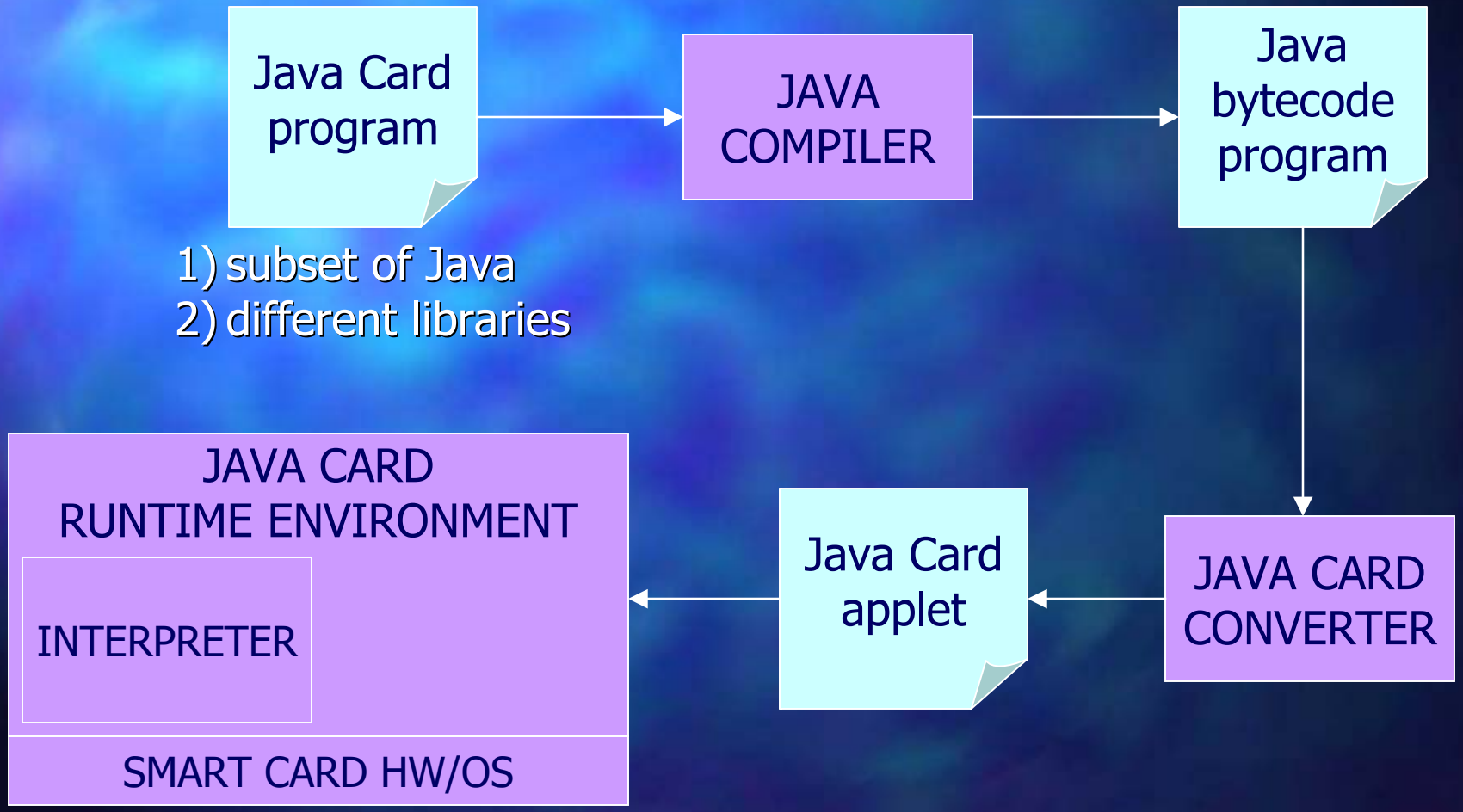

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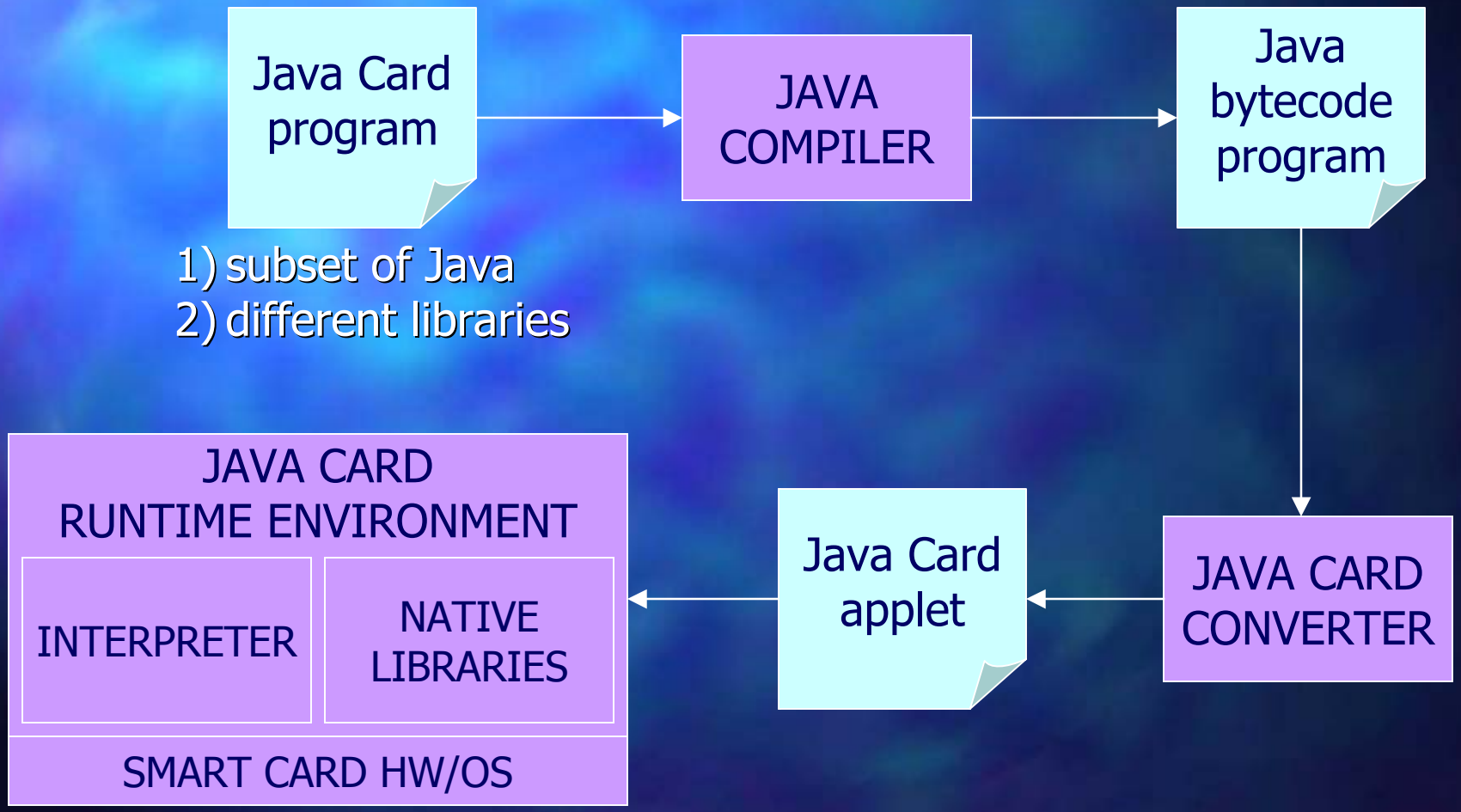

High Assurance

- Critical requirement for smart cards
- Pursued by smart card vendors
- Measurable (Common Criteria, FIPS-140)
- Focus of Kestrel Institute's research
  - automated synthesis ("specs to code")
  - formal analysis

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Kestrel's Synthesis Systems

- Specware
  - formal specs
  - refinement
  - composition
  - code generation
- Designware
  - libraries of specs and refinements embodying software design knowledge (algorithms, optimizations, …)
  - tactics for automated refinement in Specware
- Planware
  - automatic generator of high-performance, complex resource systems (allocation, transportation schedulers, …)
  - on top of Specware
- MoBIES, HARBINGER, SVA, protocols, …

Our Work on Java Card

- Platform
  - synthesis (specs to code) of
    - Java Card Runtime Environment
    - simulator
    - possibly tools (off-card verifier, ...)
- Applets
  - applet generator

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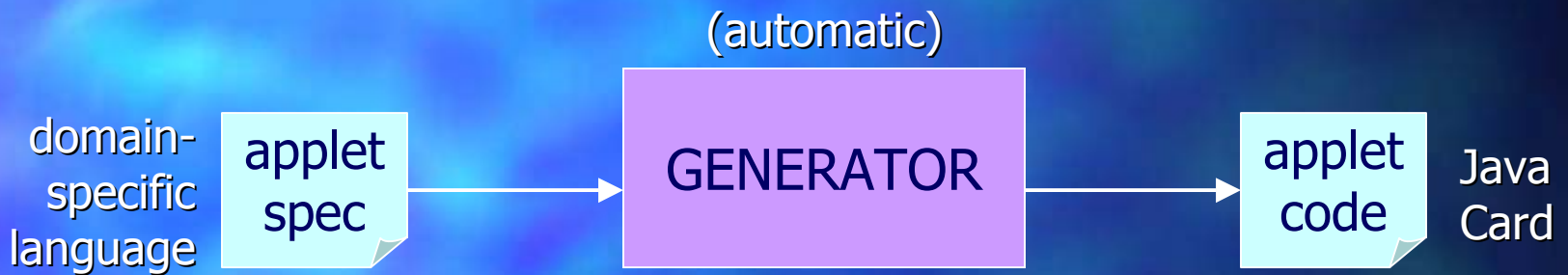

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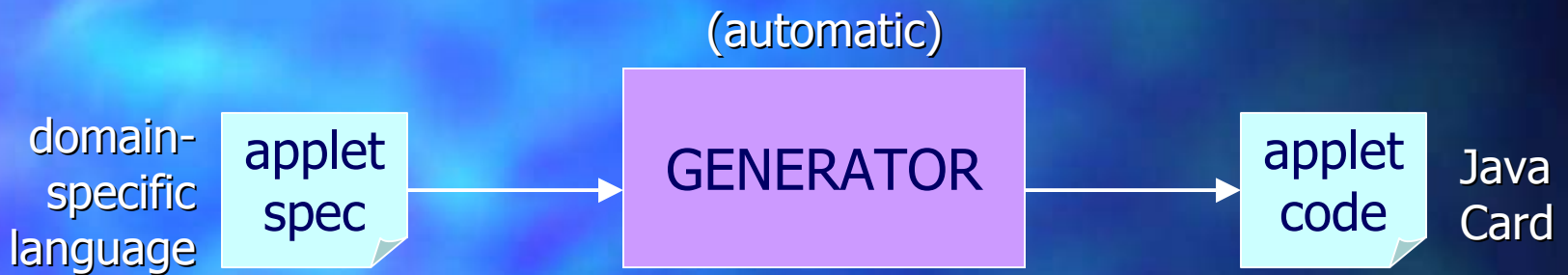

for:
- productivity
- high assurance

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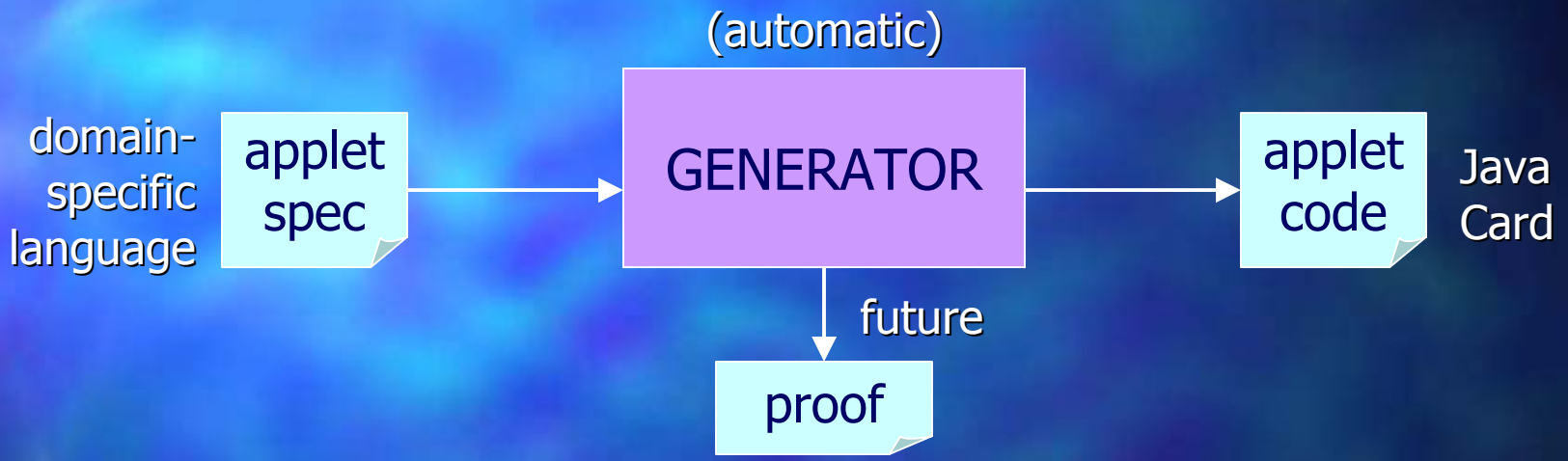

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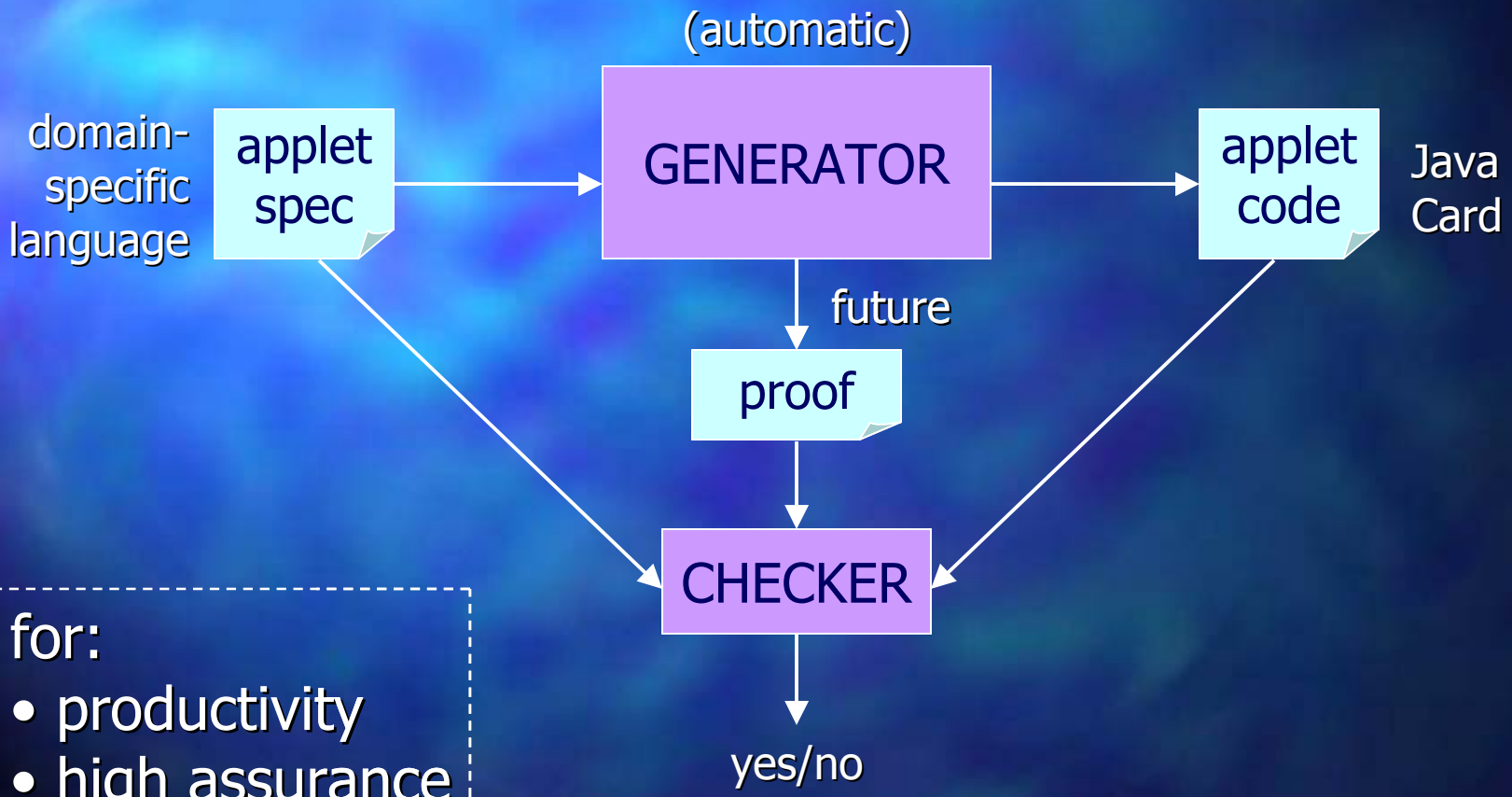

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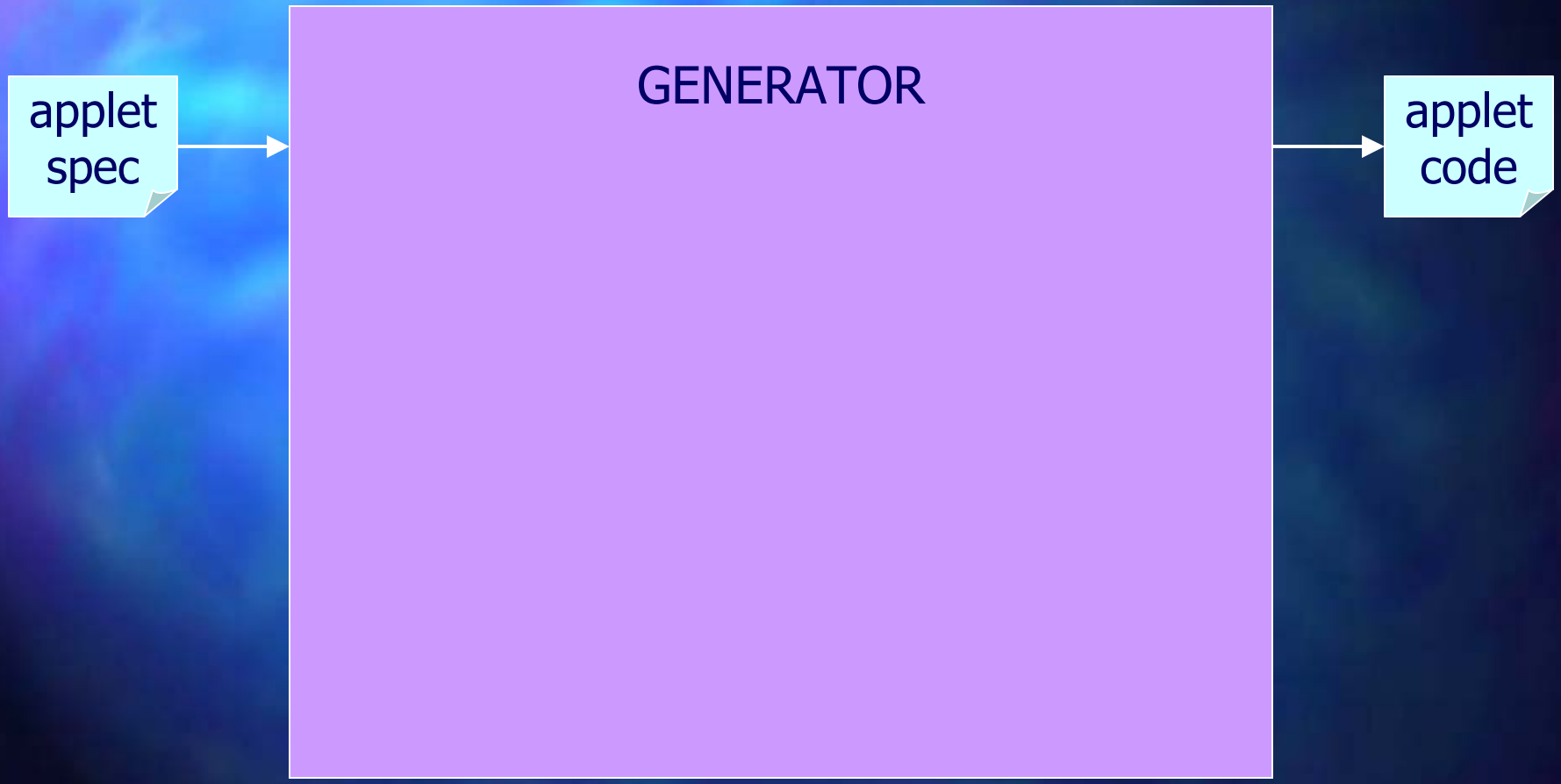
Inside the Generator



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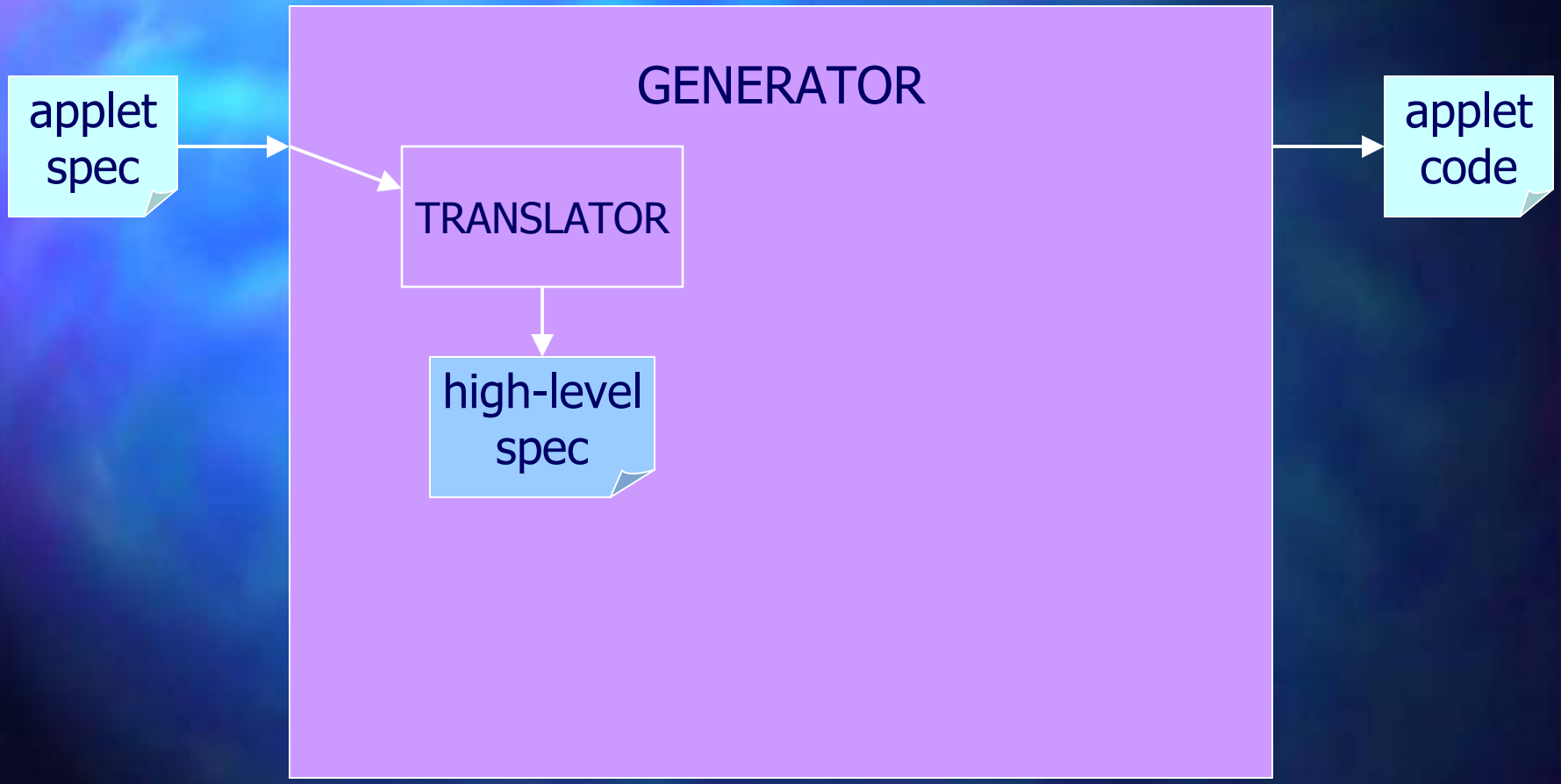

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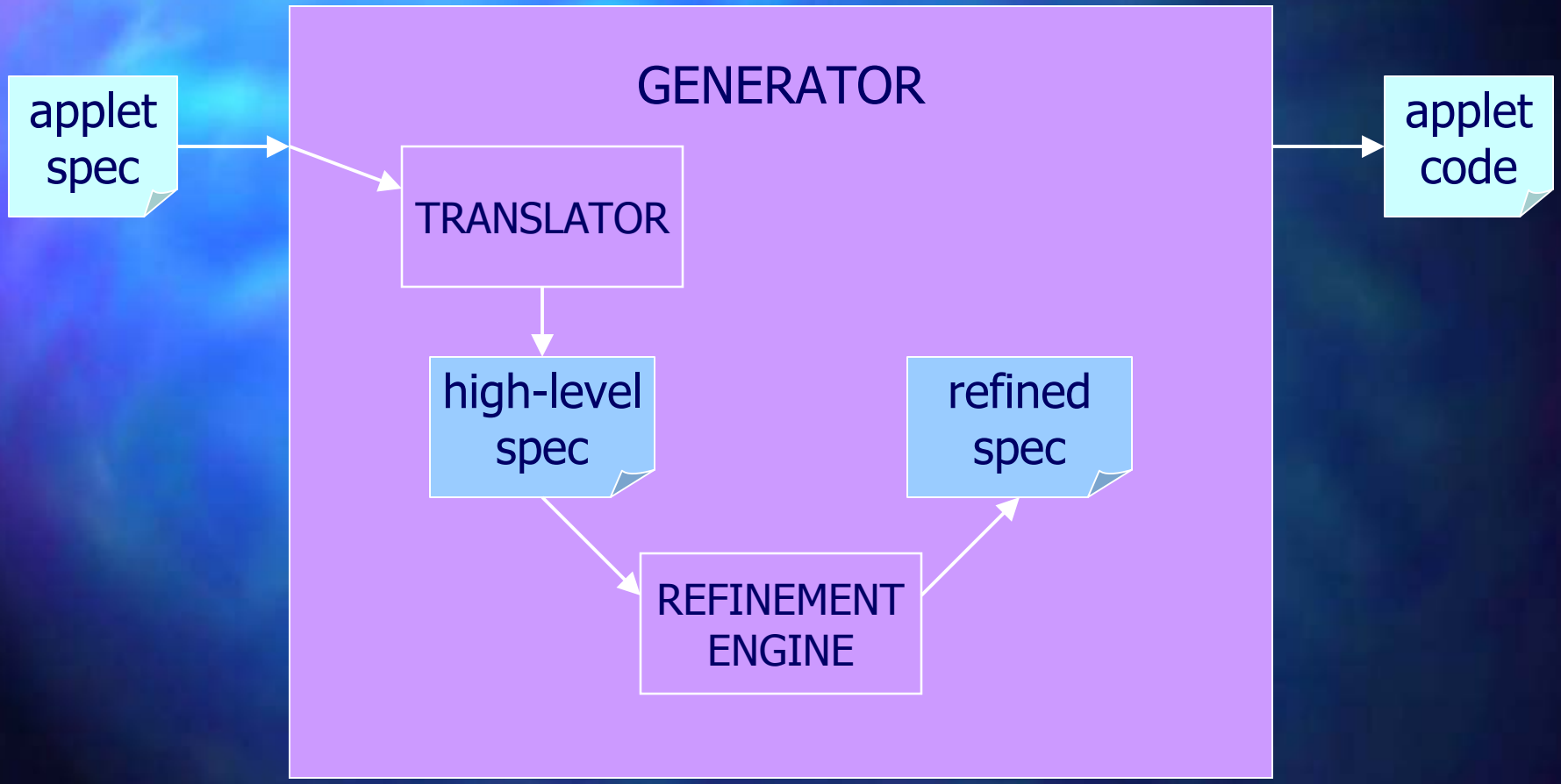

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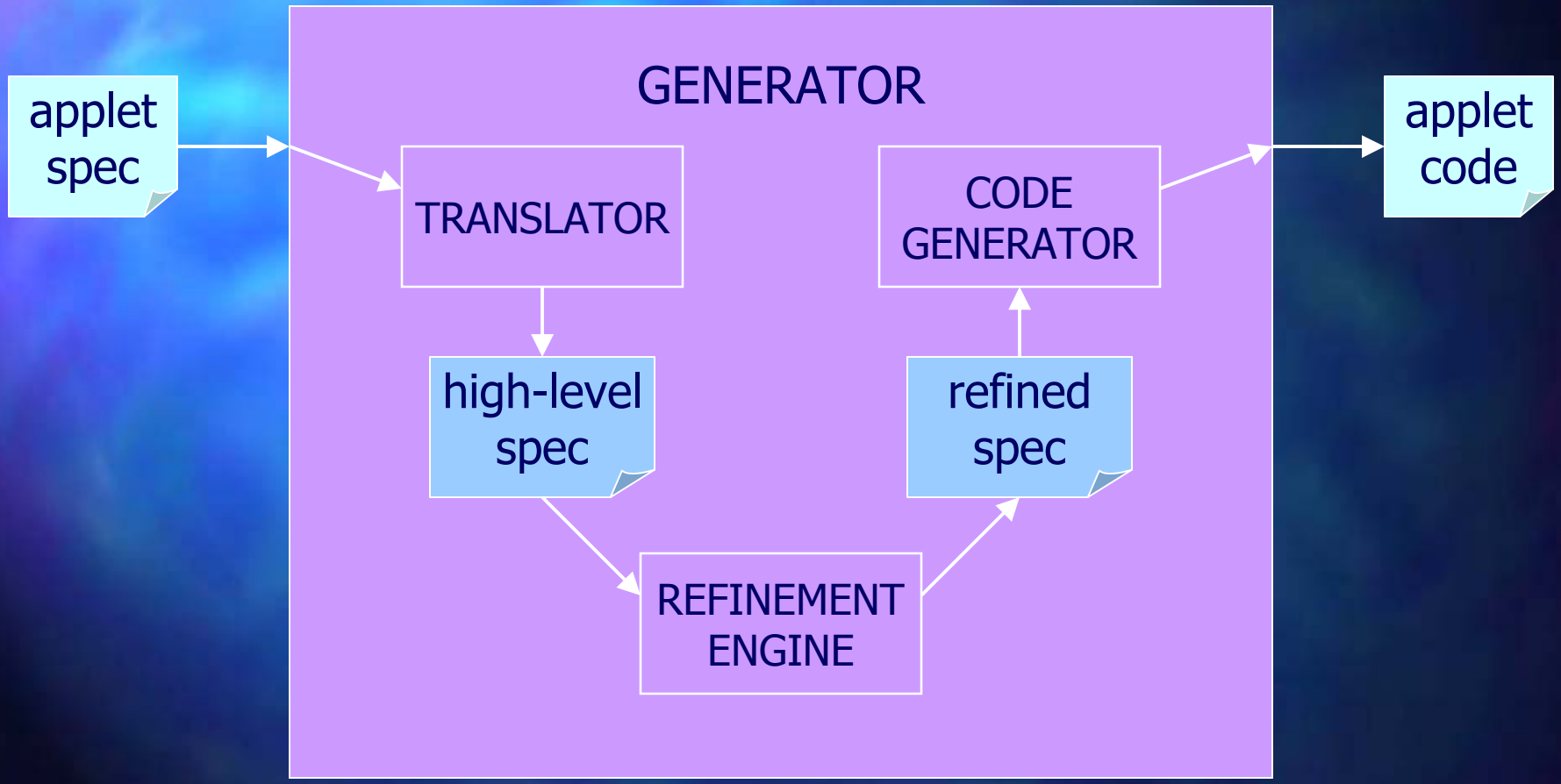

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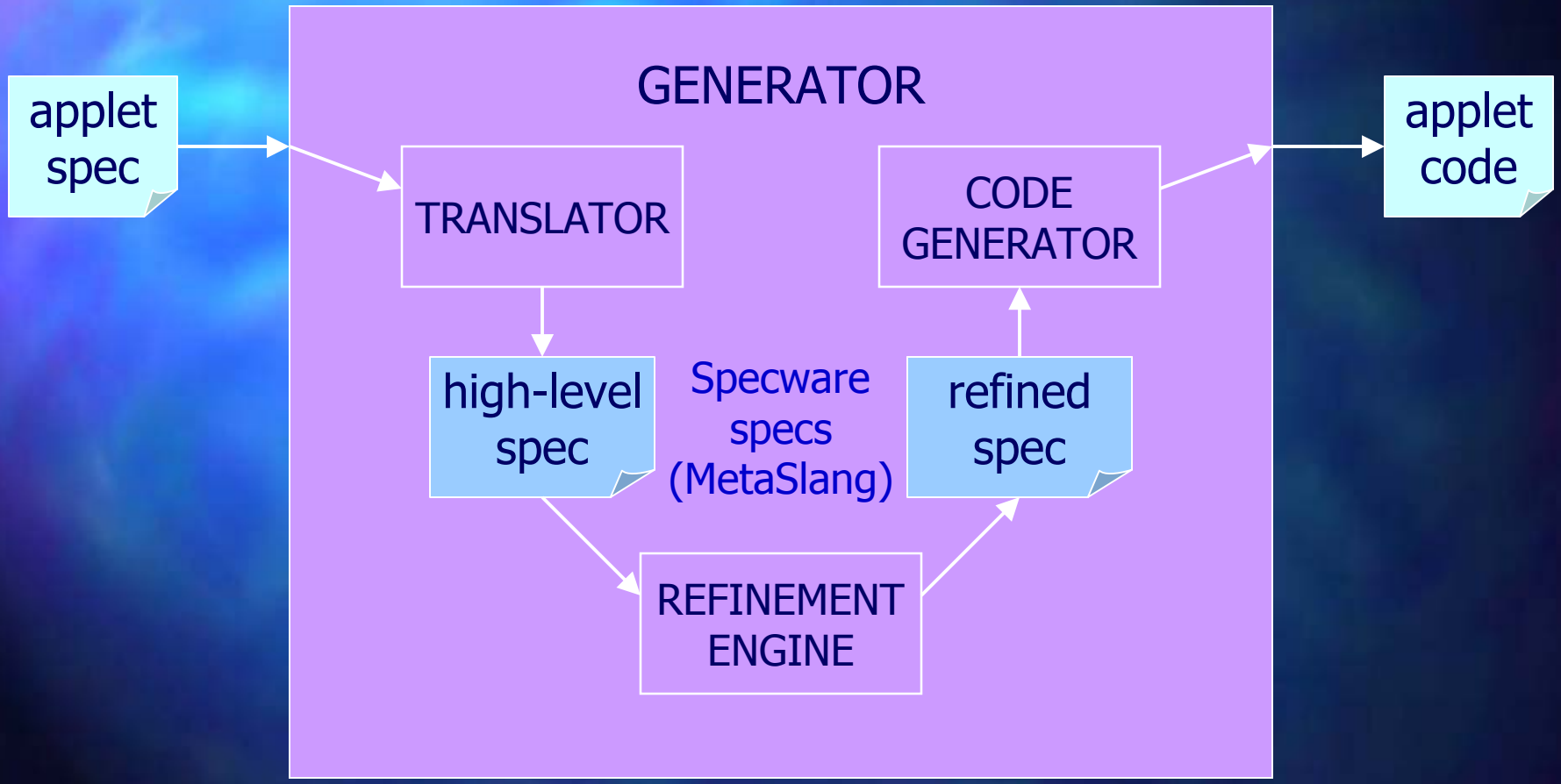

MetaSlang = spec language of Specware; version of higher-order logic

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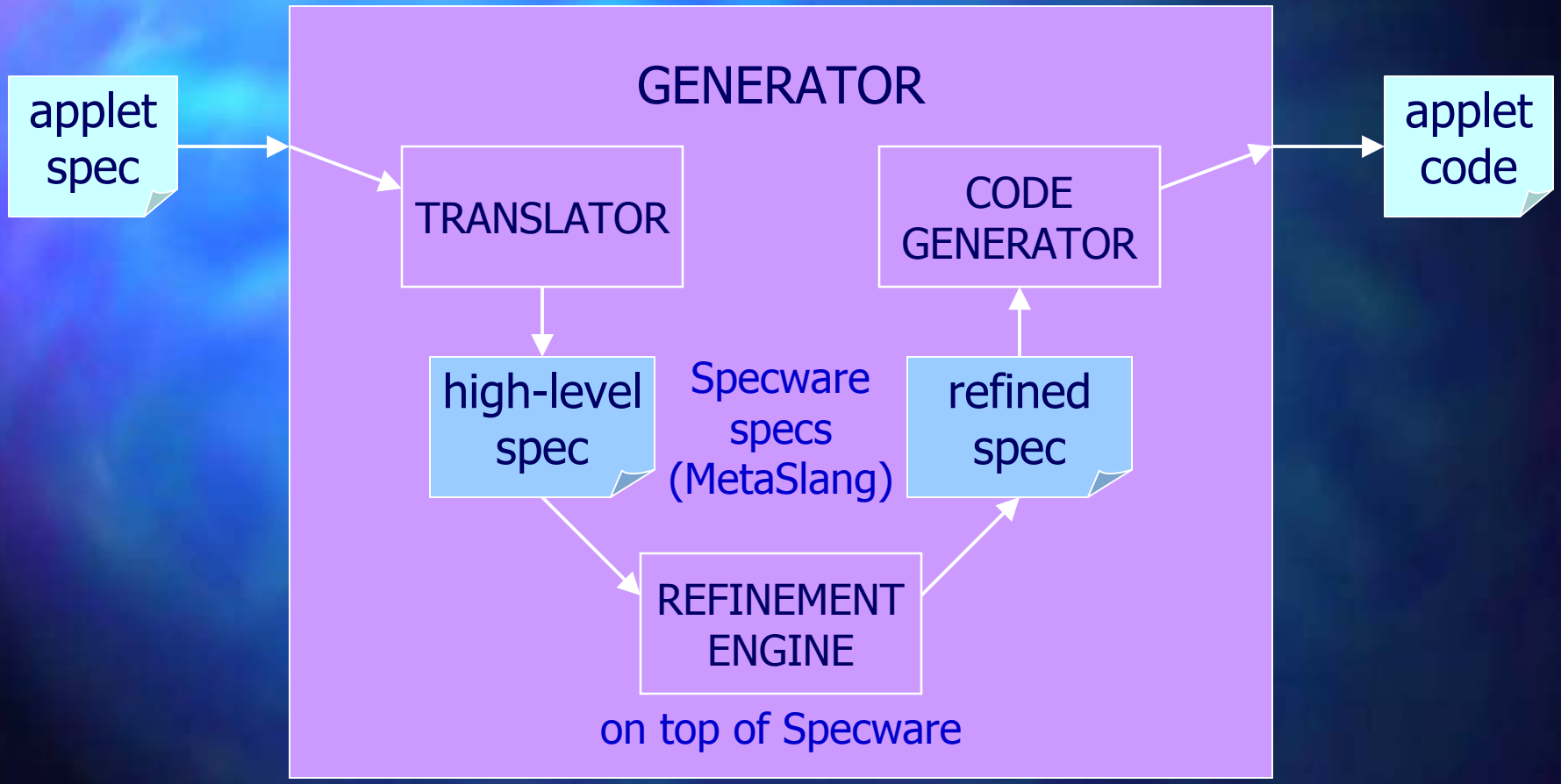

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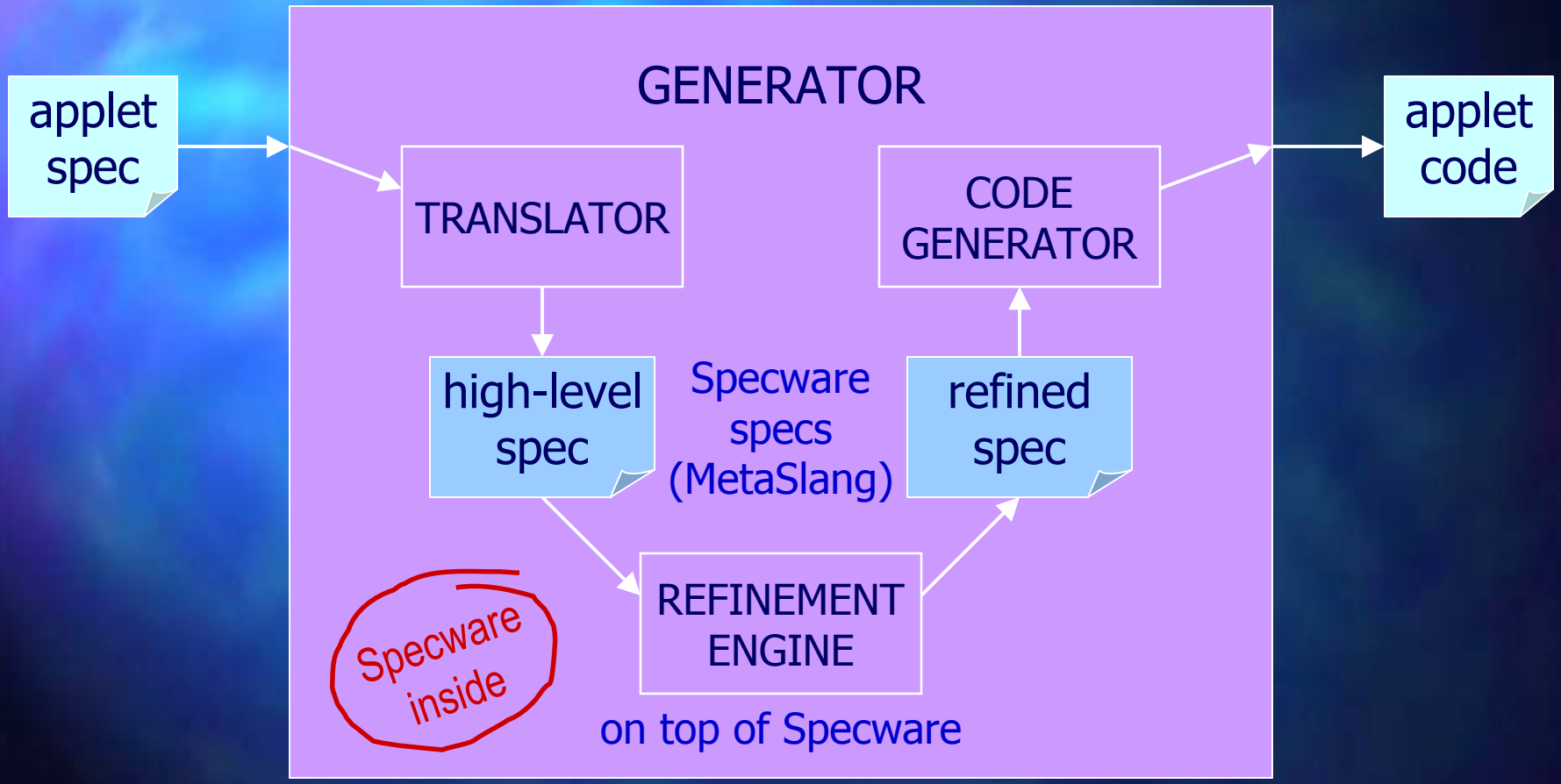

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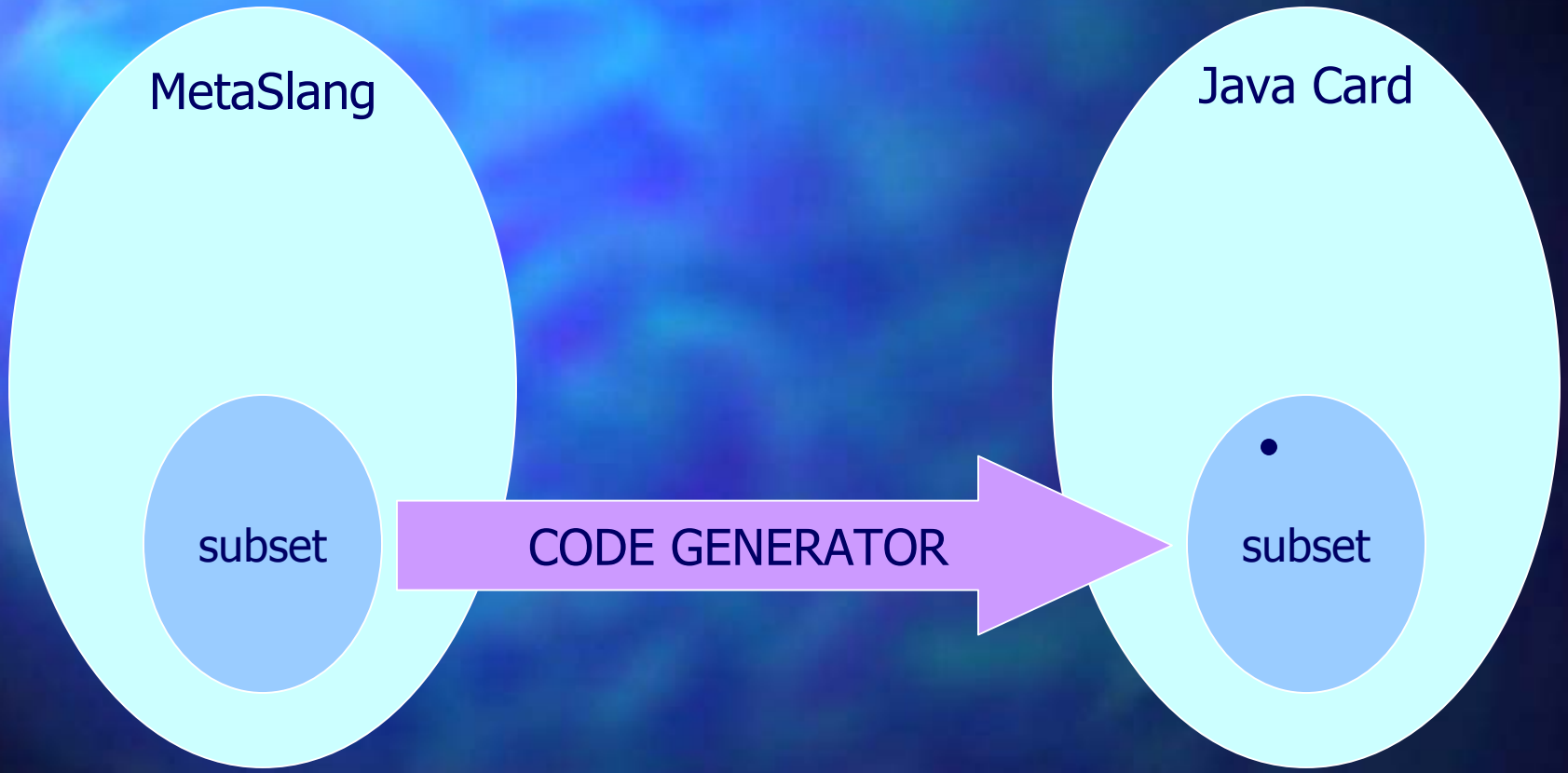

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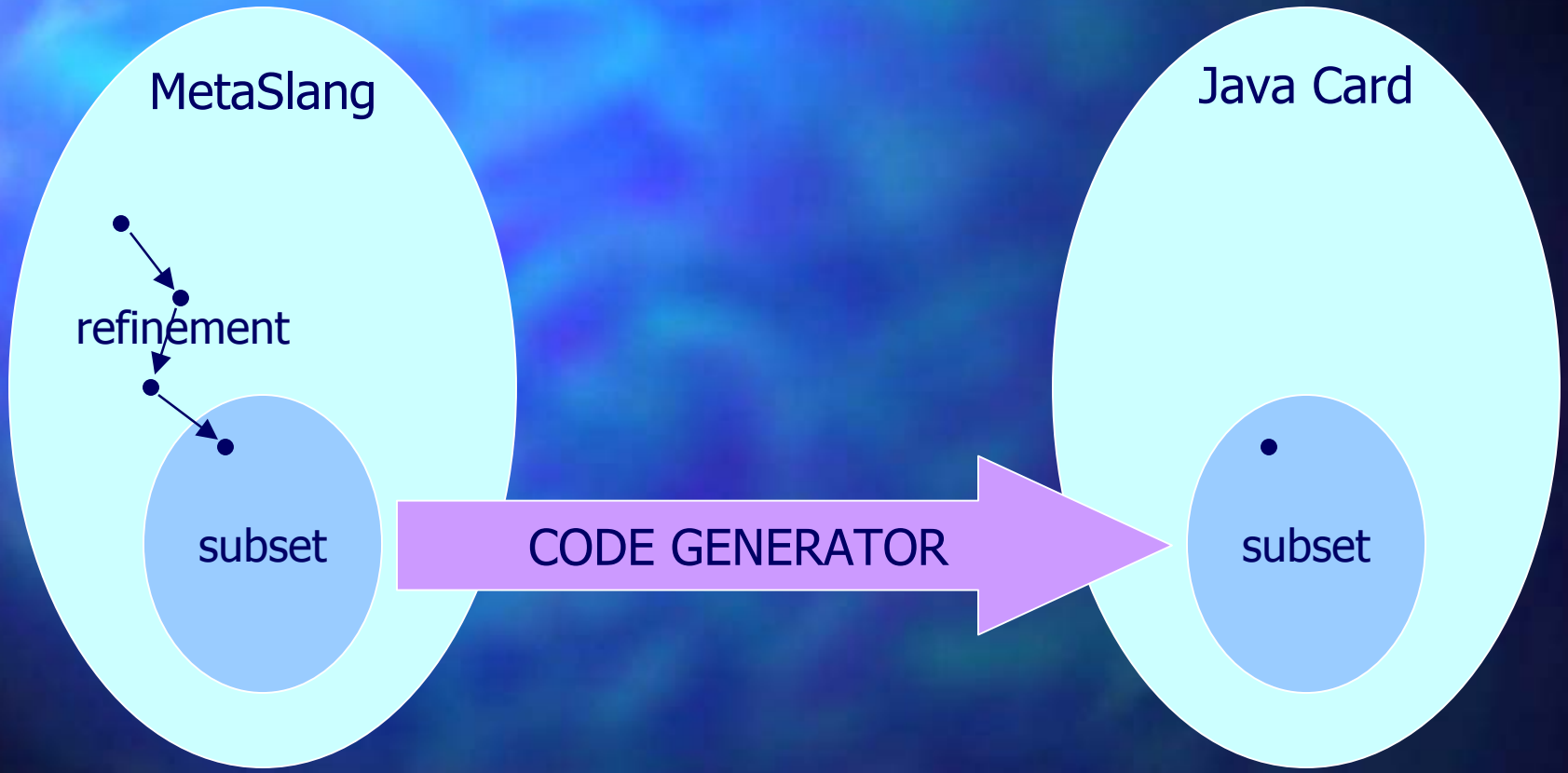

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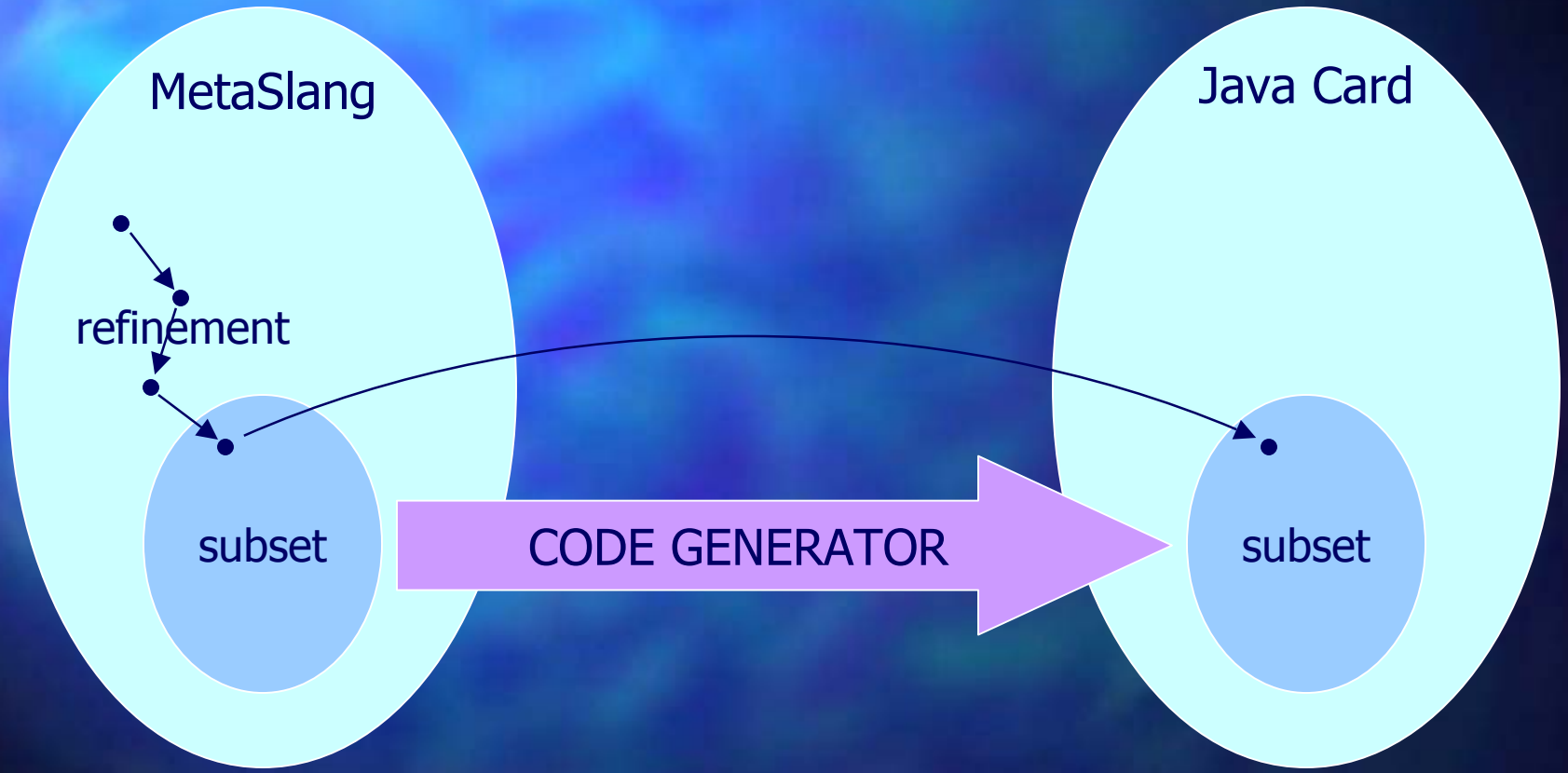

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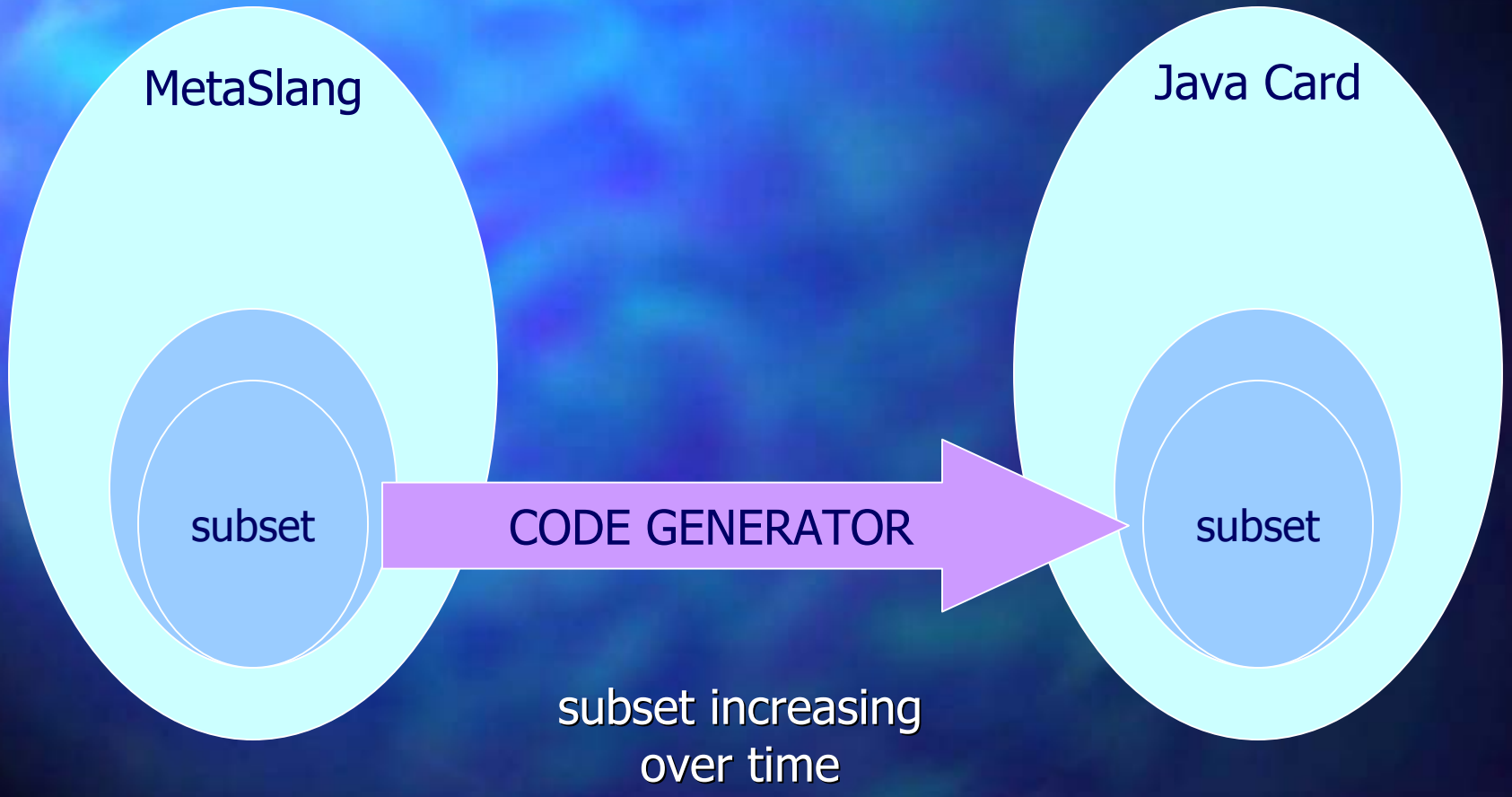

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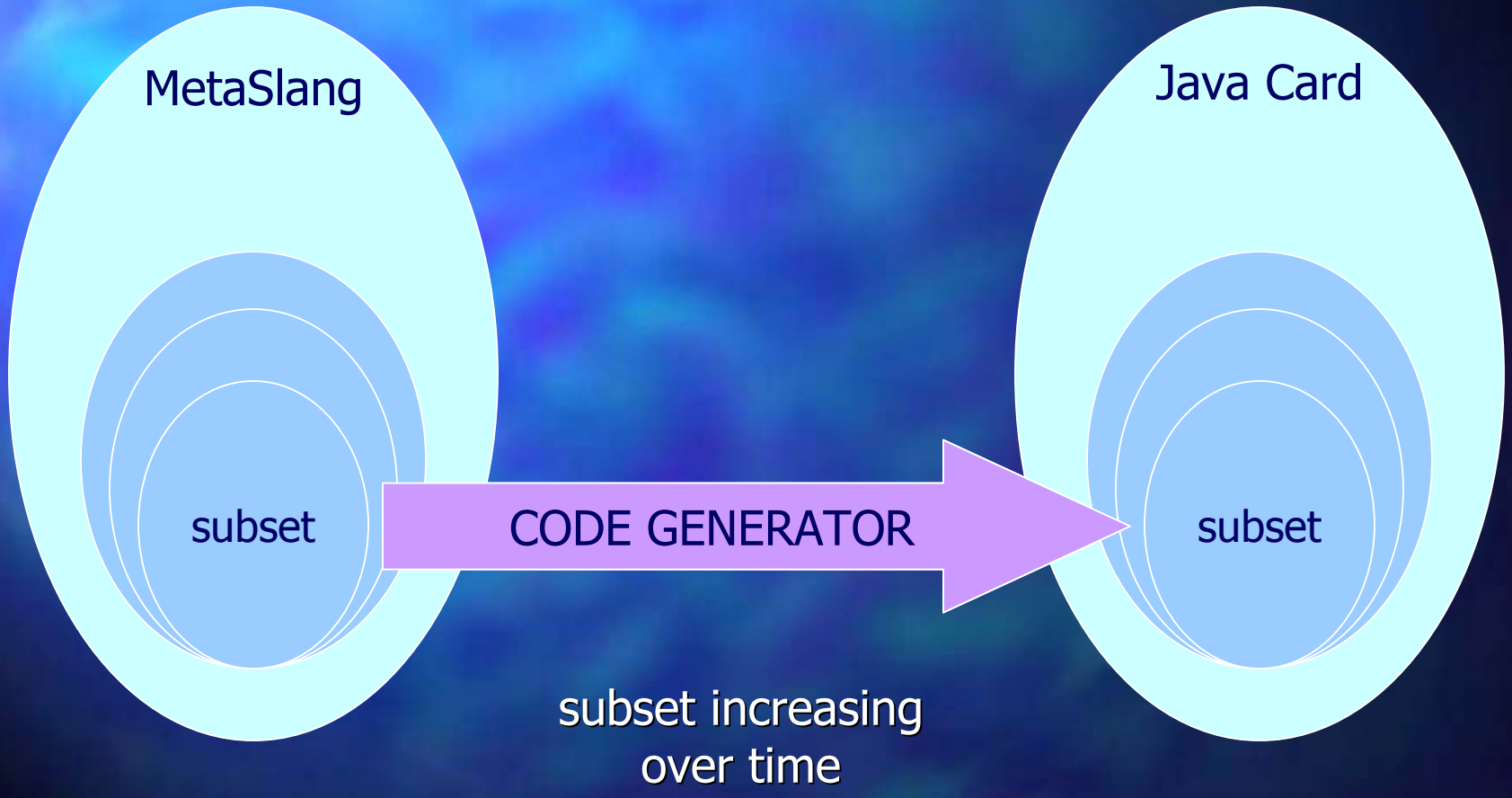

MetaSlang Subset

- $\text{MetaSlang}_{\text{JavaCard}} \subset \text{MetaSlang}$
- Specs in $\text{MetaSlang}_{\text{JavaCard}}$ represent Java Card programs
  - classes
  - fields
  - methods (incl. code)
- "Represent program" = "represent semantics of program"
- Code generator "extracts" Java Card program from its representation in $\text{MetaSlang}_{\text{JavaCard}}$

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Language Embedding

- Def.: representation of a language J in a language M (e.g. interpreter of J written in M)
- Well-researched topic
- Terminology
  - deep embedding:
    syntax and semantics of J represented in M
  - shallow embedding:
    semantics (but no syntax) of J represented in M

Deep vs. Shallow: Example

- Boolean expressions
- Syntax: variables + boolean operators
  - (x AND y) OR z
- Semantics: given a boolean value for each variable, expression evaluates to boolean value
  - x = T, y = T, z = F
  - (x AND y) OR z evaluates to T

Deep Embedding: Example

```
sort Expr = | var Var
            | and Expr * Expr
            | ...
sort Env = Var -> Bool
op eval : Expr -> (Env -> Bool)
...
axiom fa(exp1,exp2)
        eval(and(exp1,exp2)) =
        fn env -> eval(exp1)(env) &
                  eval(exp2)(env)
```

syntax

semantics

Deep Embedding: Example

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sort Expr = | var Var
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sort Env = Var -> Bool
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axiom fa(exp1,exp2)
        eval(and(exp1,exp2)) =
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```

syntax

semantics

boolean expressions are assigned semantics

Shallow Embedding: Example

```
sort Env = Var -> Bool
sort Expr = Env -> Bool
...
op and : Expr * Expr -> Expr
axiom fa(exp1,exp2)
          and(exp1,exp2) =
          fn env -> exp1(env) & exp2(env)
```

semantics only

Shallow Embedding: Example

```
sort Env = Var -> Bool
sort Expr = Env -> Bool
...
op and : Expr * Expr -> Expr
axiom fa(exp1,exp2)
        and(exp1,exp2) =
        fn env -> exp1(env) & exp2(env)
```

semantics only

boolean expressions are identified with their semantics

MetaSlang$_{\text{JavaCard}}$

- Shallow embedding of (subset of) Java Card into MetaSlang
- Subset of Java Card chosen
  - sufficient for non-trivial applets
  - will grow over time
- Why not deep embedding?
  - because shallow embedding is simpler (smaller)
  - we may switch to deep embedding in the future
- Includes Java Card APIs

Chosen Java Card Subset

- Includes
  - primitive values and types
  - classes and limited interfaces
  - instance fields, final static fields
  - methods
  - most expressions and statements
  - objects (class instances & arrays)
  - exceptions
- Excludes
  - full interfaces
  - inheritance, hiding, overriding
  - access modifiers (public, private, …)
  - packages
  - optional type int

Java Card Language Embedding (1)

```
sort Class    % classes in program
sort Field    % fields  in program
sort Method   % methods in program
op field_owner : Field -> Class
op method_owner : Method -> Class
sort Type = | boolean | byte | short
            | class Class | ...
op field_type : Field -> Type
op method_arg_types : Method -> FSeq(Type)
op method_res_type : Method ->
                     | void | nonvoid Type
...
```

Java Card Language Embedding (2)

```
sort ByteValue = {b : Int | -128 <= b & b < 128}
...
sort Value = | byte ByteValue
             | ref Reference
             | ...
sort ClassInstance = ...
sort Array = ...
sort Object = | clins ClassInstance | arr Array
sort Heap = FMap(Reference,Object)
...
```

Java Card Language Embedding (3)

```
sort LocalVariableStore = ...
sort State = {heap  : Heap,
              local : LocalVariableStore}
sort Expression = ...   % later
sort Statement = ...    % later
op plus : Expression * Expression -> Expression
axiom def_of_plus is ...
op while : Expression * Statement -> Statement
axiom def_of_while is ...
op method_body : Method -> Statement
...
```

Expressions and Statements

- May have side effects (i.e., cause state changes)
- May throw exceptions
- May return a value
- May cause input/output events
  - Java:
```
if (infile.read() == 3)
outfile.print("hello");
```
  - Java Card: `apdu.setIncomingAndReceive()`
- State changes may be non-deterministic
  - Java Card: `random.generateData()`

Expression and Statement Embedding: Attempt #1

```
sort Expression =
  State -> State * ExprResult

sort Statement =
  State -> State * StatResult
```

Expression and Statement Embedding: Attempt #1

```
sort Expression =
  State -> State * ExprResult

sort Statement =
  State -> State * StatResult
```

but: deterministic, no input/output events

Expression and Statement Embedding: Attempt #2a

```
sort Expression =
  State * InputEvent ->
  State * OutputEvent * ExprResult

sort Statement =
  State * InputEvent ->
  State * OutputEvent * StatResult
```

Expression and Statement Embedding: Attempt #2a

```
sort Expression =
  State * InputEvent ->
  State * OutputEvent * ExprResult

sort Statement =
  State * InputEvent ->
  State * OutputEvent * StatResult
```

but: deterministic

Expression and Statement Embedding: Attempt #2b

```
sort Expression =
  State * State * ExprResult -> Boolean

sort Statement =
  State * State * StatResult -> Boolean
```

Expression and Statement Embedding: Attempt #2b

```
sort Expression =
  State * State * ExprResult -> Boolean

sort Statement =
  State * State * StatResult -> Boolean
```

but: no input/output events

Expression and Statement Embedding: Attempt #3

```
sort Expression =
  State * InputEvent *
  State * OutputEvent * ExprResult ->
  Boolean


sort Statement =
  State * InputEvent *
  State * OutputEvent * StatResult ->
  Boolean
```

Expression and Statement Embedding: Attempt #3

```
sort Expression =
  State * InputEvent *
  State * OutputEvent * ExprResult ->
  Boolean

sort Statement =
  State * InputEvent *
  State * OutputEvent * StatResult ->
  Boolean
```

OK: input/output events, non-deterministic!

Expression and Statement Embedding (1)

```
sorts InputEvent, OutputEvent
sort SideEffect = {old : State,
                   new : State,
                   in  : FSeq(InputEvent),
                   out : FSeq(OutputEvent)}
sort ExprResult = ...
sort StatResult = ...
sort Expression =  % relation
     SideEffect * ExprResult -> Boolean
sort Statement =   % relation
     SideEffect * StatResult -> Boolean
```

Expression and Statement Embedding (2)

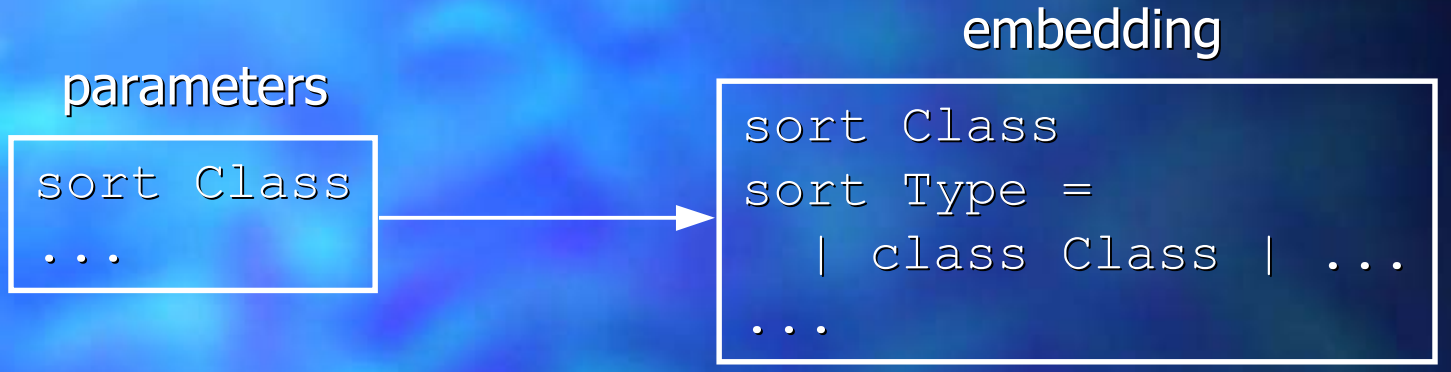
```
op plus : Expression * Expression -> Expression
axiom def_of_plus is
  fa(exp1,exp2)
    plus(exp1,exp2) =
    fn(seff,eres) ->
      (ex(seff1,eres1,seff2,eres2)
         exp1(seff1,eres1) &
         exp2(seff2,eres2) &
         seff.old = seff1.old &
         seff1.new = seff2.old &
         seff2.new = seff.new &
         seff.in = seff1.in || seff2.in &
         seff.out = seff1.out || seff2.out &
         eres = eres1 + eres2)
```

Program Representation by Instantiation of Embedding

embedding

```
sort Class
sort Type =
  | class Class | ...
...
```

Program Representation by Instantiation of Embedding



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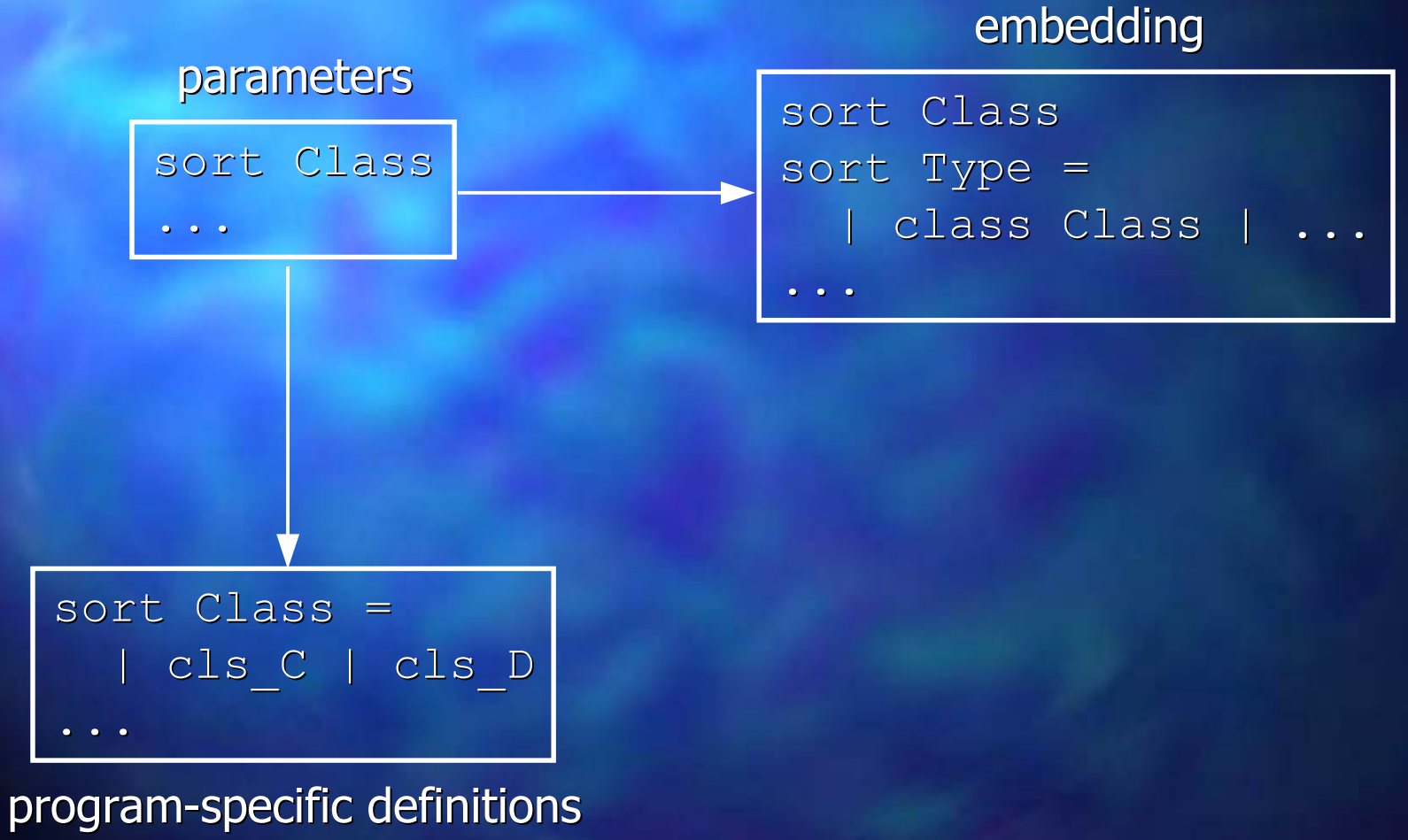

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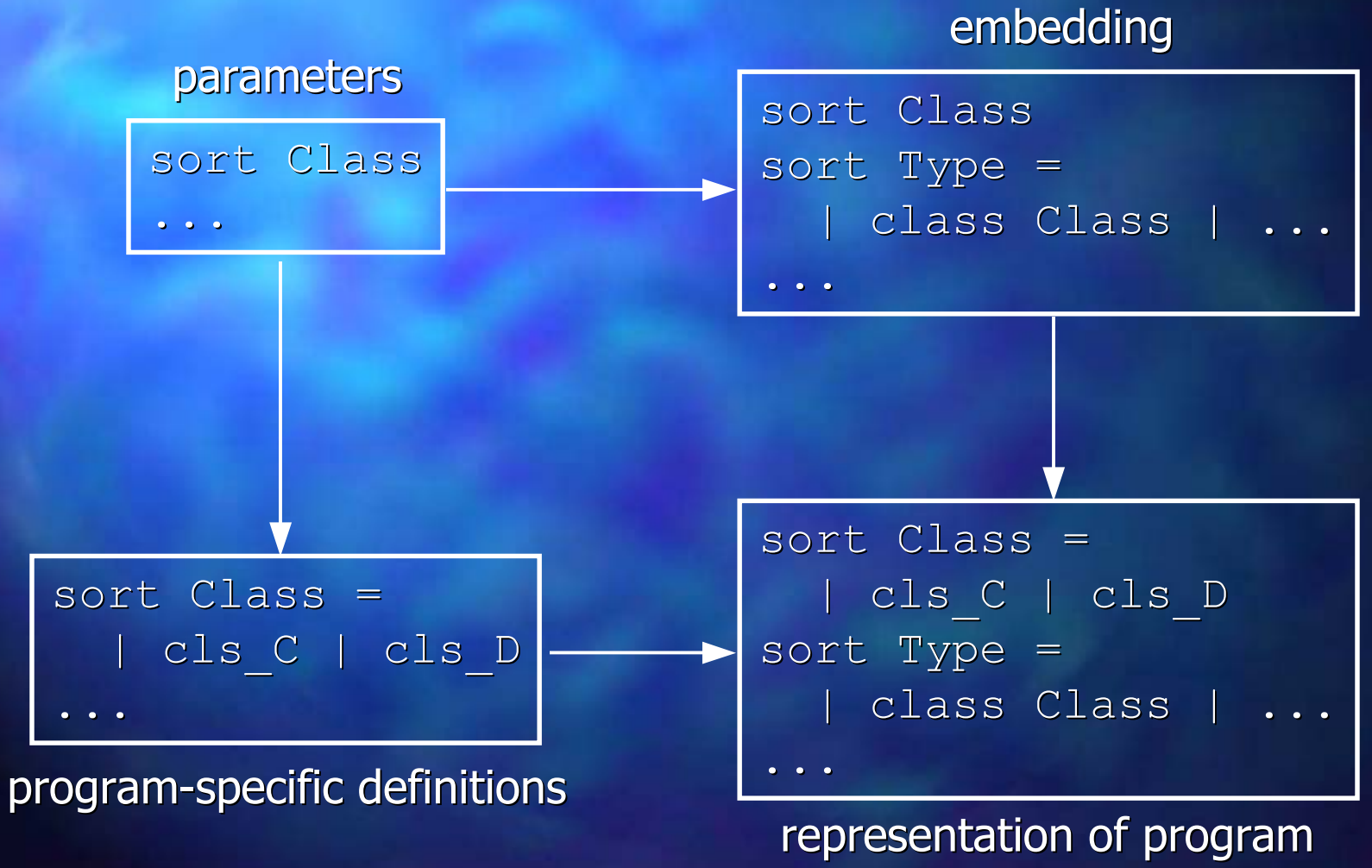

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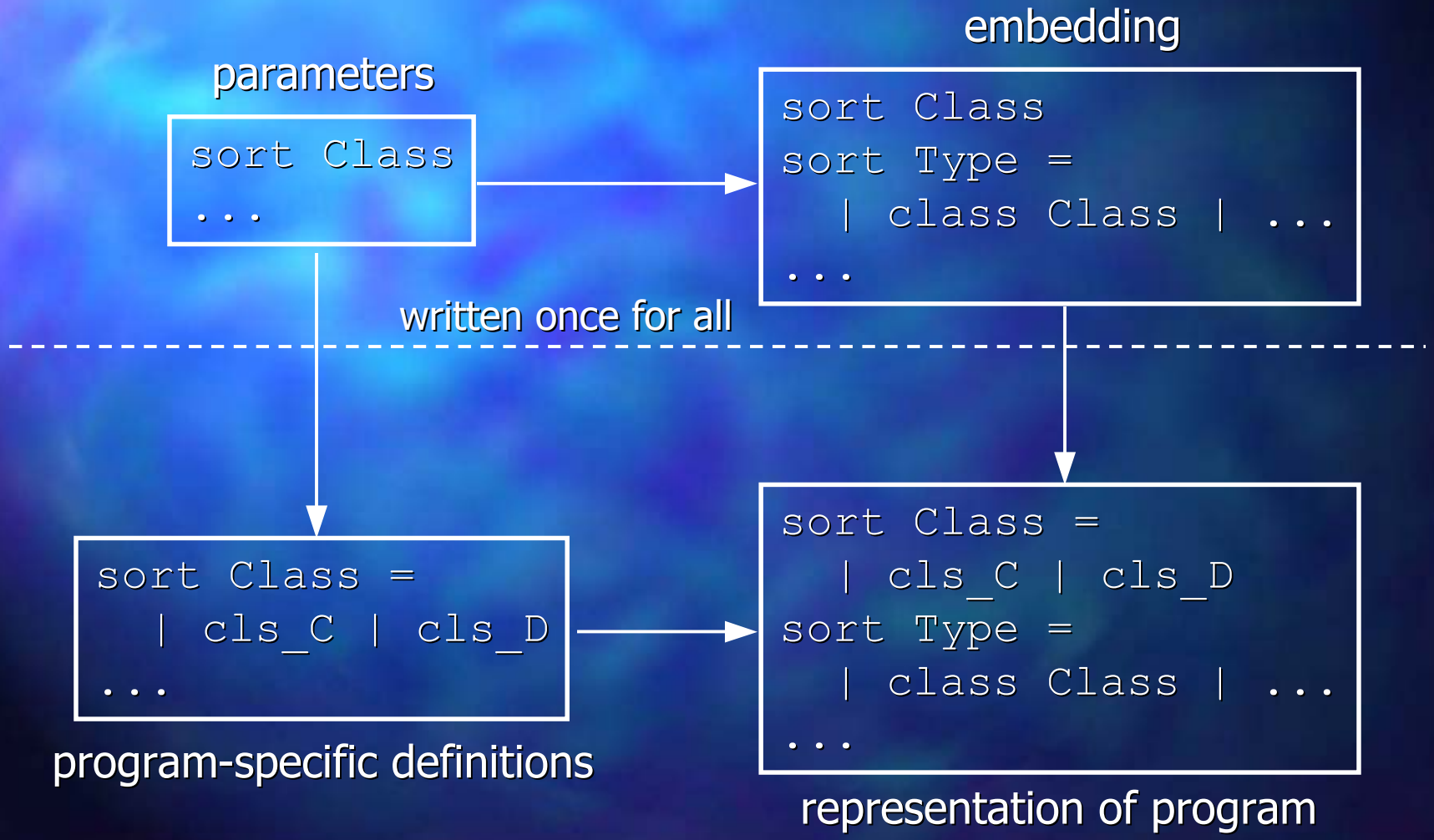

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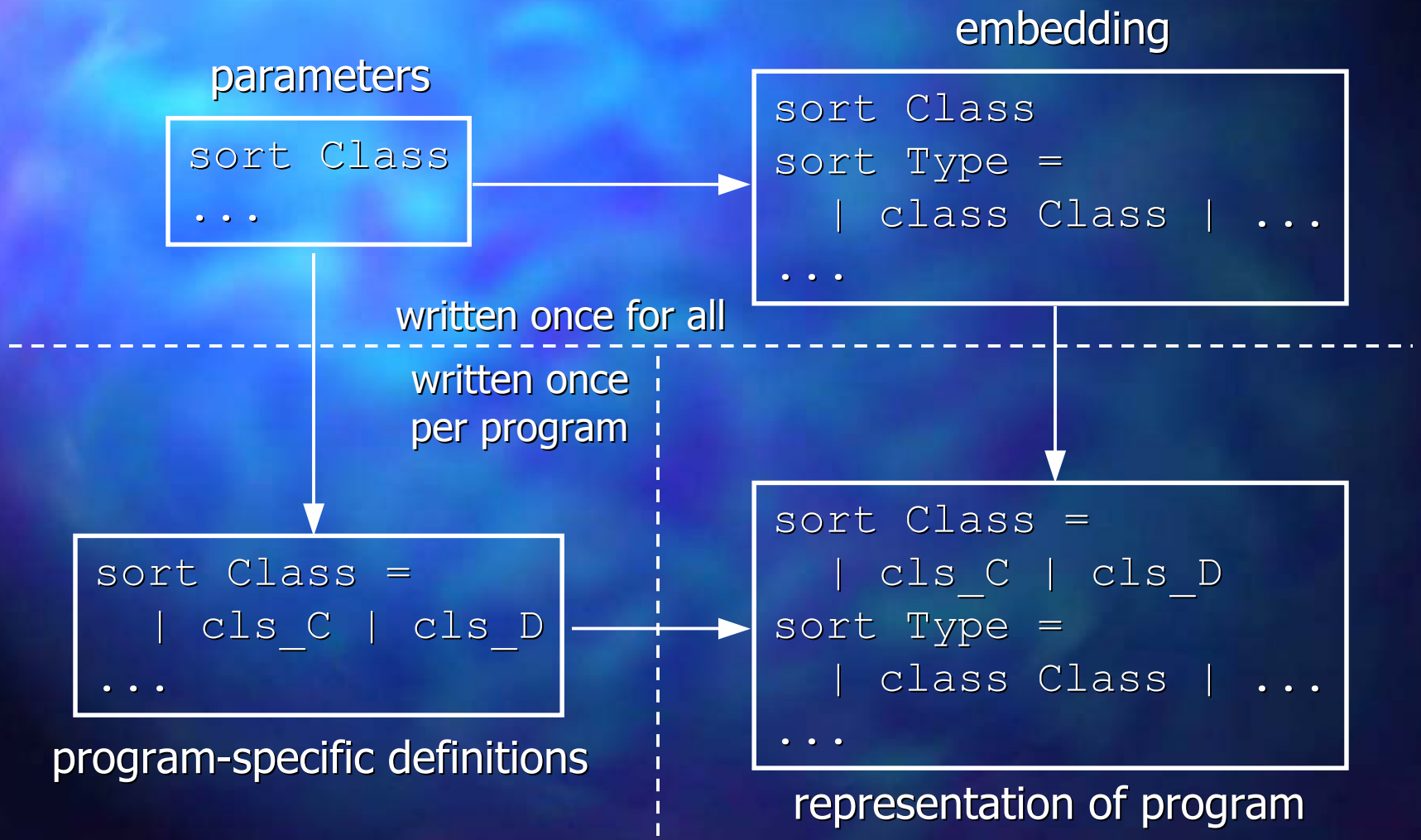

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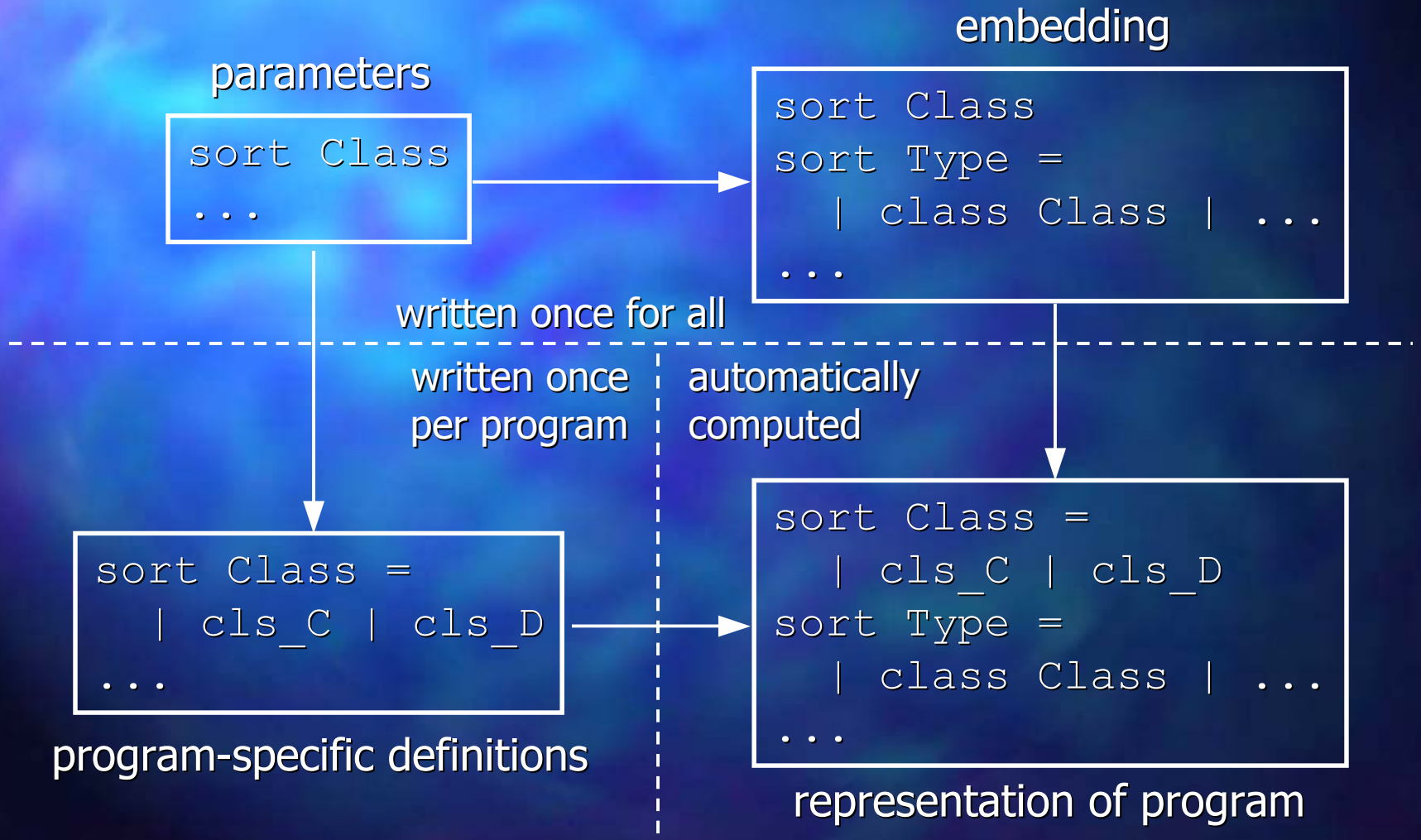


Example

```
class C {
  byte f;
}

class D {
  C g;
  byte m() {
    return g.f;
  }
}
```

```
sort Class = | cls_C | cls_D
sort Field = | fld_f | fld_g
sort Method = | mth_m
axiom field_owner(fld_f) = cls_C
axiom field_type(fld_f) = prim(byte)
axiom field_owner(fld_g) = cls_D
axiom field_type(fld_g) = class(cls_C)
axiom method_owner(mth_m) = cls_D
...
axiom
  method_body(mth_m) =
  stat_return
    (field_access
      (field_access expr_this_D fld_g)
      fld_f)
```

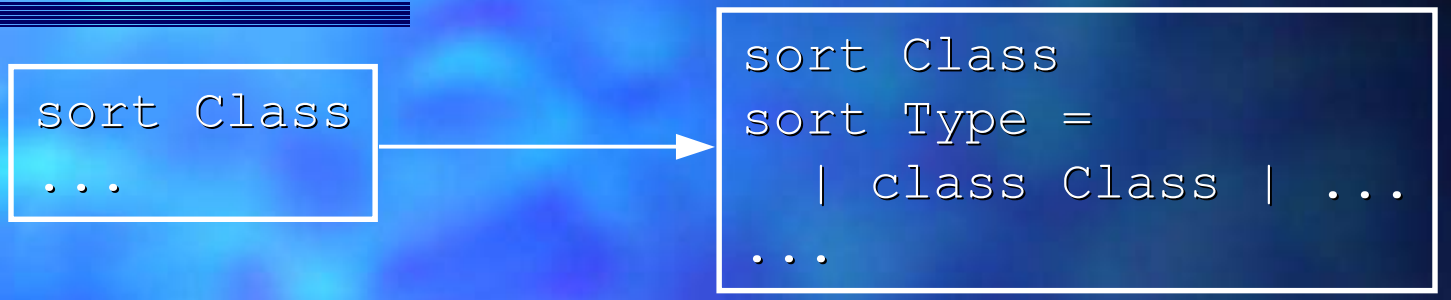
Chosen Java Card APIs

- Formalized substantial subsets of
  - APDU (most complex class)
  - ISOException
  - DESKey
  - RSAPrivateKey
  - RandomData
  - Cipher
  - KeyBuilder
  - ISO7816
  - Key

API Formalization

```
sort APIClass = | cls_APDU | cls_Cipher | ...
sort APDUState = | received_header
                 | receiving_data
                 | received_data
                 | sending_data
                 | sent_data
sort RSAKey = {modulus  : FSeq ByteValue,
               exponent : FSeq ByteValue}
...
op APDU_sendBytes : APIMethod
axiom APDU_sendBytes = ...
```

API Formalization by Partial Instantiation of Embedding



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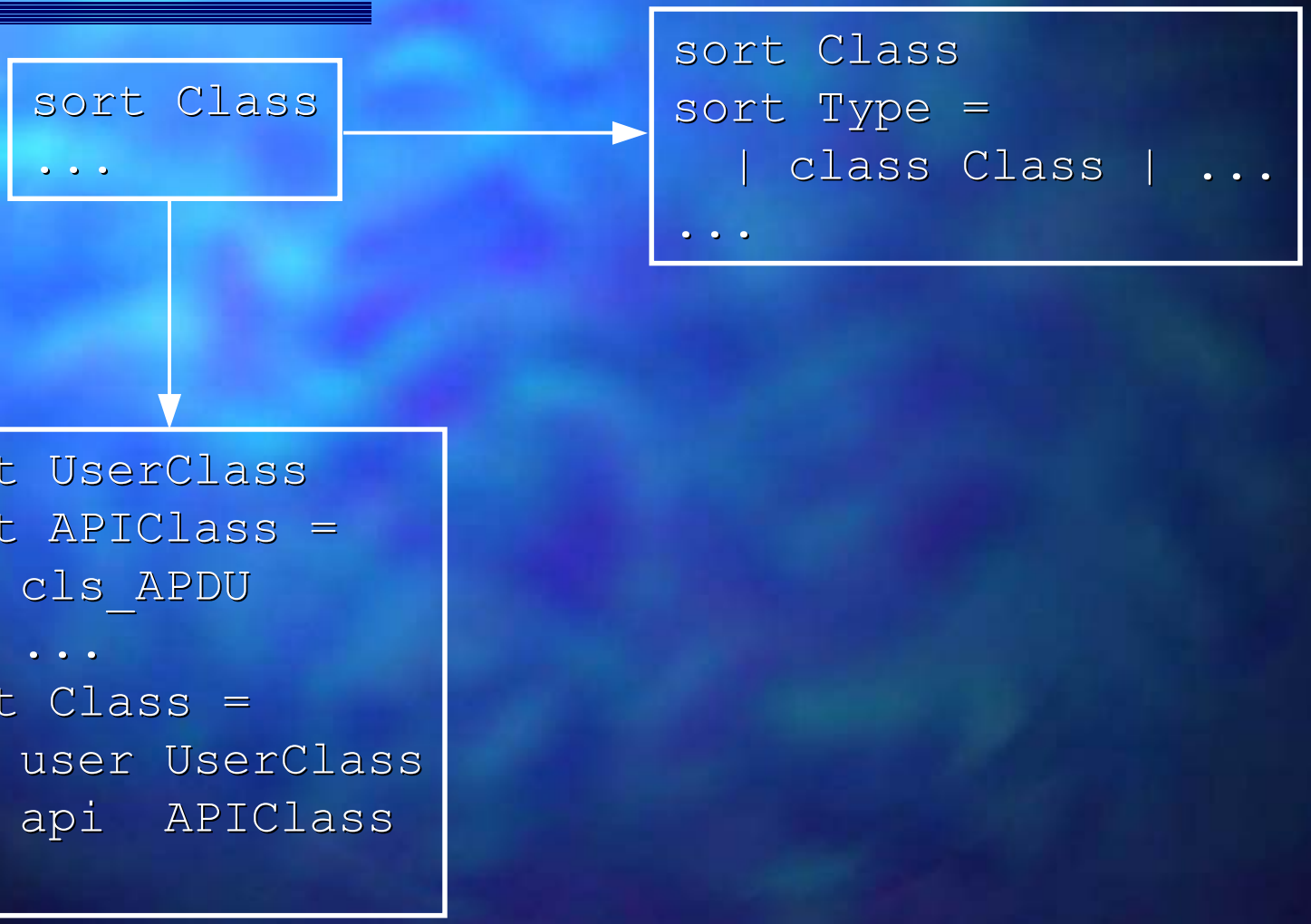

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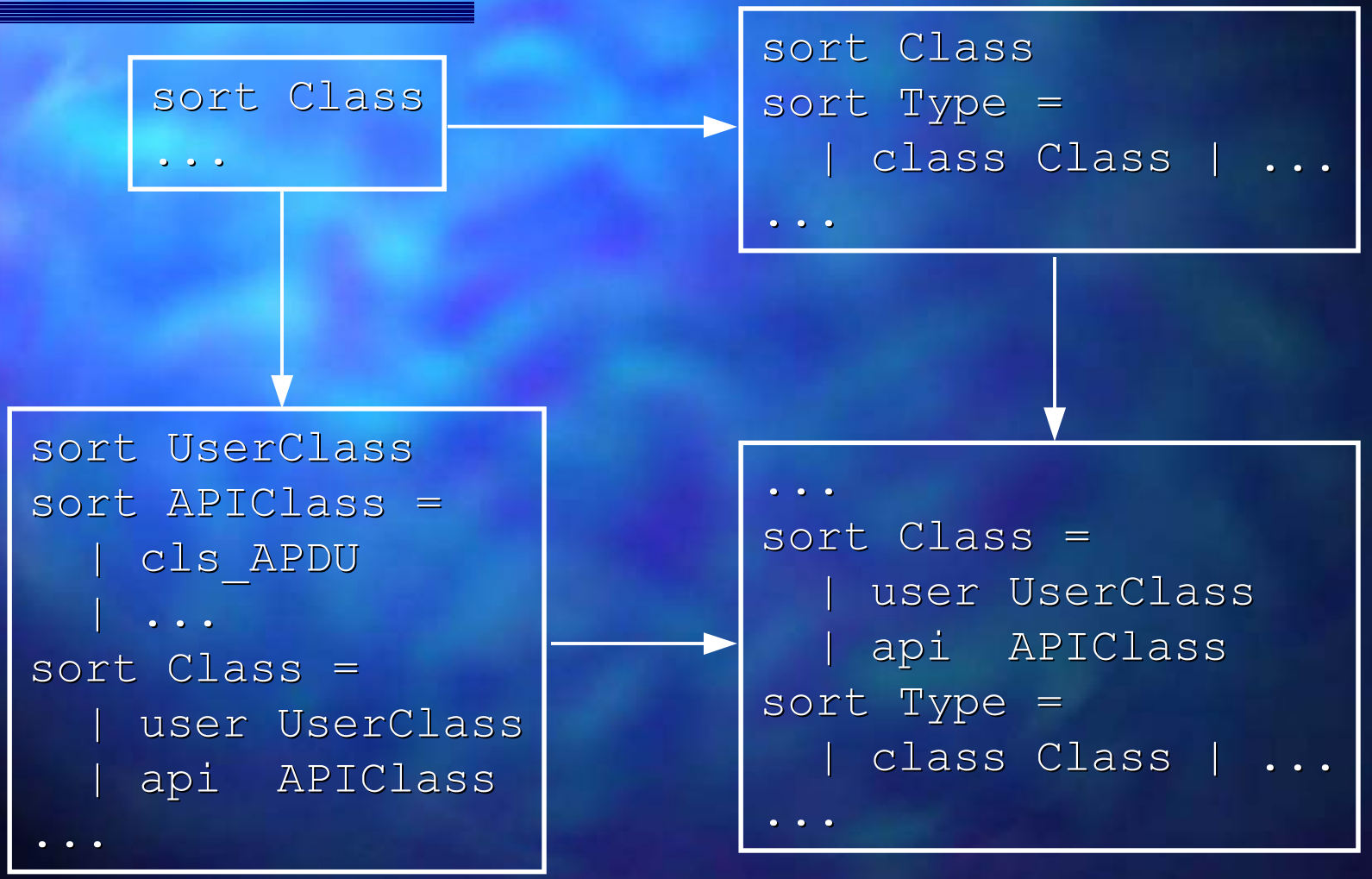
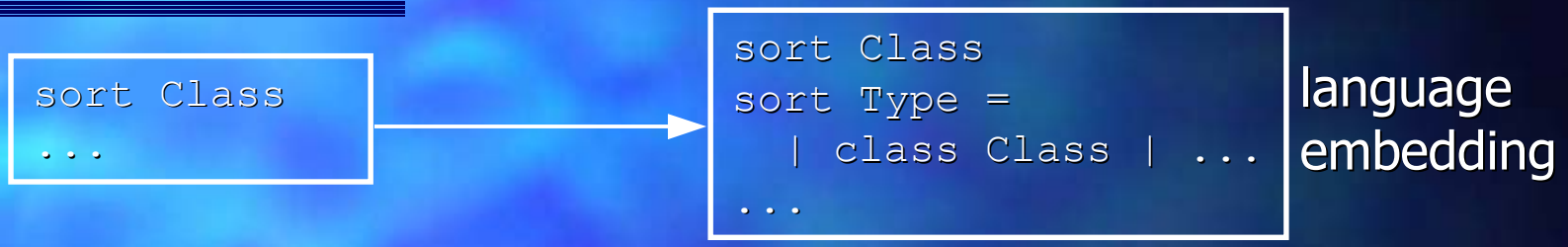
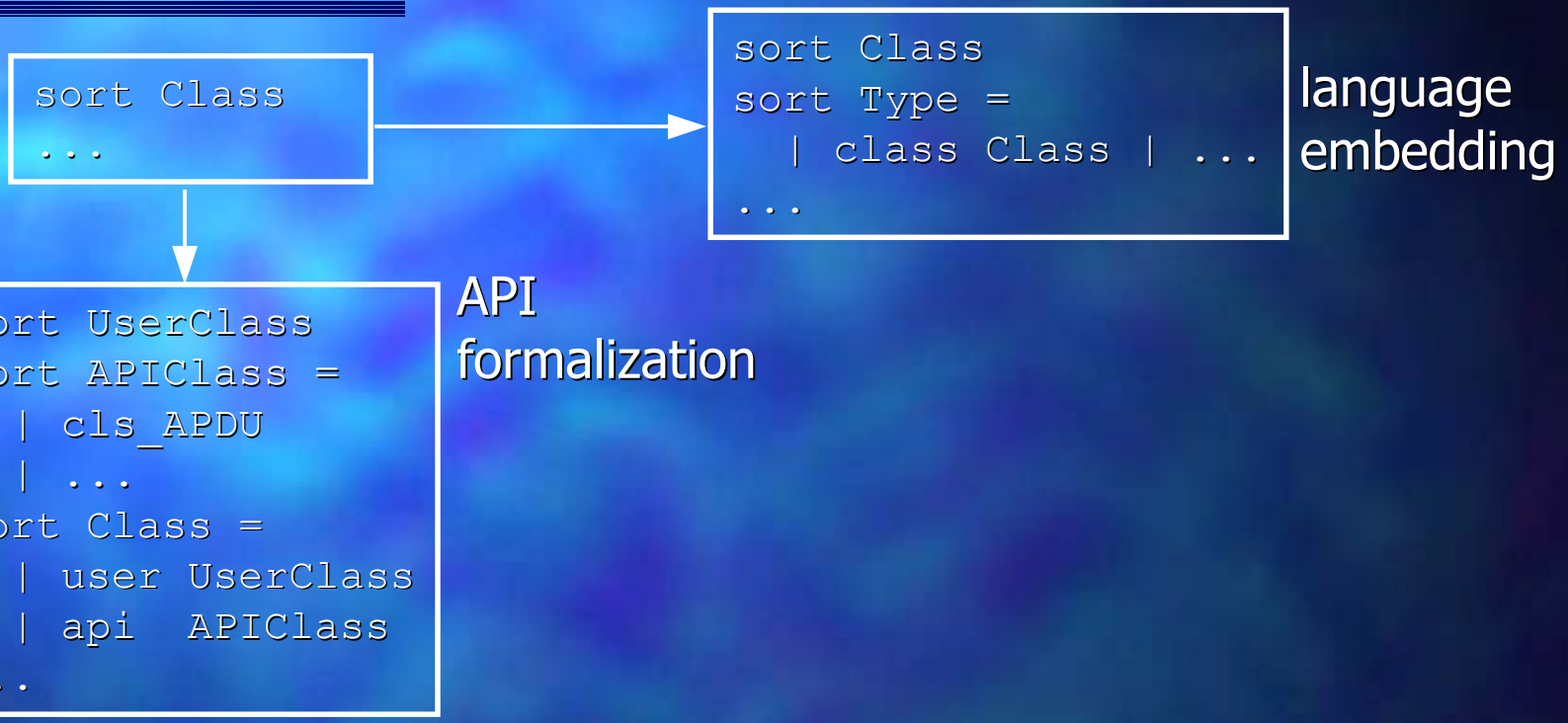


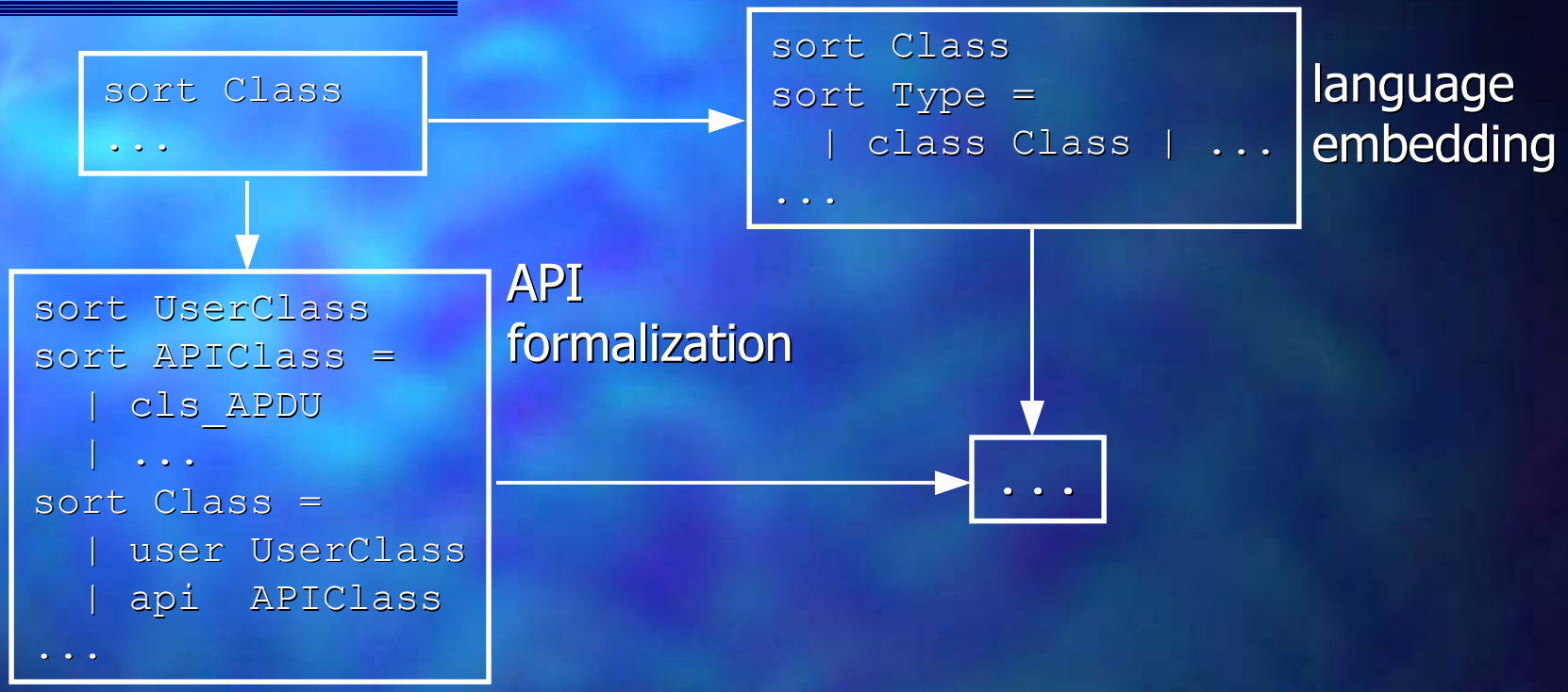
Program Representation by Complete Instantiation



Program Representation by Complete Instantiation



Program Representation by Complete Instantiation



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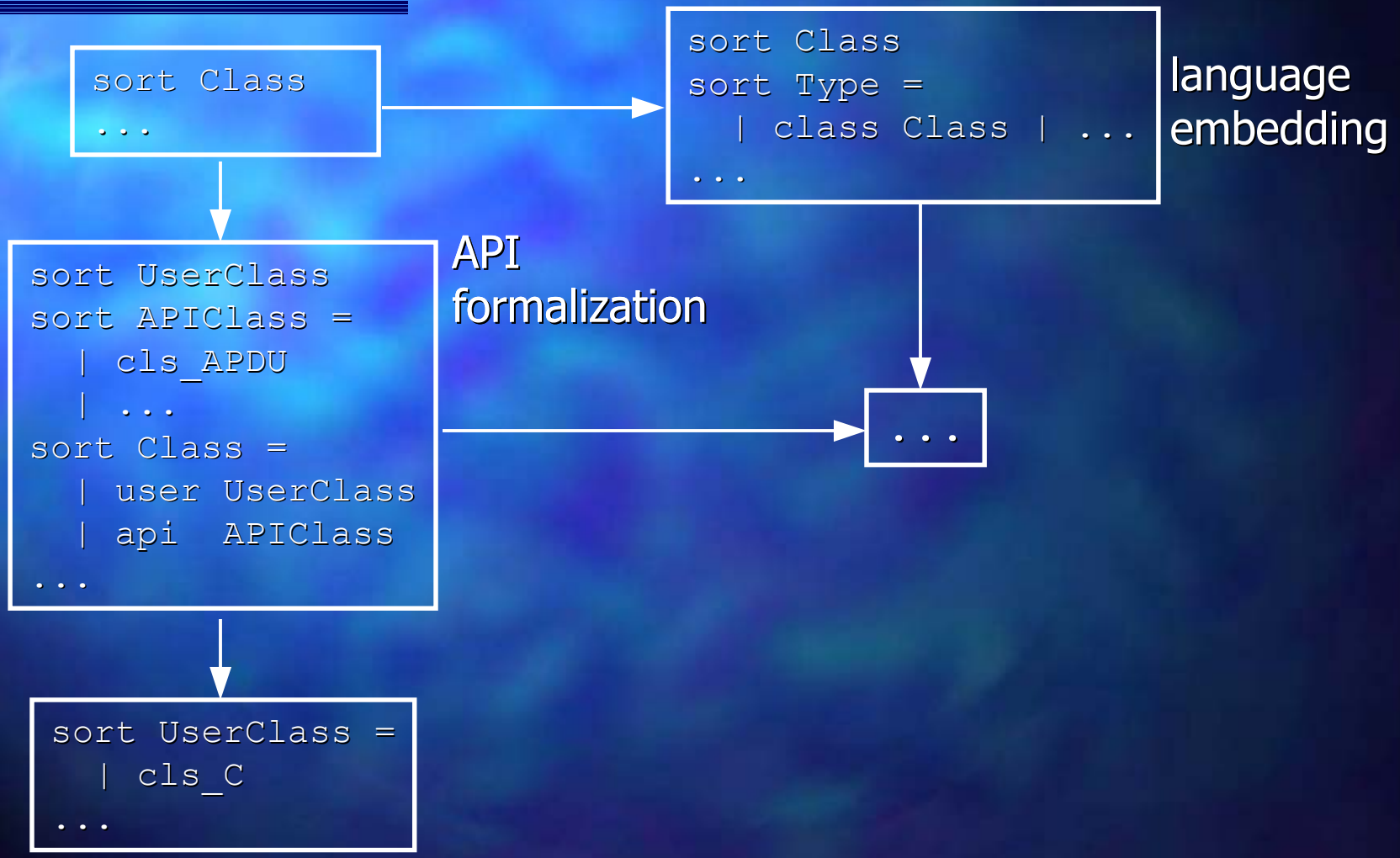

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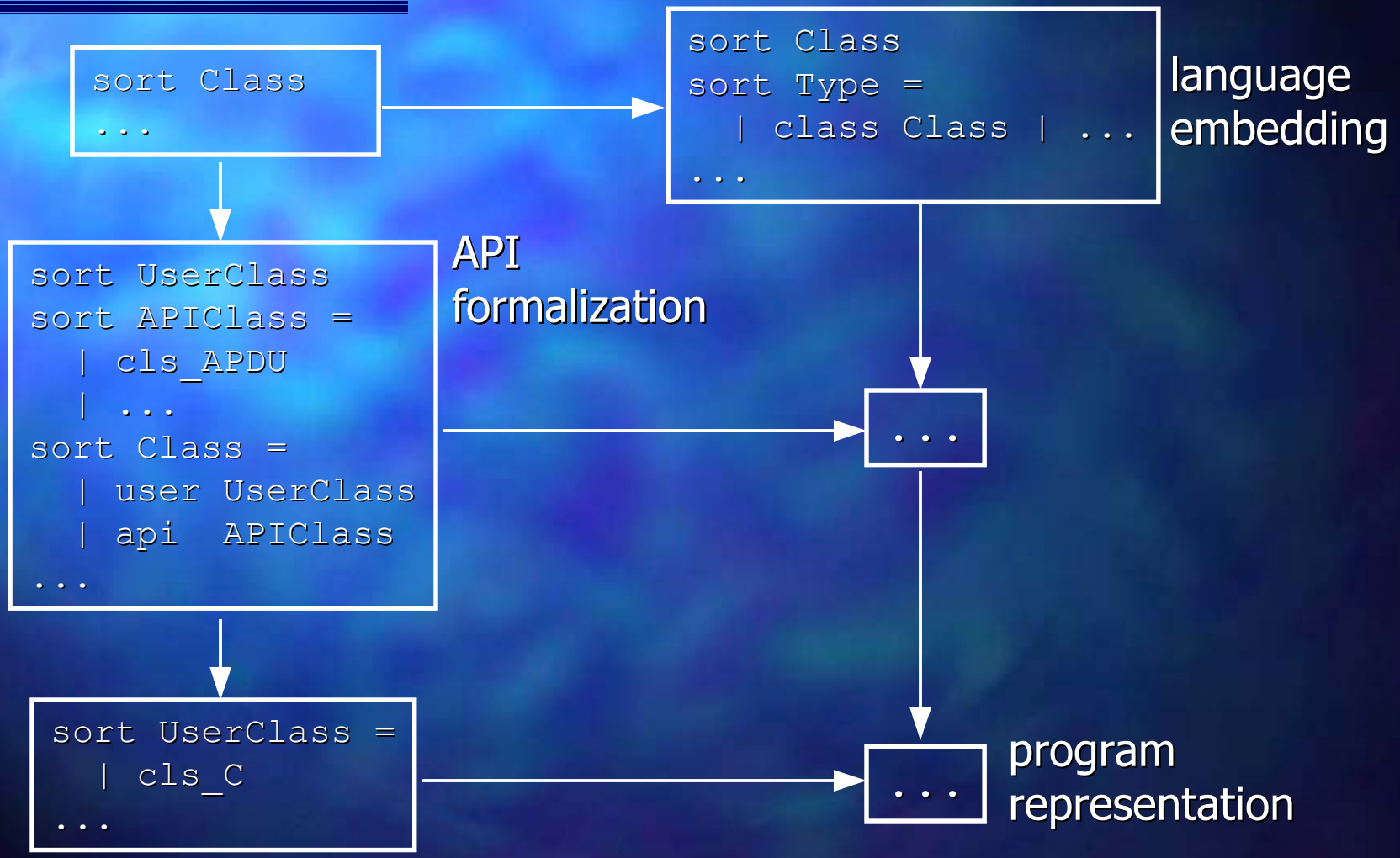

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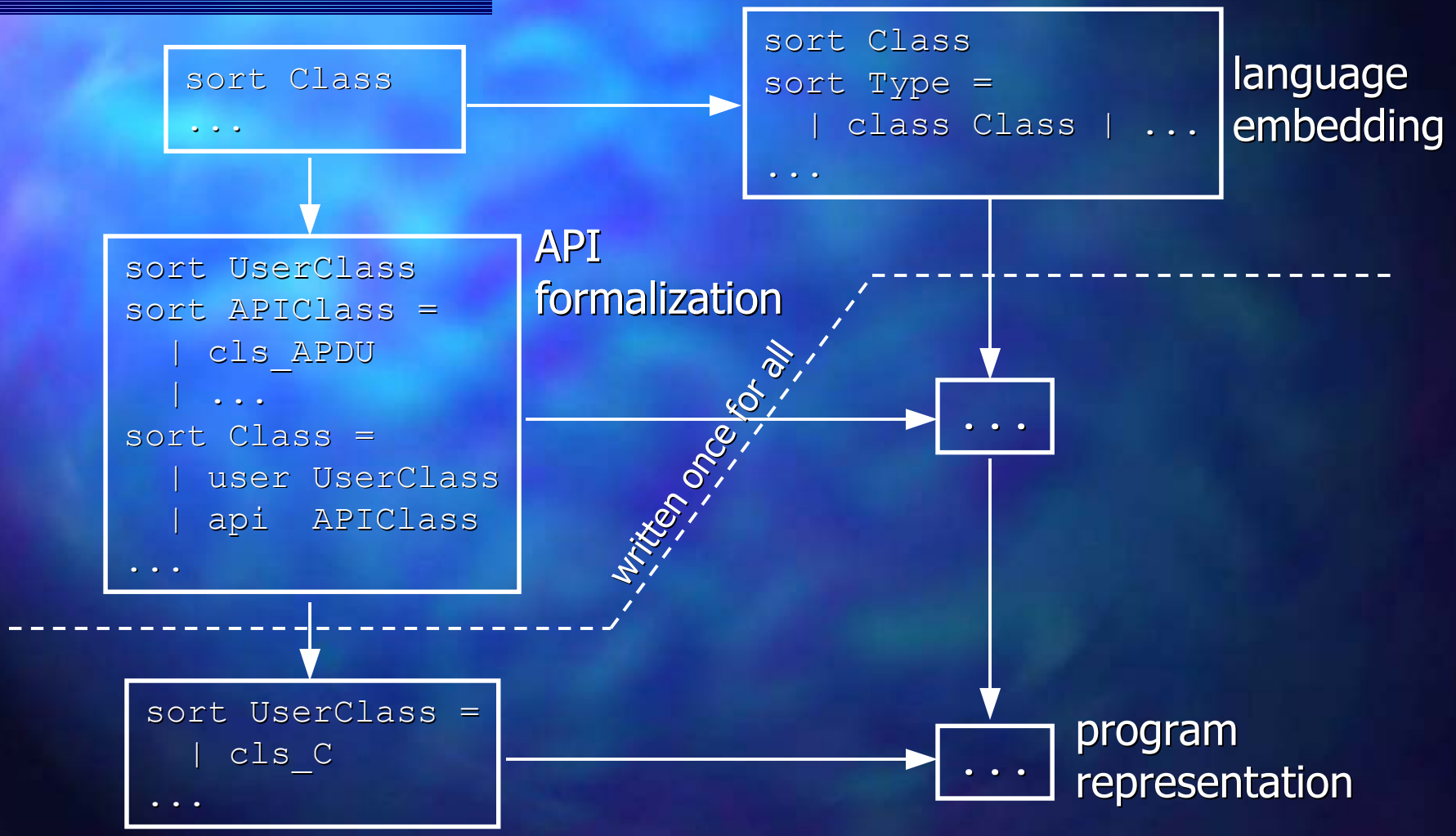

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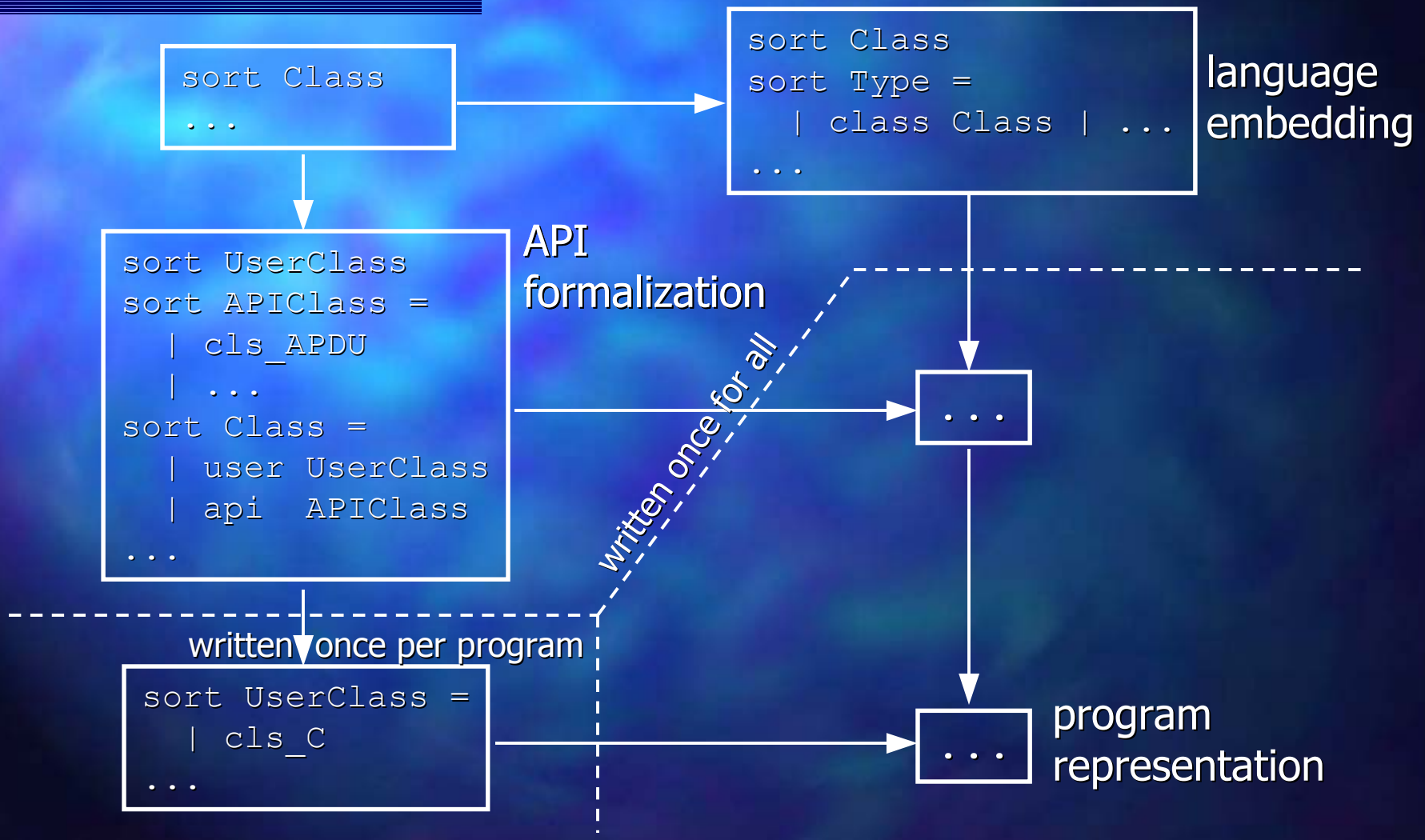

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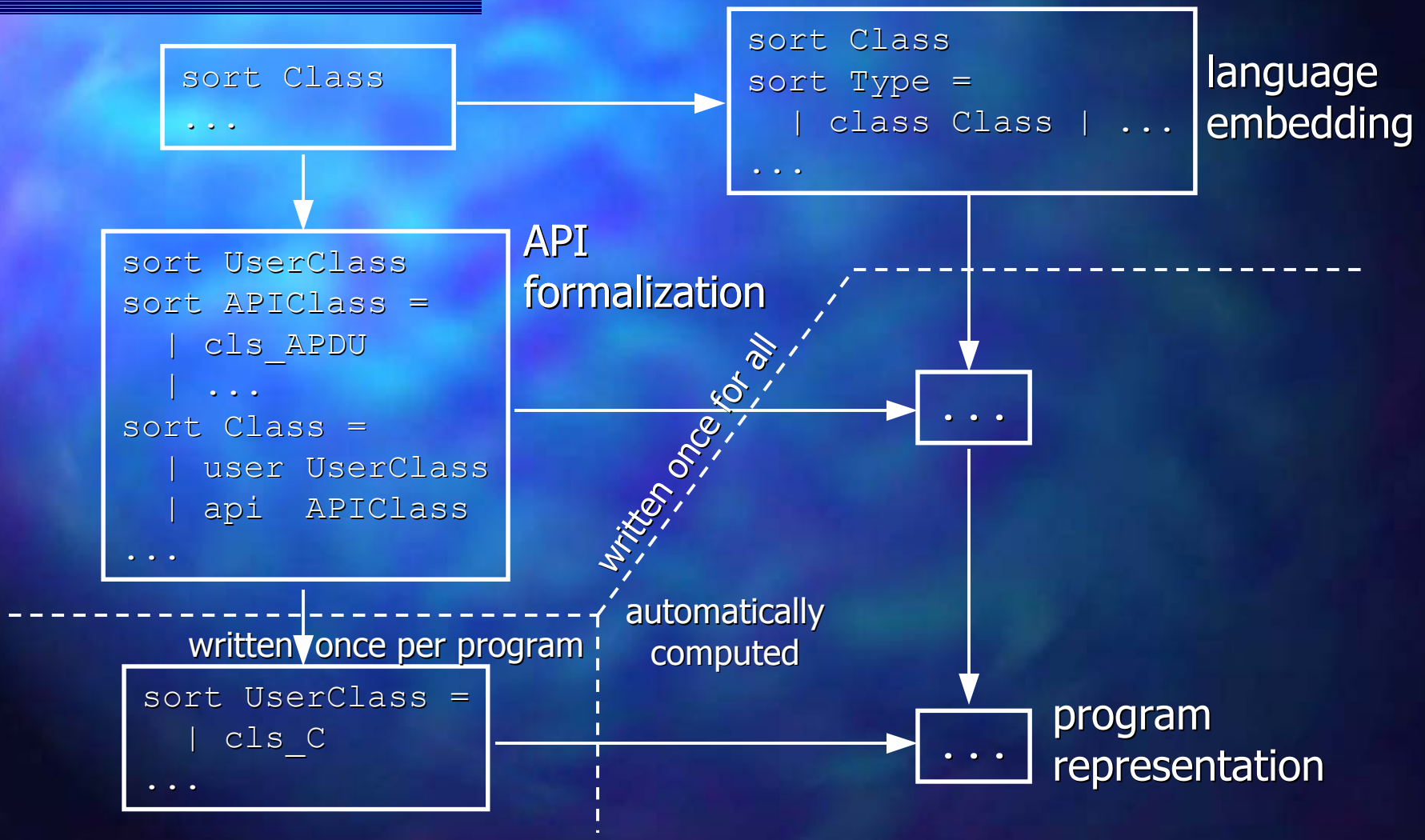

Example

```
class C {
 void m(APDU apdu)
 {
  byte[] buf;
  buf =
    apdu.getBuffer();
 }
}
```

```
sort UserClass = | cls_C
sort UserLocalVariable =
   | locvar_apdu
   | locvar_buf
sort Method = | mth_m
...
axiom
  method_body(mth_m) =
  stat_assignment
     expr_locvar_buf
     (expr_invoke_APDU_getBuffer
        expr_locvar_apdu)
```

Summary

- Java Card
- Kestrel's work
- Applet generator
- Code generator
  - approach
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One-to-one Correspondence

used by the checker

code generator checks that spec is in MetaSlang$_{JavaCard}$ and maps it to corresponding Java Card program

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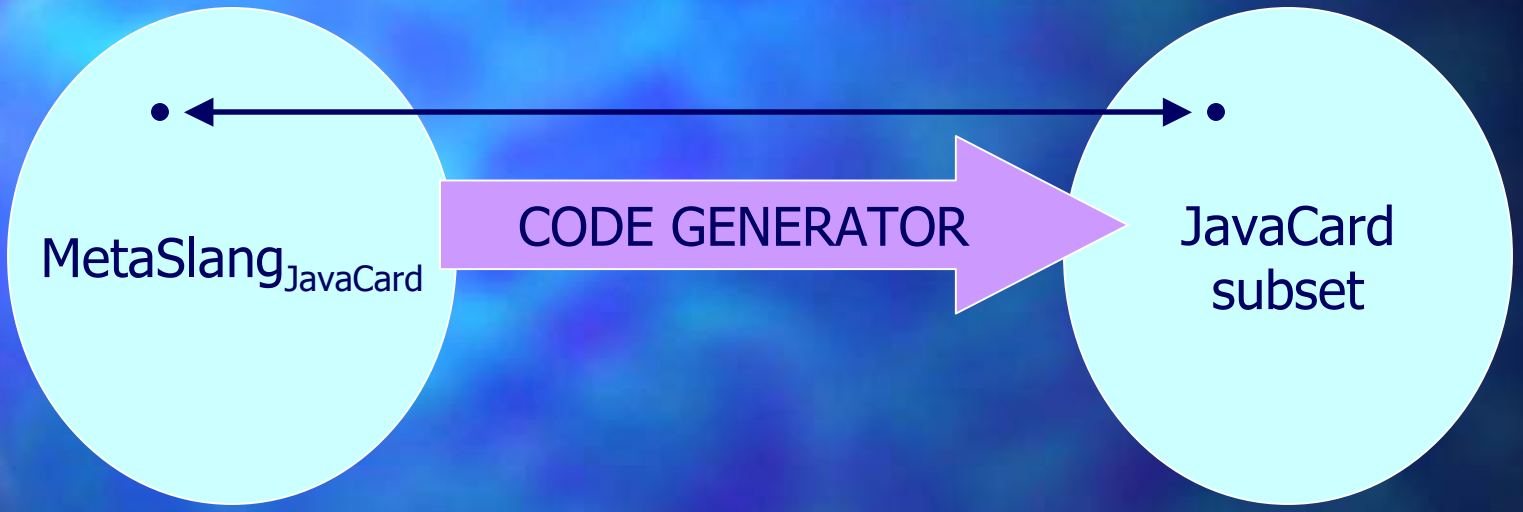

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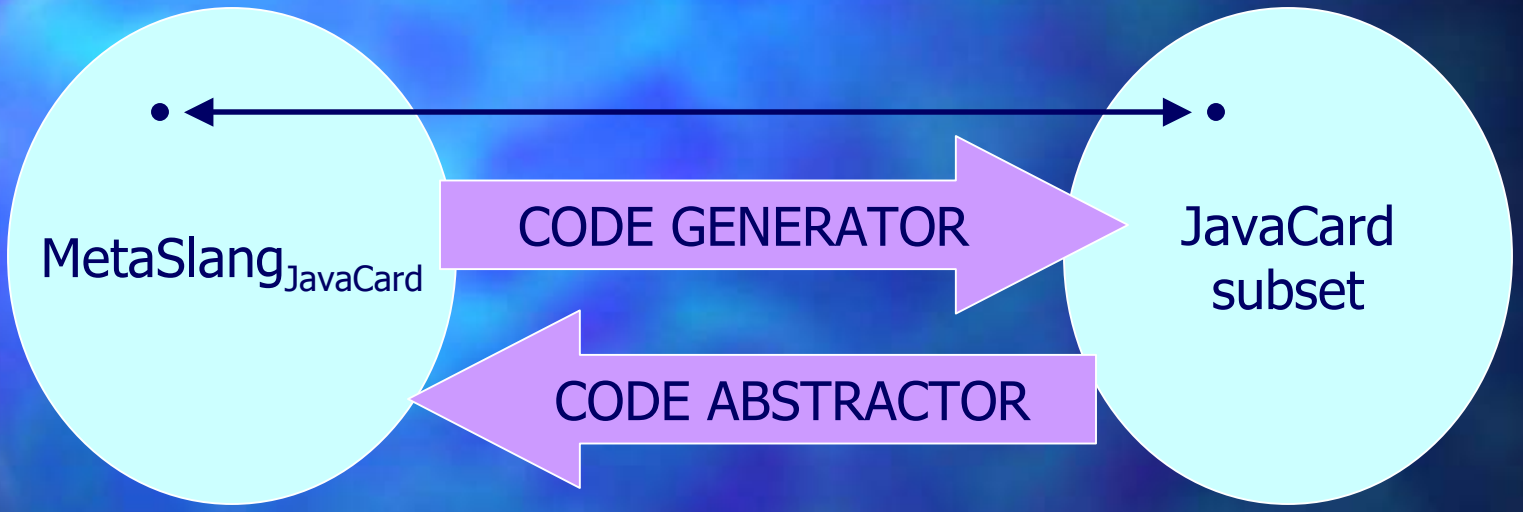

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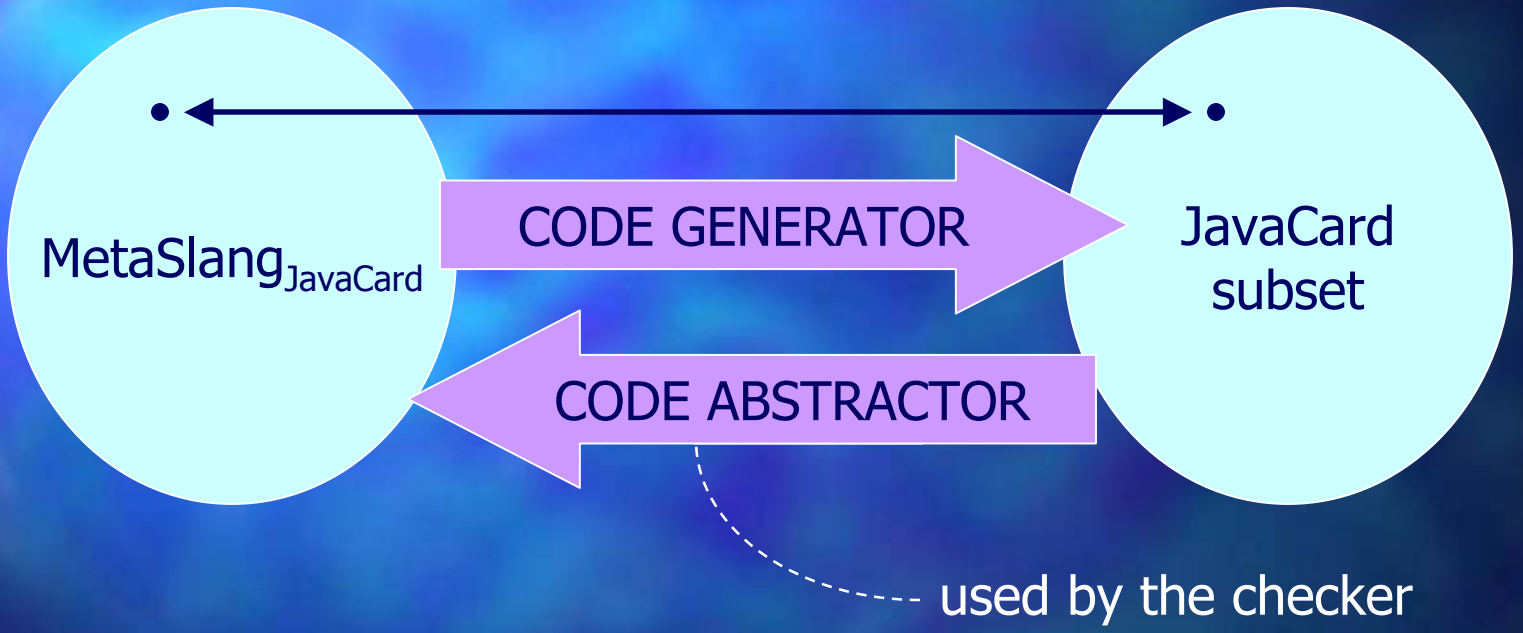

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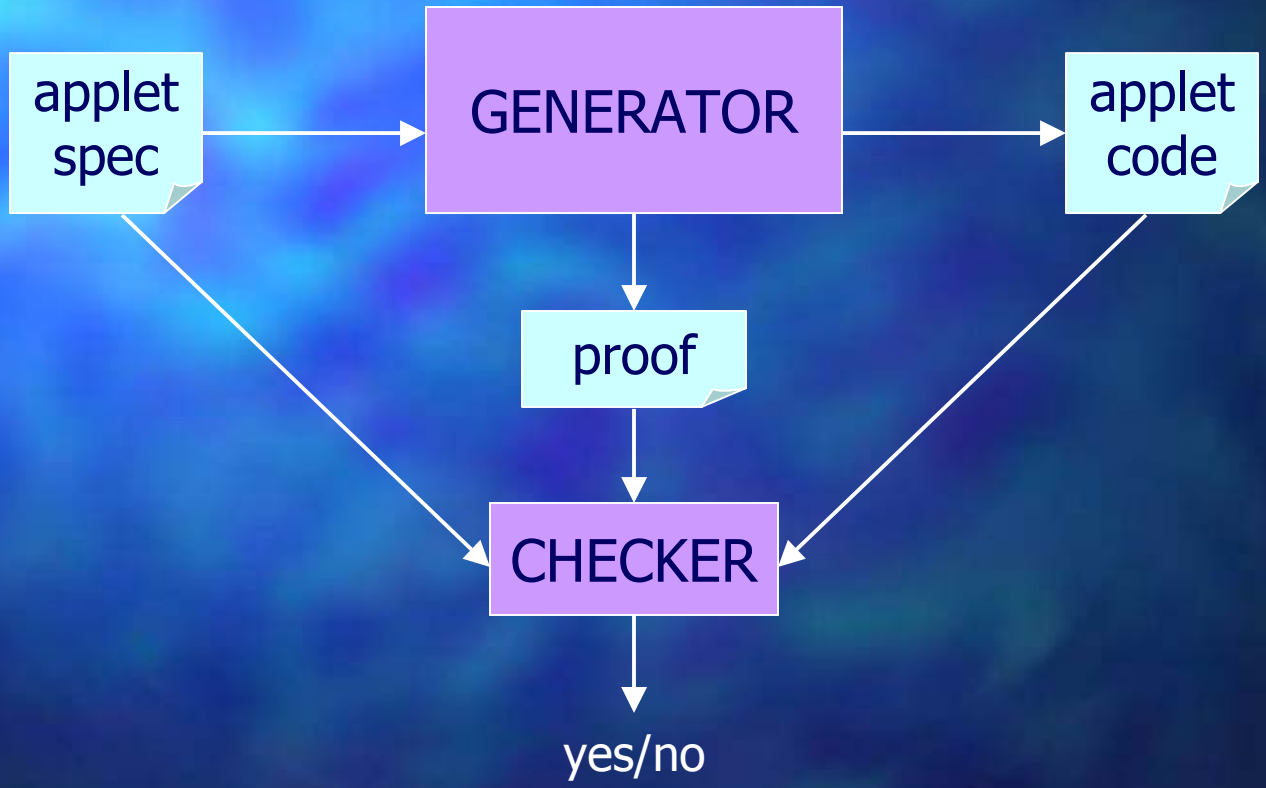
Code Abstractor



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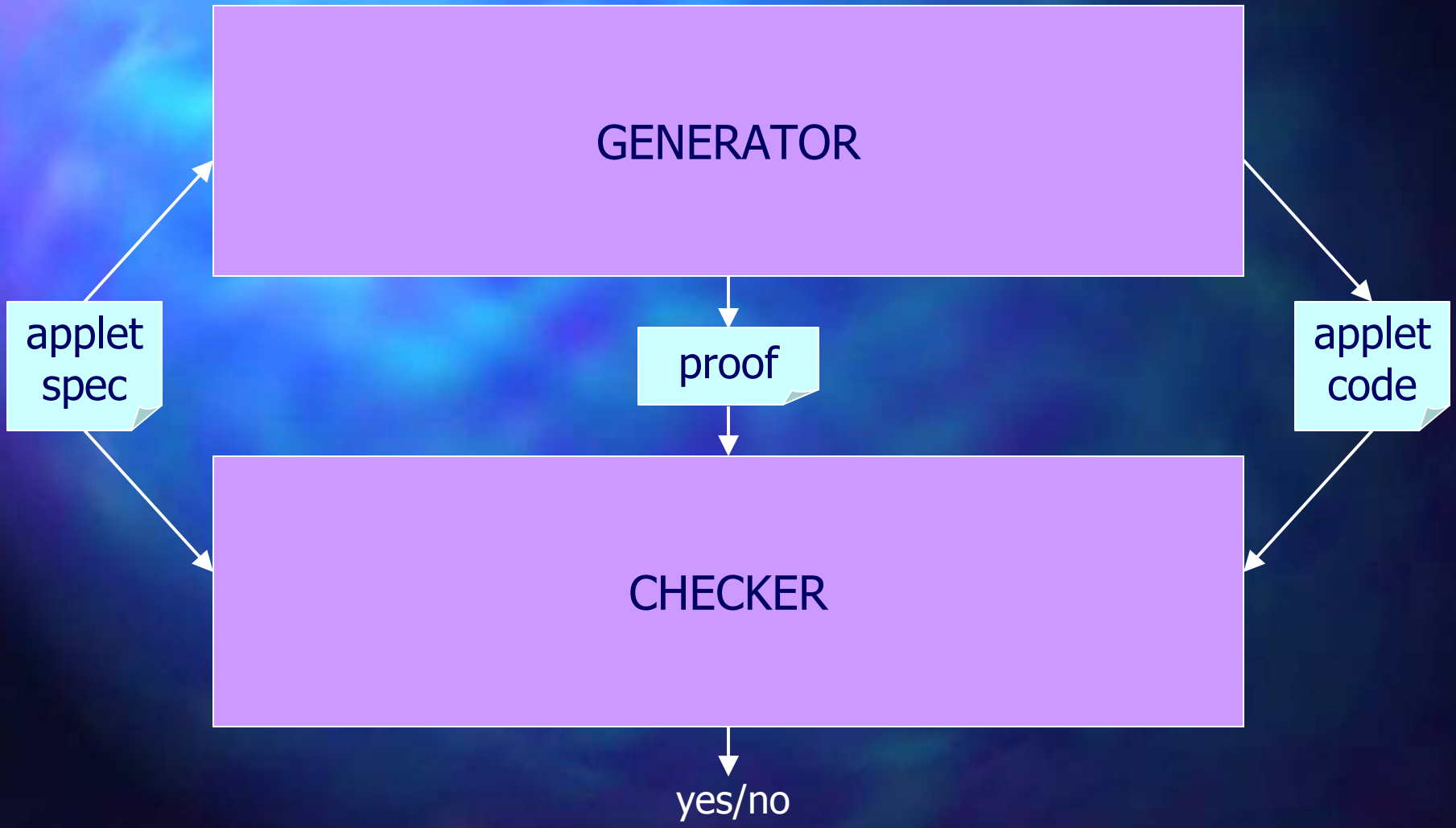

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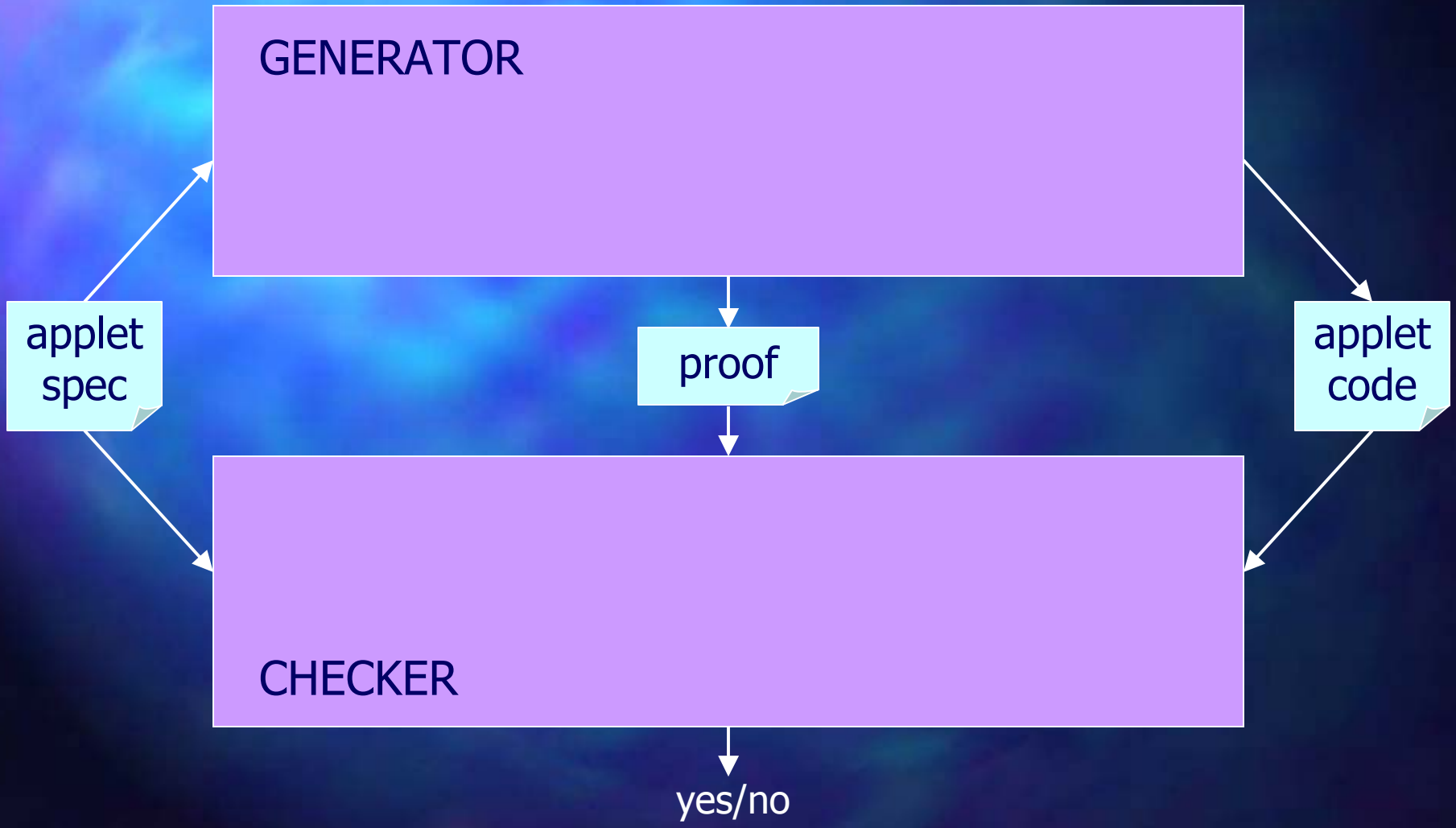

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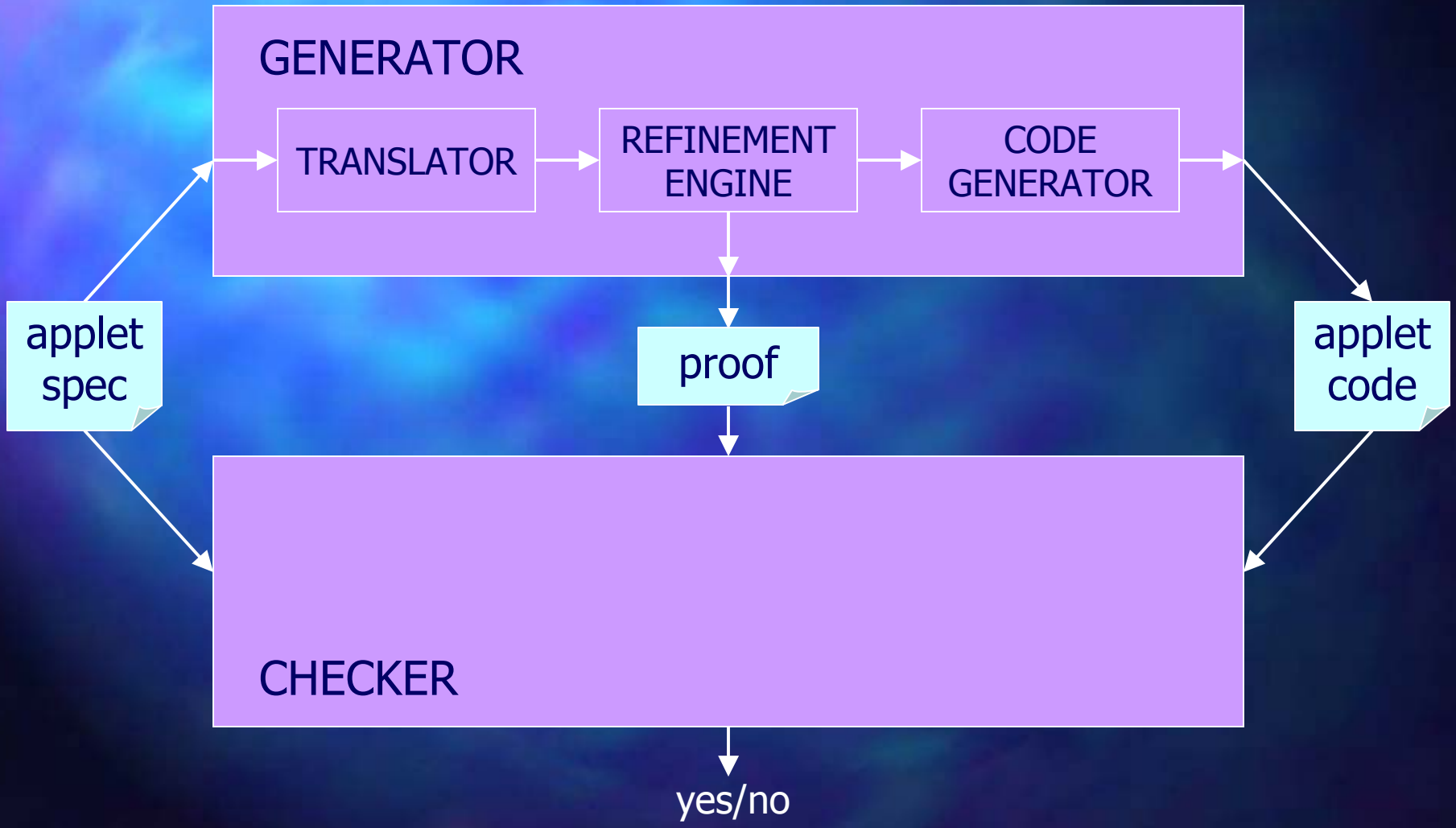

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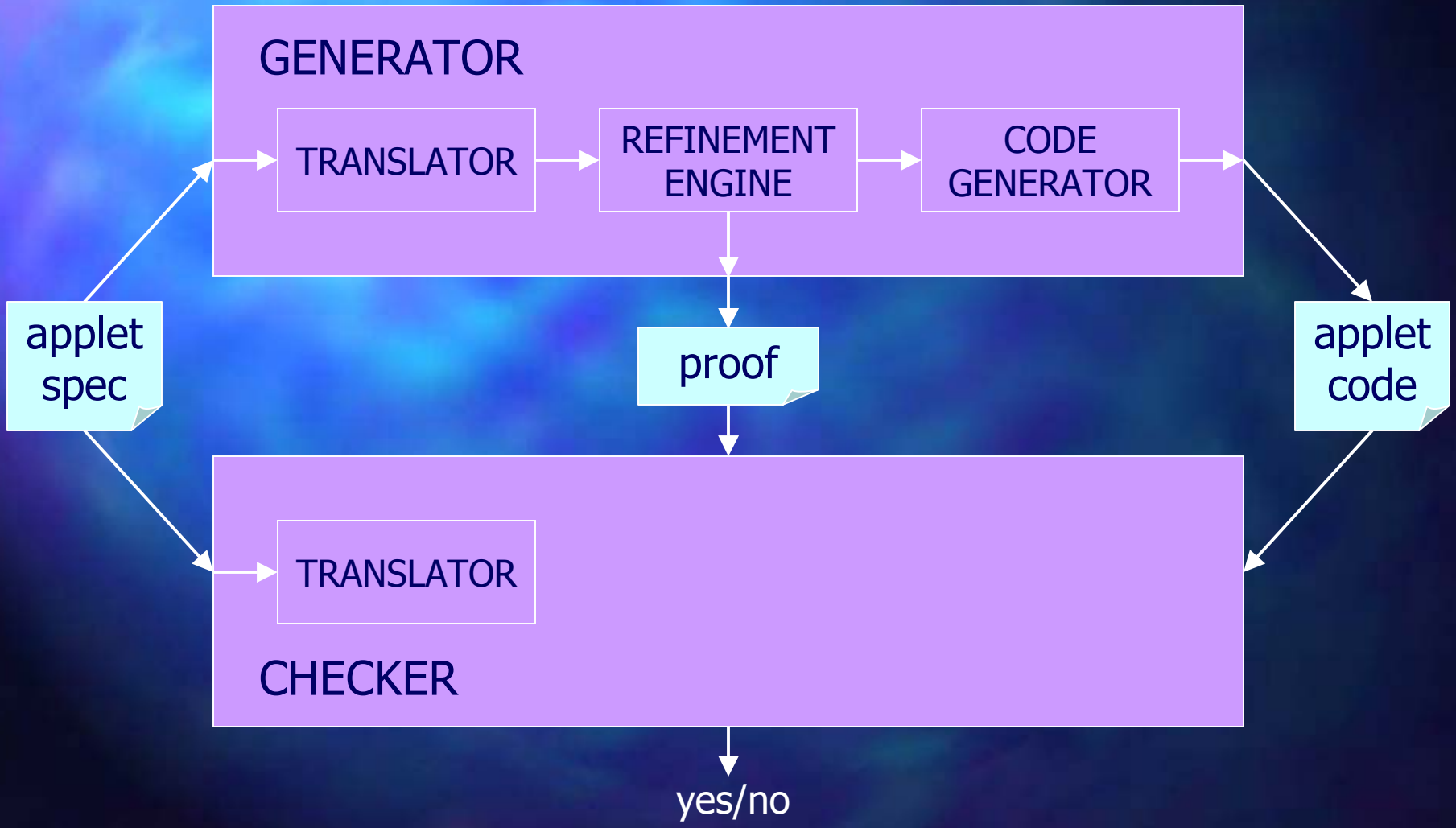

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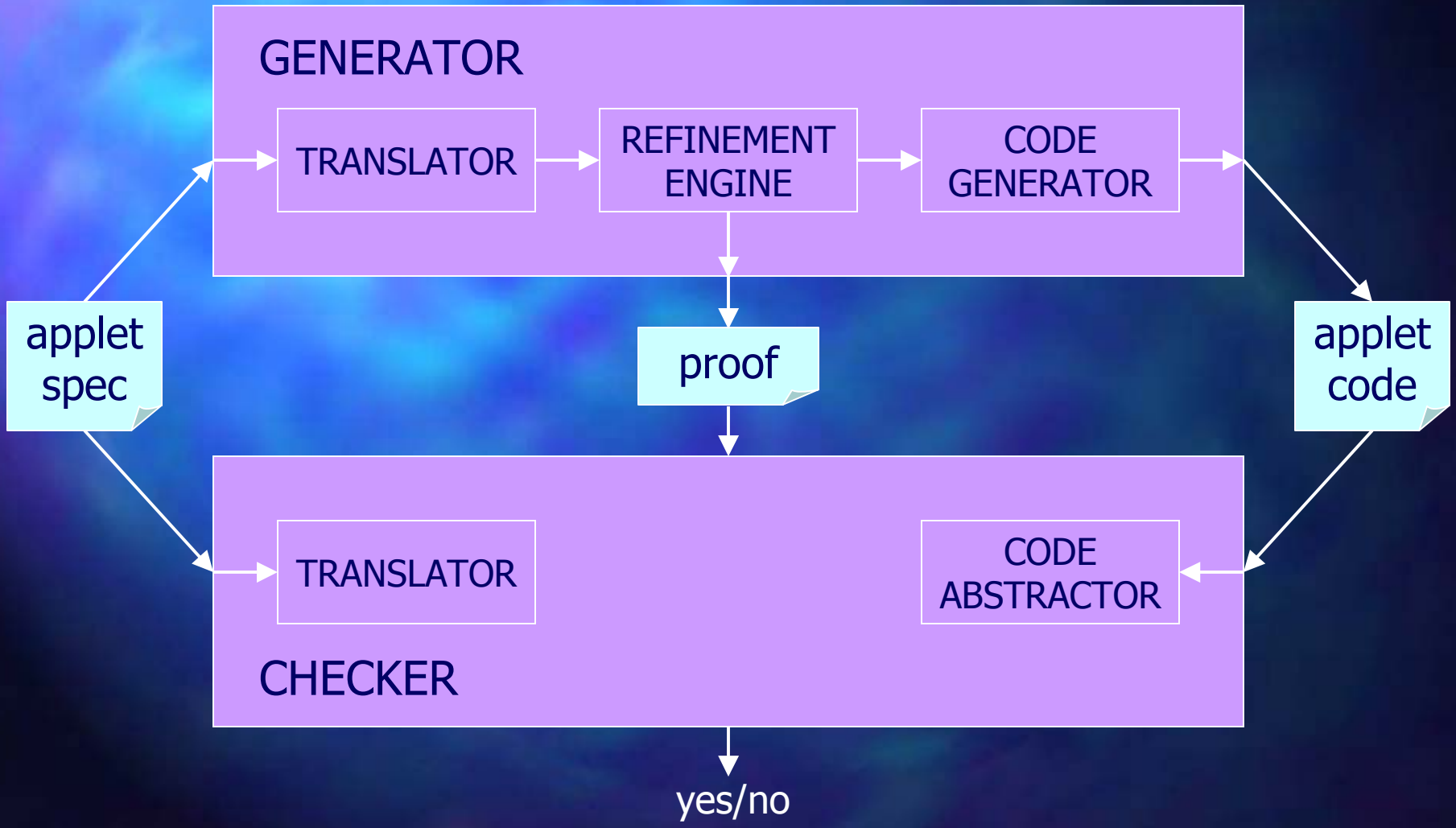

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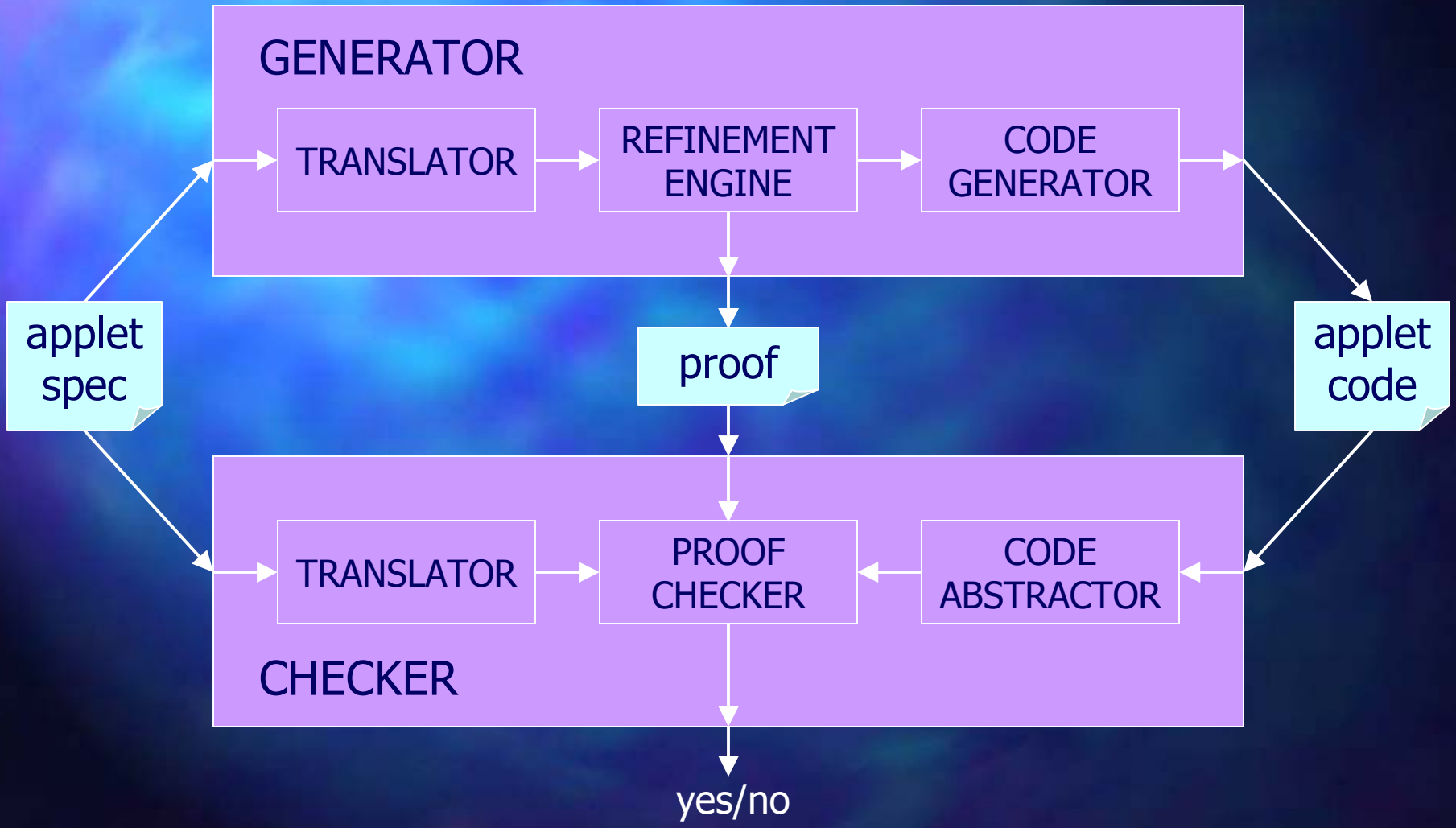

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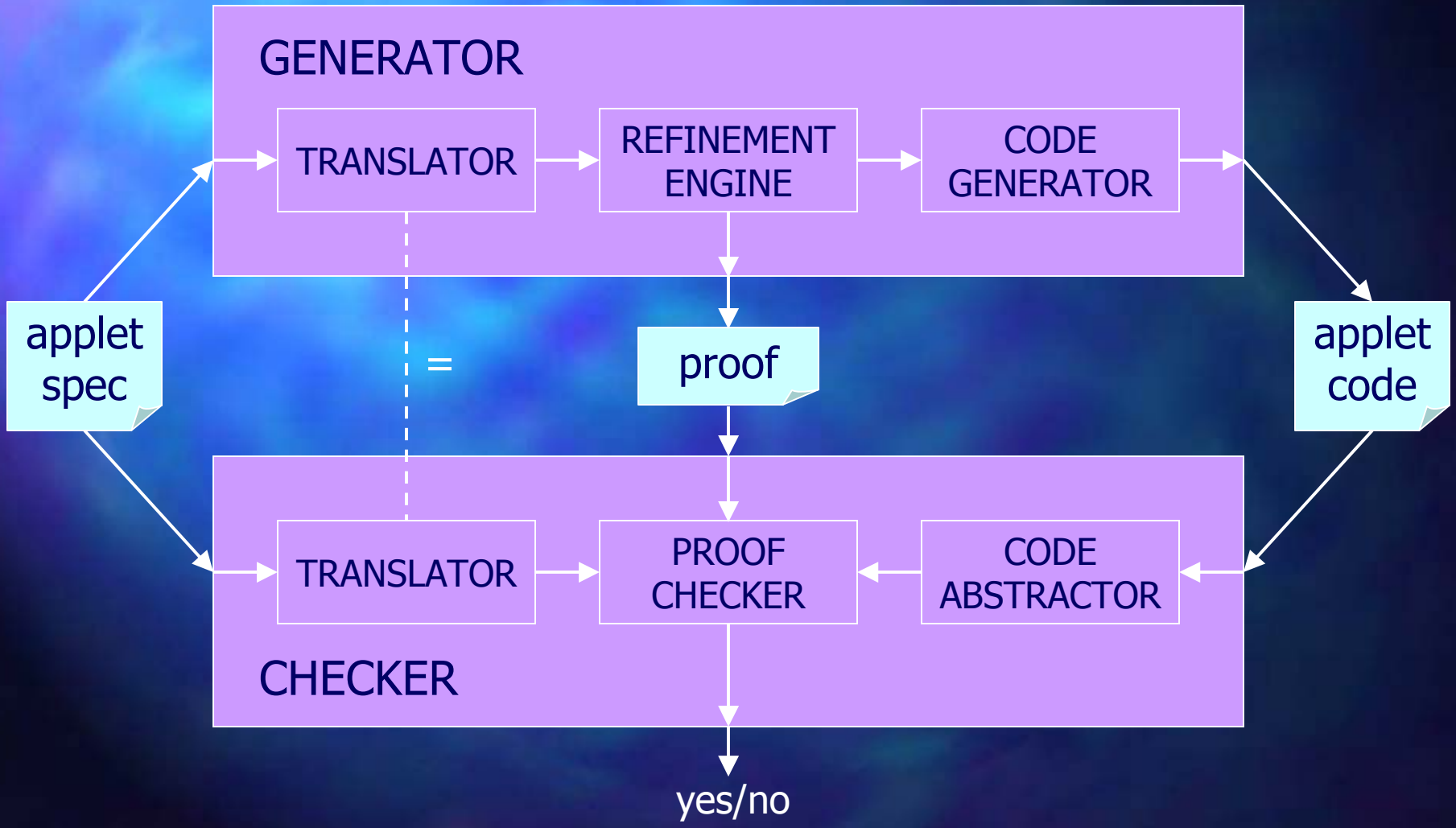

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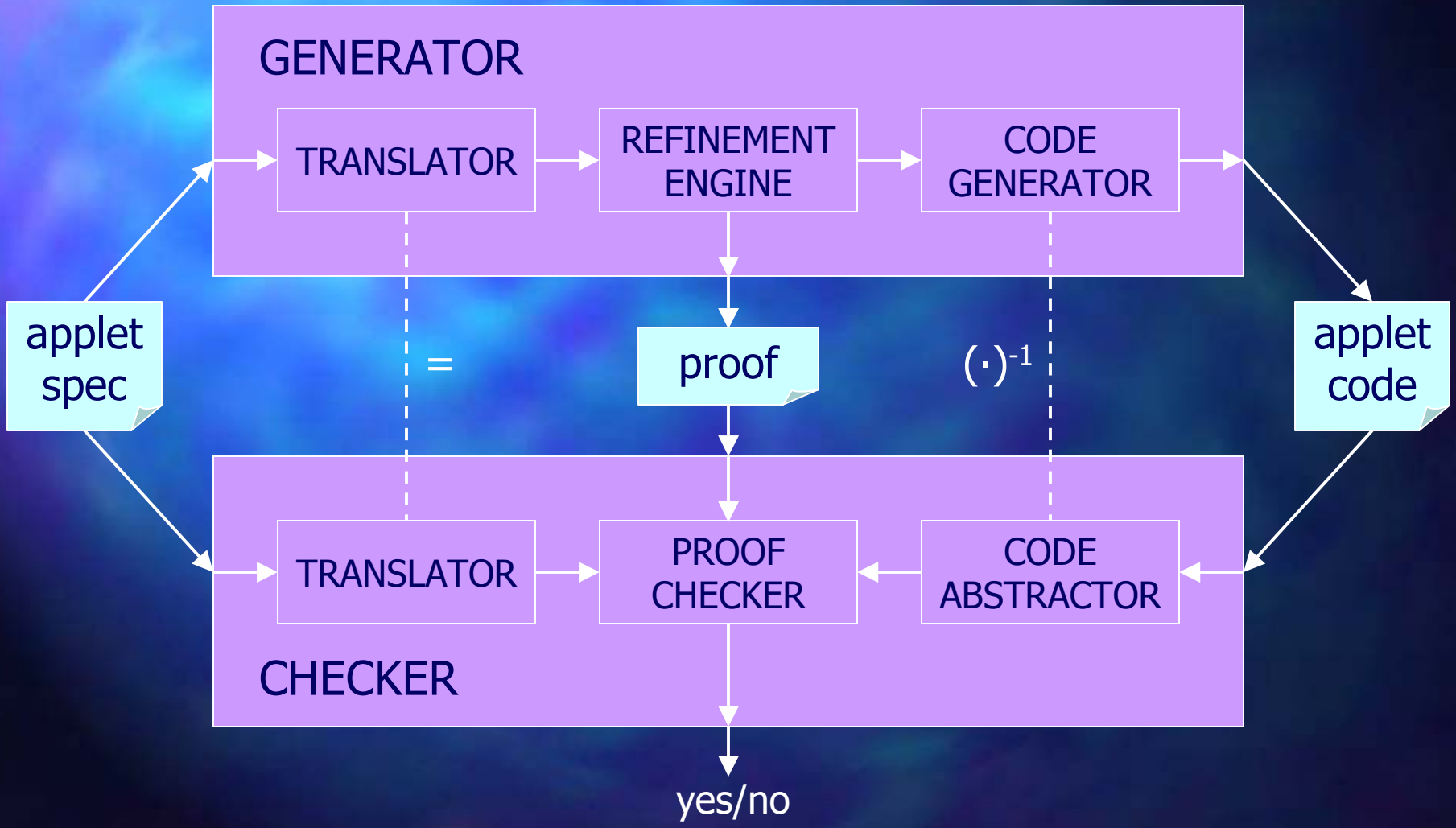

A Possible Question

If $\text{MetaSlang}_{\text{JavaCard}}$ is one-to-one with Java Card programs, why bother?

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If $\text{MetaSlang}_{\text{JavaCard}}$ is one-to-one with Java Card programs, why bother?

- Correctness of applet generator is expressed by a formal relationship between DSL and Java Card
- A formal relationship between two languages is expressed by bringing the languages into a common mathematical language (e.g. MetaSlang)
- So, $\text{MetaSlang}_{\text{JavaCard}}$ is needed for formal proofs

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Accomplishments

- Java Card language and API specs
  - ~7K lines of MetaSlang
    - ~3K for the language
    - ~4K for the APIs
  - re-usable piece of formalized knowledge (e.g., for Java Card platform specification)
- Instantiated specs to represent PKI applet for Common Access Cards (CAC)
- Implemented code generator
- Generated PKI applet code

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Current Work

- Definition of DSL
  - higher-level than Java card
  - specs shorter than corresponding Java Card programs (~ 2-5 x)
  - captures boilerplates
  - early spec error detection
- Specification of PKI applet in DSL (done)
- Implementation of translator DSL $\rightarrow$ MetaSlang

Future Work

- Design & implement refinement engine
- Integrate components (translator, refinement engine, code generator) into applet generator
- Applet checker
  - implement code abstractor
  - implement proof checker

Questions?