The K Approach

Presenter: Sandeep Dasgupta

University of Illinois at Urbana

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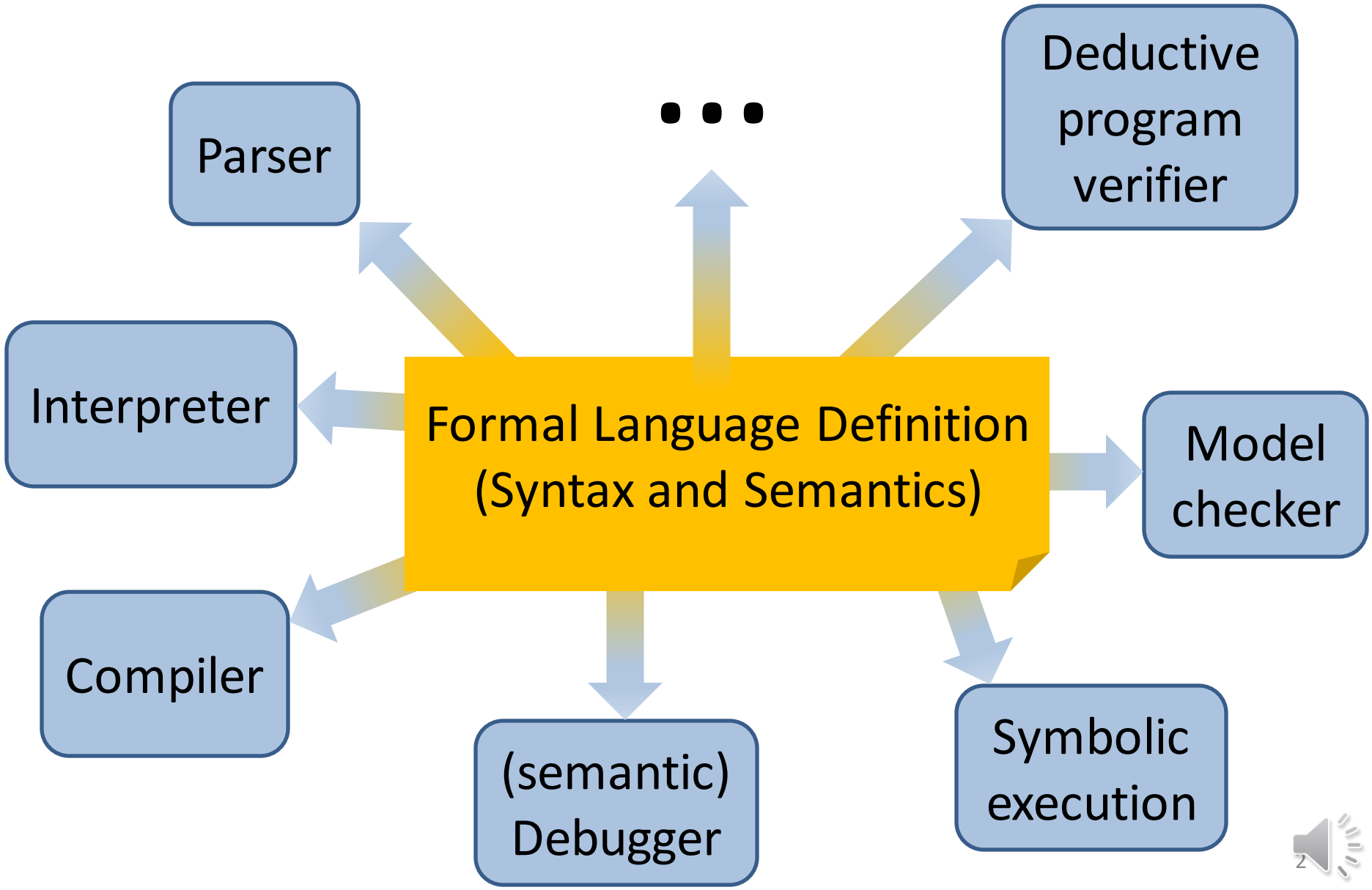
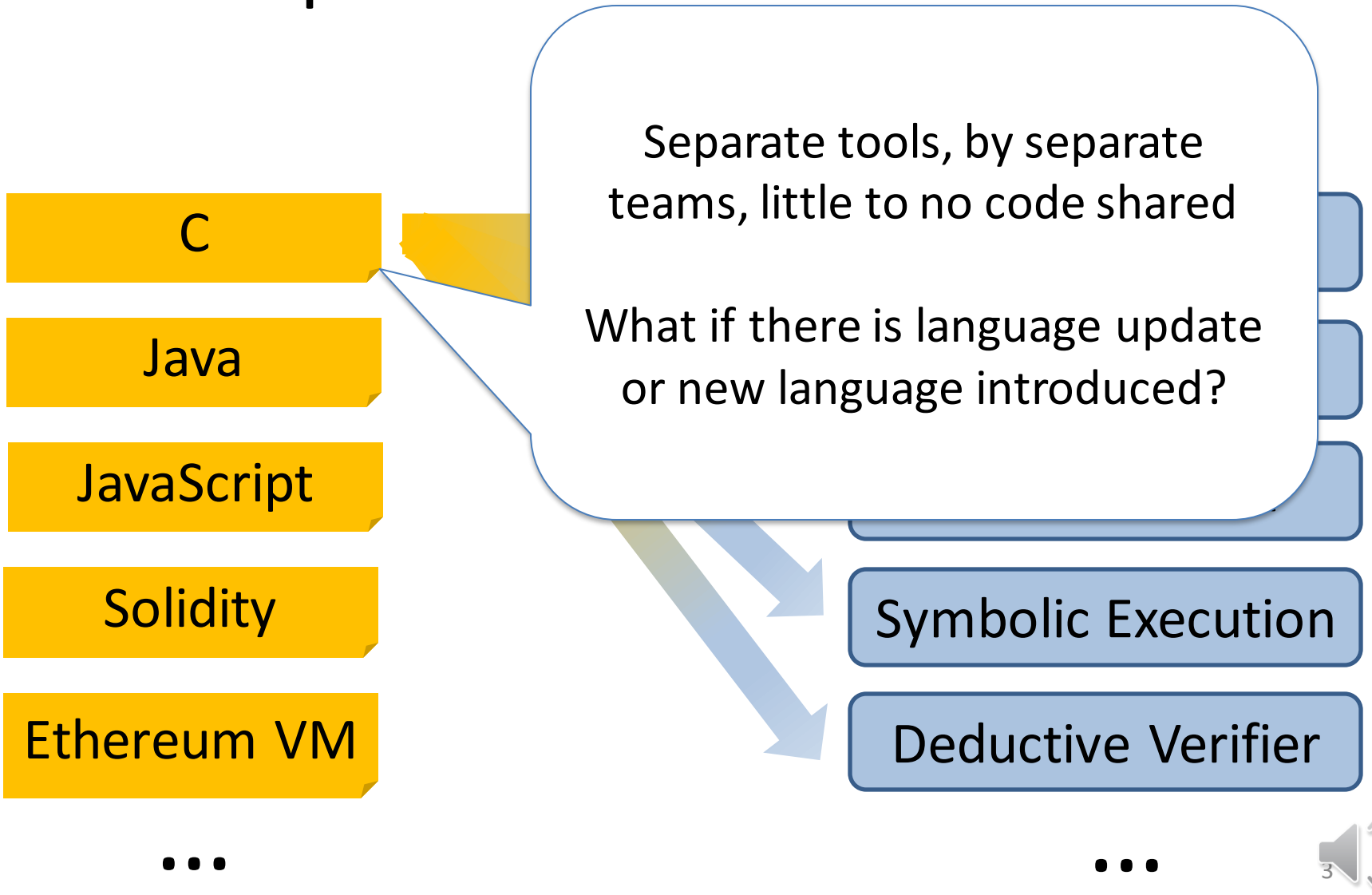
Ideal Language Framework Vision



Current State-of-the-Art
- Sharp Contrast to Ideal Vision -



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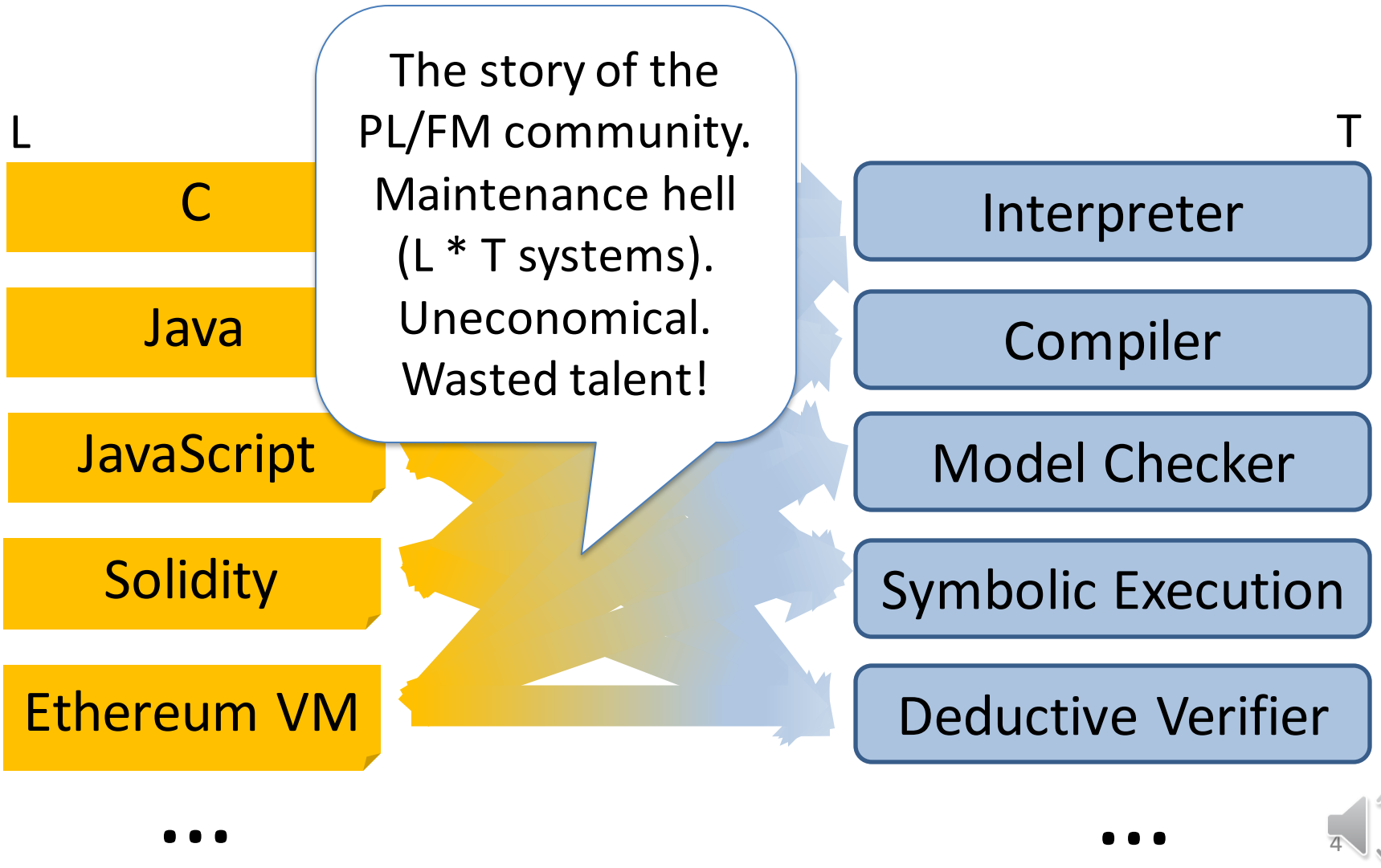
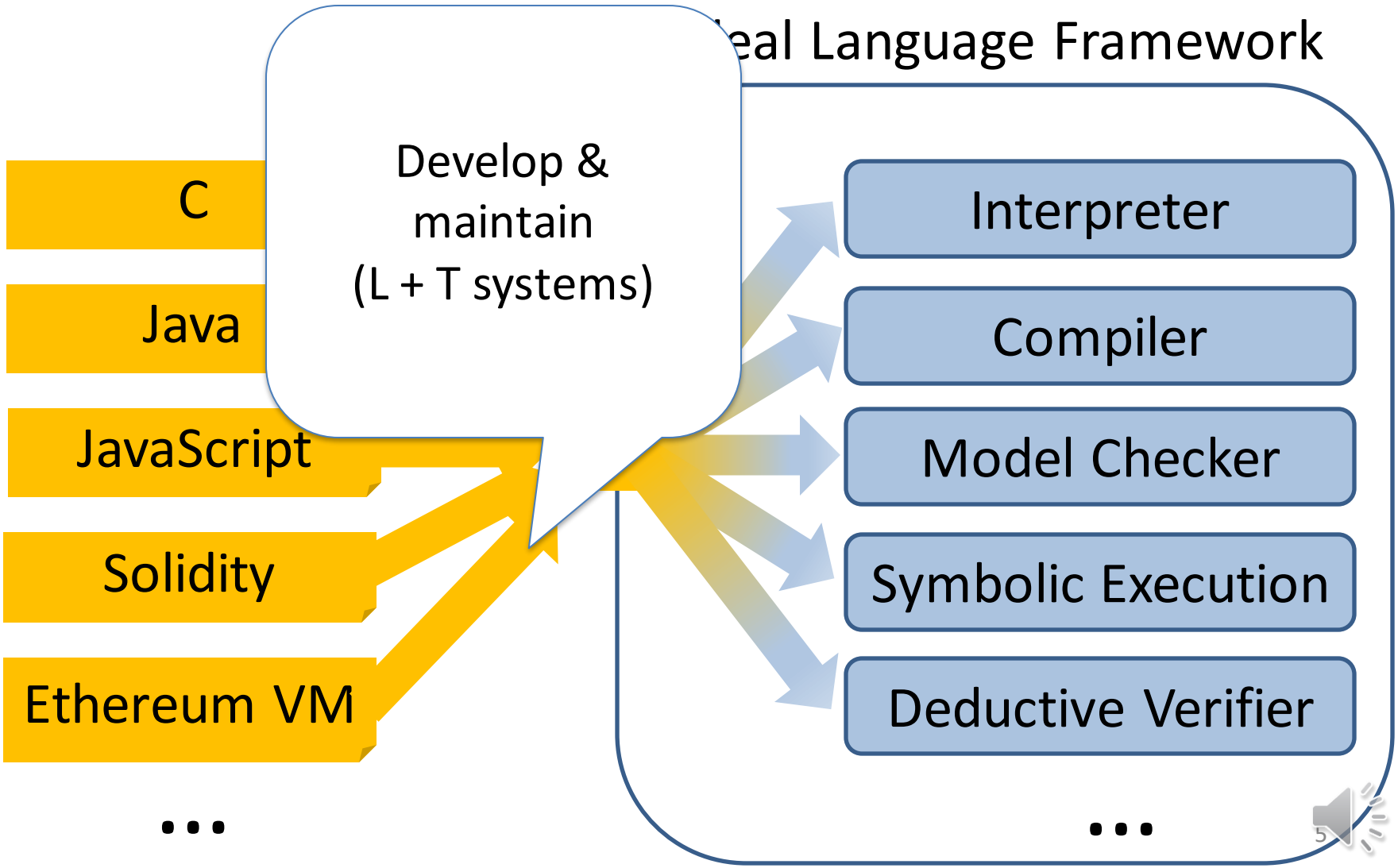


How It Should Be



Our Attempt: the K Framework

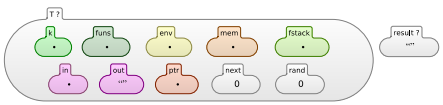
http://kframework.org

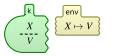
- K Framework started with the “ideal framework” vision
  - Design philosophy: Reusability & Scalability
  - Not just an academic tool, but adapted in industry
- K framework initially *engineered*: keep advantages and avoid limitations of various semantic styles
  - Then theory came
  - Engineering effort is largely focused in providing better experience to language developers
- We tried various semantic styles, for >15y and >100 top-tier conference and journal papers
  - Big emphasis on modularity and expressiveness
  - Simplified language design experience

Complete K Definition of KernelC

```
MODULE KERNELC-SYNTAX
  IMPORTS K-LATEX+PL-ID+PL-INT
  SYNTAX  Exp ::= Exp + Exp [strict]
                | DeclId
                | Id
                | Int
                | Exp - Exp [strict]
                | Exp ++
                | Exp == Exp [strict]
                | Exp != Exp [strict]
                | Exp <= Exp [strict]
                | Exp < Exp [strict]
                | Exp % Exp [strict]
                | ! Exp
                | Exp && Exp
                | Exp ? Exp : Exp
                | Exp || Exp
                | printf("%d;", Exp ) [strict]
                | scanf("%d",& Exp )
                | scanf("%d", Exp ) [strict]
                | NULL
                | PointerId
                | (int*)malloc( Exp *sizeof(int)) [strict]
                | free( Exp ) [strict]
                | * Exp [strict]
                | Exp [ Exp ]
                | Exp = Exp [strict(2)]
                | Id ( List{Exp} ) [strict(2)]
                | Id ( )
                | random()
                | srandom( Exp ) [strict]
  SYNTAX  Stmt ::= Exp ; [strict]
                | {}
                | { StmtList }
                | if( Exp ) Stmt
                | if( Exp ) Stmt else Stmt [strict(1)]
                | while( Exp ) Stmt
                | return Exp ; [strict]
                | DeclId List{DeclId} { StmtList }
                | #include< StmtList >
  SYNTAX  StmtList ::= StmtList StmtList
                | Stmt
  SYNTAX  Pgm ::= StmtList
  SYNTAX  Id ::= main
  SYNTAX  PointerId ::= * PointerId [ditto]
                | Id
  SYNTAX  DeclId ::= int Exp
                | void PointerId
  SYNTAX  StmtList ::= stdio.h
                | stdlib.h
  SYNTAX  List{Bottom} ::= List{Bottom} , List{Bottom} [assoc hybrid id: () strict]
                | ()
                | Bottom
  SYNTAX  List{PointerId} ::= List{PointerId} , List{PointerId} [ditto]
                | List{Bottom}
                | PointerId
  SYNTAX  List{DeclId} ::= List{DeclId} , List{DeclId} [ditto]
                | DeclId
                | List{Bottom}
  SYNTAX  List{Exp} ::= List{Exp} , List{Exp} [ditto]
                | Exp
                | List{DeclId}
                | List{PointerId}
END MODULE

MODULE KERNELC-DESUGARED-SYNTAX
  IMPORTS K-LATEX
  IMPORTS KERNELC-SYNTAX
  MACRO  ! E = E ? 0 : 1

  MACRO  E1 && E2 = E1 ? E2 : 0

  MACRO  E1 || E2 = E1 ? 1 : E2

  MACRO  if( E ) St = if( E ) St else {}

  MACRO  NULL = 0

  MACRO  I ( ) = I ( ( ) )

  MACRO  int * PointerId = int PointerId

  MACRO  #include< Stmts > = Stmts

  MACRO  E1 [ E2 ] = * E1 + E2

  MACRO  scanf("%d",& * E ) = scanf("%d", E )

  MACRO  int * PointerId = E = int PointerId = E

  MACRO  int X = E ; = int X ; X = E ;

  MACRO  stdio.h = {}

  MACRO  stdlib.h = {}

END MODULE
```

```
MODULE KERNELC-SEMANTICS
  IMPORTS K-SHARED
  IMPORTS K+KERNELC-DESUGARED-SYNTAX+PL-CONVERSION+PL-RANDOM
  CONFIGURATION:
```





RULE I_1 + I_2 ⇀ I_1 $+_{Int}$ I_2

RULE I_1 - I_2 ⇀ I_1 $-_{Int}$ I_2

RULE I_1 % I_2 ⇀ I_1 $\%_{Int}$ I_2 when I_2 $\neq_{Int}$ 0

RULE I_1 <= I_2 ⇀ Bool2Int (I_1 $\leq_{Int}$ I_2)

RULE I_1 < I_2 ⇀ Bool2Int (I_1 $<_{Int}$ I_2)

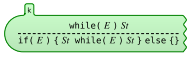
RULE I_1 == I_2 ⇀ Bool2Int (I_1 $==_{Int}$ I_2)

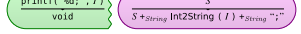
RULE I_1 != I_2 ⇀ Bool2Int (I_1 $\neq_{Int}$ I_2)

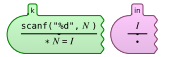
RULE _?_:_ ⇀ if(_)_else_

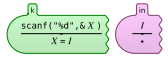
RULE if(I) – else St ⇀ St when I $==_{Int}$ 0

RULE if(I) St else – ⇀ St when $\neg_{Bool}$ I $==_{Int}$ 0







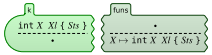


RULE V ; ⇀ •

RULE { Sts } ⇀ Sts

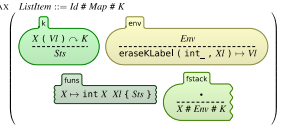
RULE {} ⇀ •

RULE St Sts ⇀ St ↷ Sts

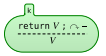


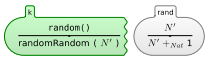
RULE void X Xl { Sts } ⇀ int X Sts return void ;

```
SYNTAX  ListItem ::= Id # Map # K
```



CONTEXT: int – = □

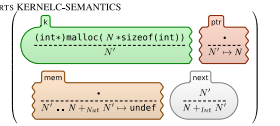


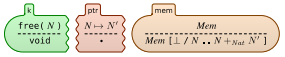


CONTEXT: * □ = –

CONTEXT: * □ ++

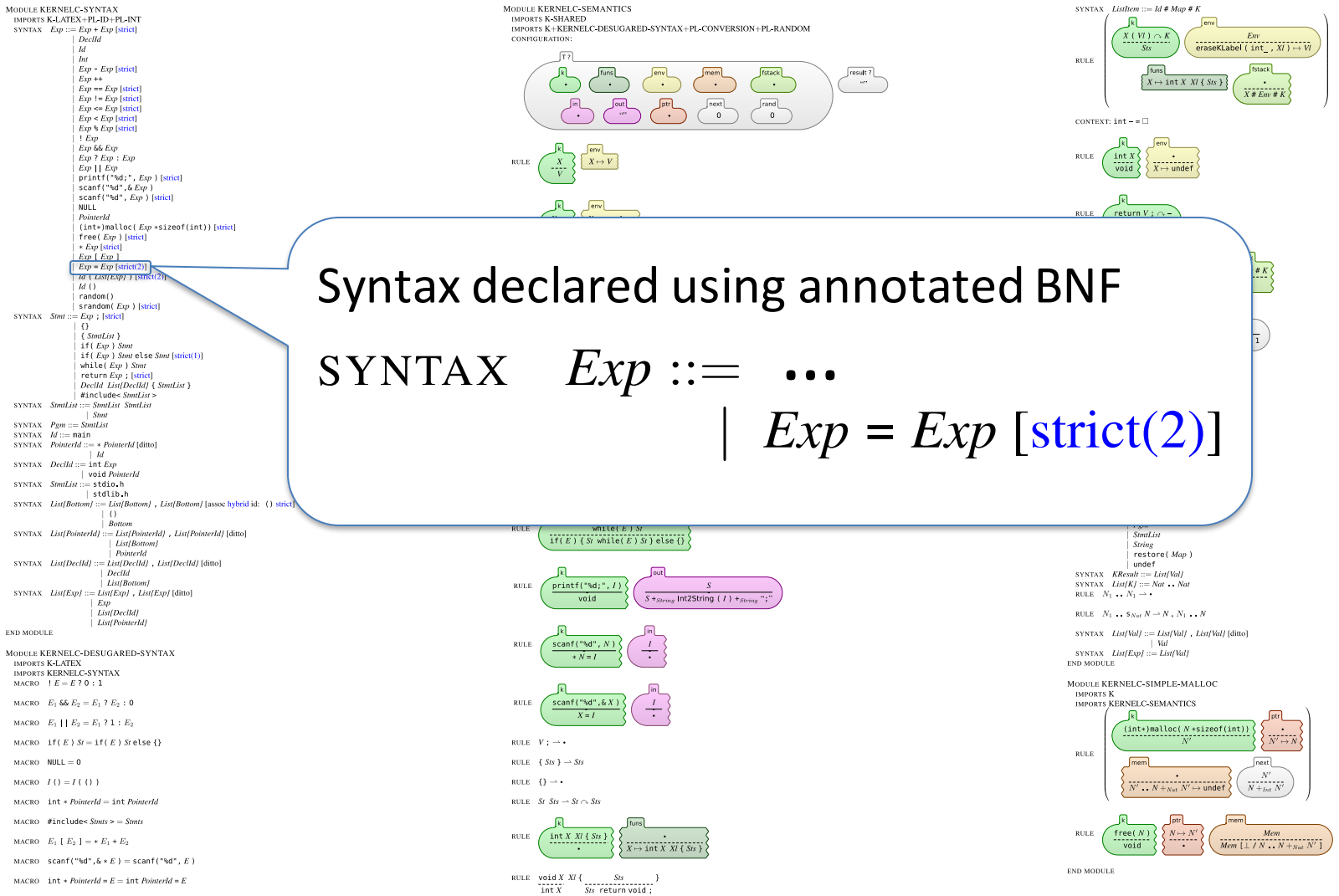
```
  SYNTAX  Val ::= Int
                | void
  SYNTAX  Exp ::= Val
  SYNTAX  K ::= List{DeclId}
                | List{Exp}
                | List{PointerId}
                | Pgm
                | StmtList
                | String
                | restore( Map )
                | undef
  SYNTAX  KResult ::= List{Val}
  SYNTAX  List{K} ::= Nat .. Nat
  RULE  N1 .. N1 ⇀ •

  RULE  N1 .. sNat N ⇀ N , N1 .. N

  SYNTAX  List{Val} ::= List{Val} , List{Val} [ditto]
                | Val
  SYNTAX  List{Exp} ::= List{Val}
END MODULE

MODULE KERNELC-SIMPLE-MALLOC
  IMPORTS K
  IMPORTS KERNELC-SEMANTICS
```





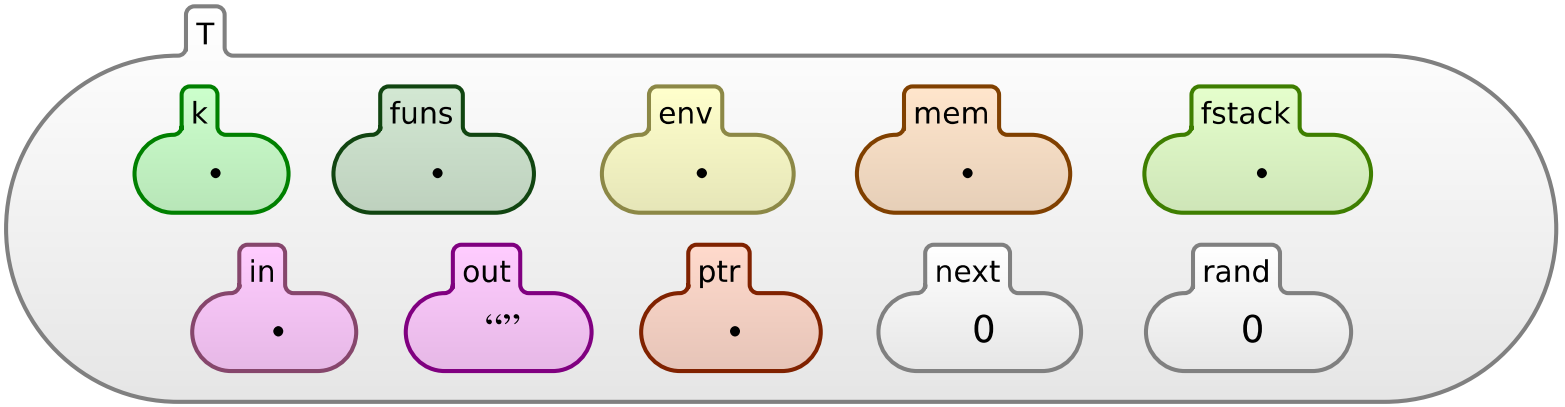

```
END MODULE
```

Complete K Definition of KernelC



Complete K Definition of KernelC

Configuration given as a nested cell structure.
Leaves can be sets, multisets, lists, maps, or syntax



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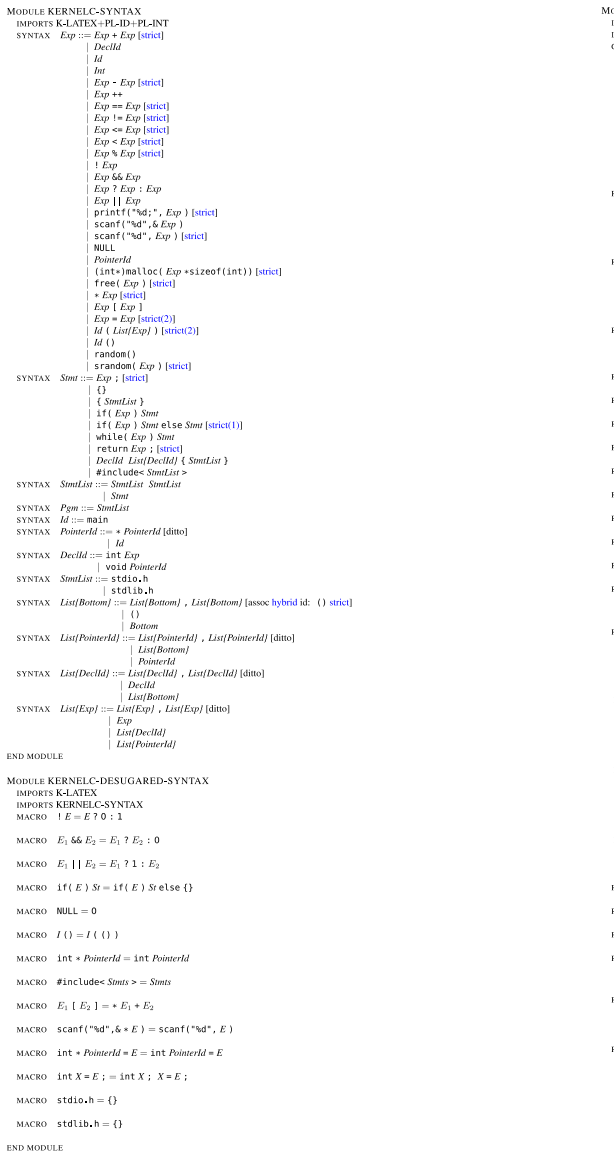
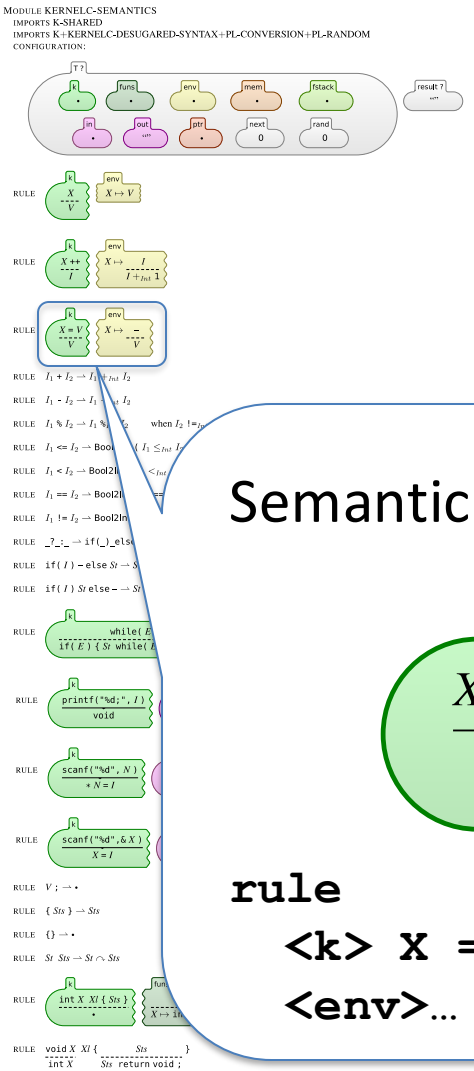
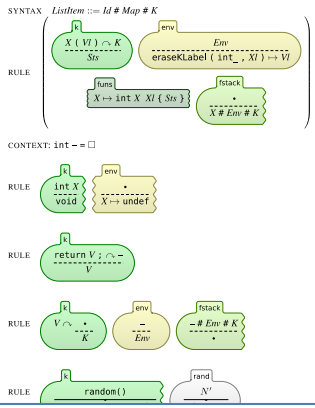
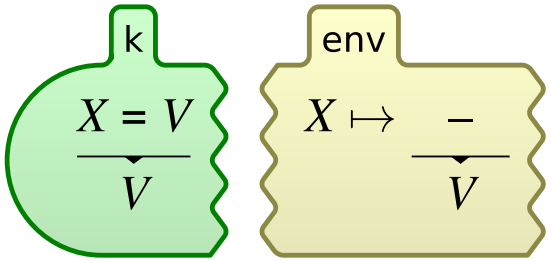






Semantic rules given contextually




```
rule
  <k> X = V => V ...</k>
  <env>... X |-> (_ => V) ...</env>
```

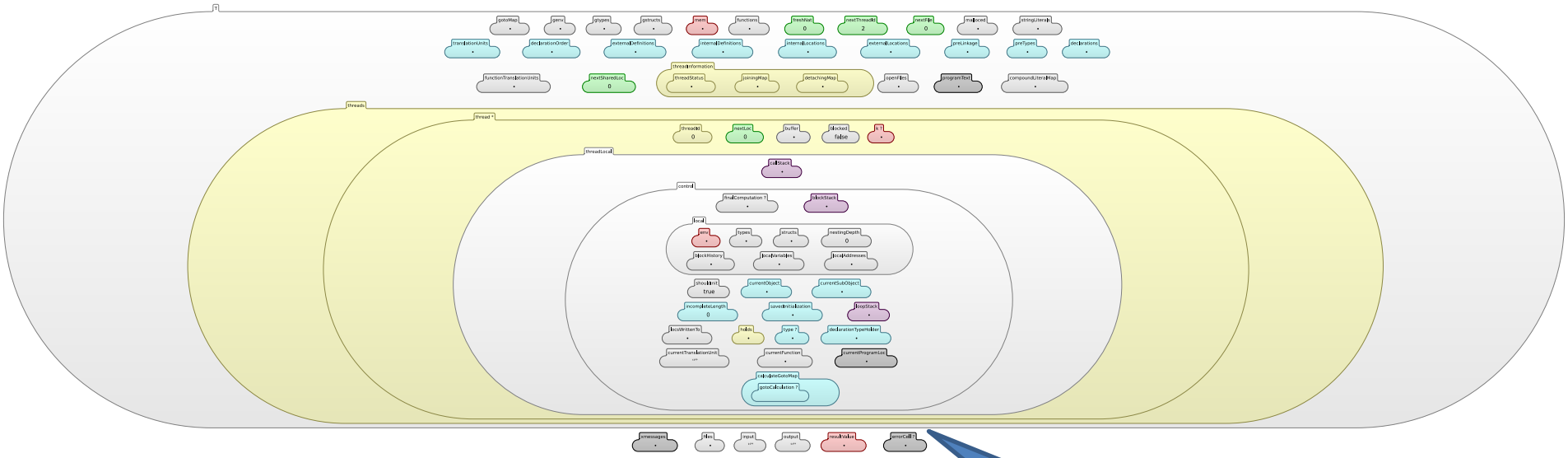
K Scales

Several large languages were recently defined in K:

- JavaScript ES5: by Park etal [PLDI'15]
  - Passes existing conformance test suite (2872 programs)
  - Found (confirmed) bugs in Chrome, IE, Firefox, Safari
- Java 1.4: by Bogdanas etal [POPL'15]
- x86-64 ISA: by Dasgupta etal [PLDI'19]
- C11: Ellison etal [POPL'12, PLDI'15]
  - 192 different types of undefined behavior
  - 10,000+ program tests (gcc torture tests, obfuscated C, …)
  - Commercialized by startup (Runtime Verification, Inc.)

+ EVM [CSF'18], Solidity, IELE, Plutus, Vyper, …

K Configuration and Definition of C



… plus ~5000 rules …

120 Cells!

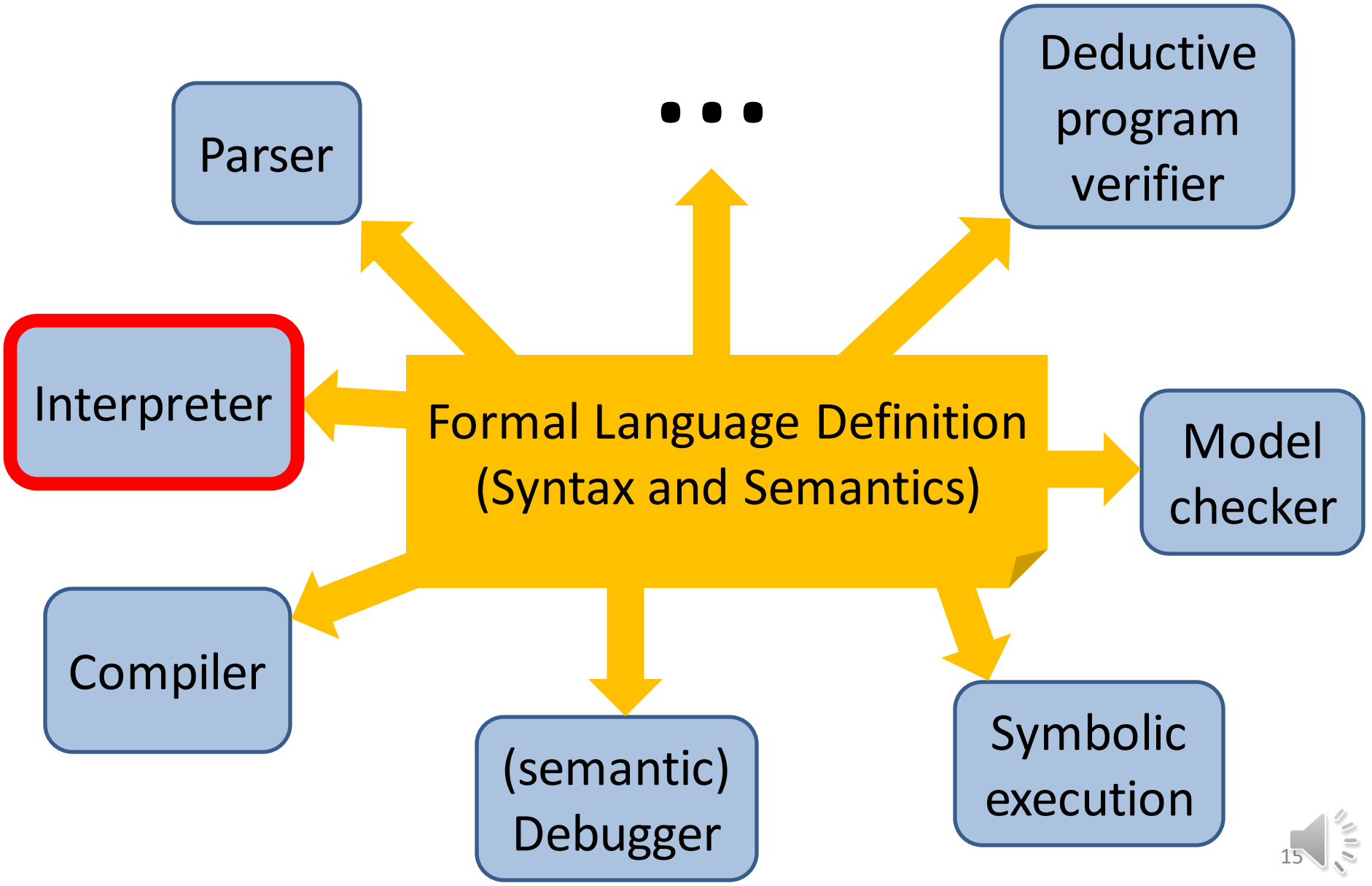
Definition of x86-64 ISA (PLDI'19)

- Complexity of the ISA
  - One of the most complex ISAs widely used in desktop and servers
  - Consists of 3736 instructions with various degree of complexity
    - Previous works formalizes a fraction of instruction semantics

Definition of x86-64 ISA (PLDI'19)

- Few highlights of our work
  - The semantic of the defined ISA includes ~5200 semantic rules
  - Modeled the IEEE-754 floating point standard in K
  - The semantics is validated by co-simulation against hardware
    - Validation includes unit testing with 7000+ input states and executing the entire GCC-c torture test using the semantics
    - Thanks to the K interpreter we leveraged for free
  - Demonstrated the applicability of the semantics for program verification, security vulnerability tracking
    - Thanks to K program verifier and symbolic execution engine we leveraged for free

Ideal Language Framework Vision [K]



OCAML backend: K -> OCAML

1. Translate K lang def to OCAML
2. Compile OCAML code natively

runtime verification match

Code (6-int-overflow.c)

```
int main() {
  short int a = 1;
  int i;
  for (i = 0; i < 15; i++) {
    a *= 2;
  }
  return a;
}
```

RV-Match: **Commercial tool**

- Instance of K -> OCAML with ISO C11 language
- an automatic debugger for subtle bugs other tools can't find, with no false positives
- seamless integration with unit tests, build infrastructure, and continuous integration
- a platform for analyzing programs, boosting standards compliance and assurance

Conventional compilers do not detect problem

```
$ gcc 6-int-overflow.c
$ ./a.out
$
$ kcc 6-int-overflow.c
$ ./a.out
Error: IMPL-CCV2
Description: Conversion to signed integer outside the range that can be represented.
Type: Implementation defined behavior.
See also: C11 sec. 6.3.1.3:3, J.3.5:1 item 4
  at main(6-int-overflow.c:29)
```

RV-Match's kcc tool precisely detects and reports error, and points to ISO C11 standard

RV-Match on Toyota ITC Benchmark
- Comparison with Static Analysis Tools -

[CAV'16]

Toyota Benchmark ISSRE '15 (1276 tests)	RV-Match			GrammaTech CodeSonar			MathWorks Code Prover			MathWorks Bug Finder			GCC			Clang		
	DR	FPR	PM	DR	FPR	PM	DR	FPR	PM	DR	FPR	PM	DR	FPR	PM	DR	FPR	PM
Static memory	100	100	100	100	100	100	97	100	98	97	100	98	0	100	0	15	100	39
Dynamic memory	94	100	97	89	100	94	92	95	93	90	100	95	0	100	0	0	100	0
Stack-related	100	100	100	0	100	0	60	70	65	15	85	36	0	100	0	0	100	0
Numerical	96	100	98	48	100	69	55	99	74	41	100	64	12	100	35	11	100	33
Resource management	93	100	96	61	100	78	20	90	42	55	100	74	6	100	25	3	100	18
Pointer-related	98	100	99	52	96	71	69	93	80	69	100	83	9	100	30	13	100	36
Concurrency	67	100	82	70	77	73	0	100	0	0	100	0	0	100	0	0	100	0
Miscellaneous	63	100	79	69	100	83	83	100	91	69	100	83	11	100	34	11	100	34
AVERAGE (Unweighted)	79	100	89	59	97	76	53	94	71	52	98	71	4	100	20	6	100	24
AVERAGE (Weighted)	82	100	91	68	98	82	53	95	71	62	99	78	5	100	22	7	100	26

DR: Percent of programs with defects where defects are reported

FPR: Percent of programs without defects, with defects incorrectly reported; $\underline{\text{FPR}} = 100 - \text{FPR}$

PM: Productivity metric: $\sqrt{\text{DR} \times (100 - \text{FPR})}$

RV-Match on Toyota ITC Benchmark
- Comparison with Other Analysis Tools -

Toyota Benchmark ISSRE '15 (1276 tests)	RV-Match			Valgrind + Helgrind (GCC)			UBSan + TSan + MSan + ASan (Clang)			Frama-C (Value Analysis Plugin)			Compcert Interpreter		
	DR	FPR	PM	DR	FPR	PM	DR	FPR	PM	DR	FPR	PM	DR	FPR	PM
Static memory	100	100	100	9	100	30	79	100	89	82	96	89	97	82	89
Dynamic memory	94	100	97	80	95	87	16	95	39	79	27	46	29	80	48
Stack-related	100	100	100	70	80	75	95	75	84	45	65	54	35	70	49
Numerical	96	100	98	22	100	47	59	100	77	79	47	61	48	79	62
Resource management	93	100	96	57	100	76	47	96	67	63	46	54	32	83	52
Pointer-related	98	100	99	60	100	77	58	97	75	81	40	57	87	73	80
Concurrency	67	100	82	72	79	76	67	72	70	7	100	26	58	42	49
Miscellaneous	63	100	79	29	100	53	37	100	61	83	49	63	63	71	67
AVERAGE (Unweighted)	79	100	89	44	95	65	51	93	69	61	59	60	52	74	62
AVERAGE (Weighted)	82	100	91	42	97	65	47	95	67	66	55	60	51	76	63

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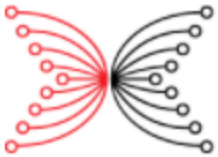
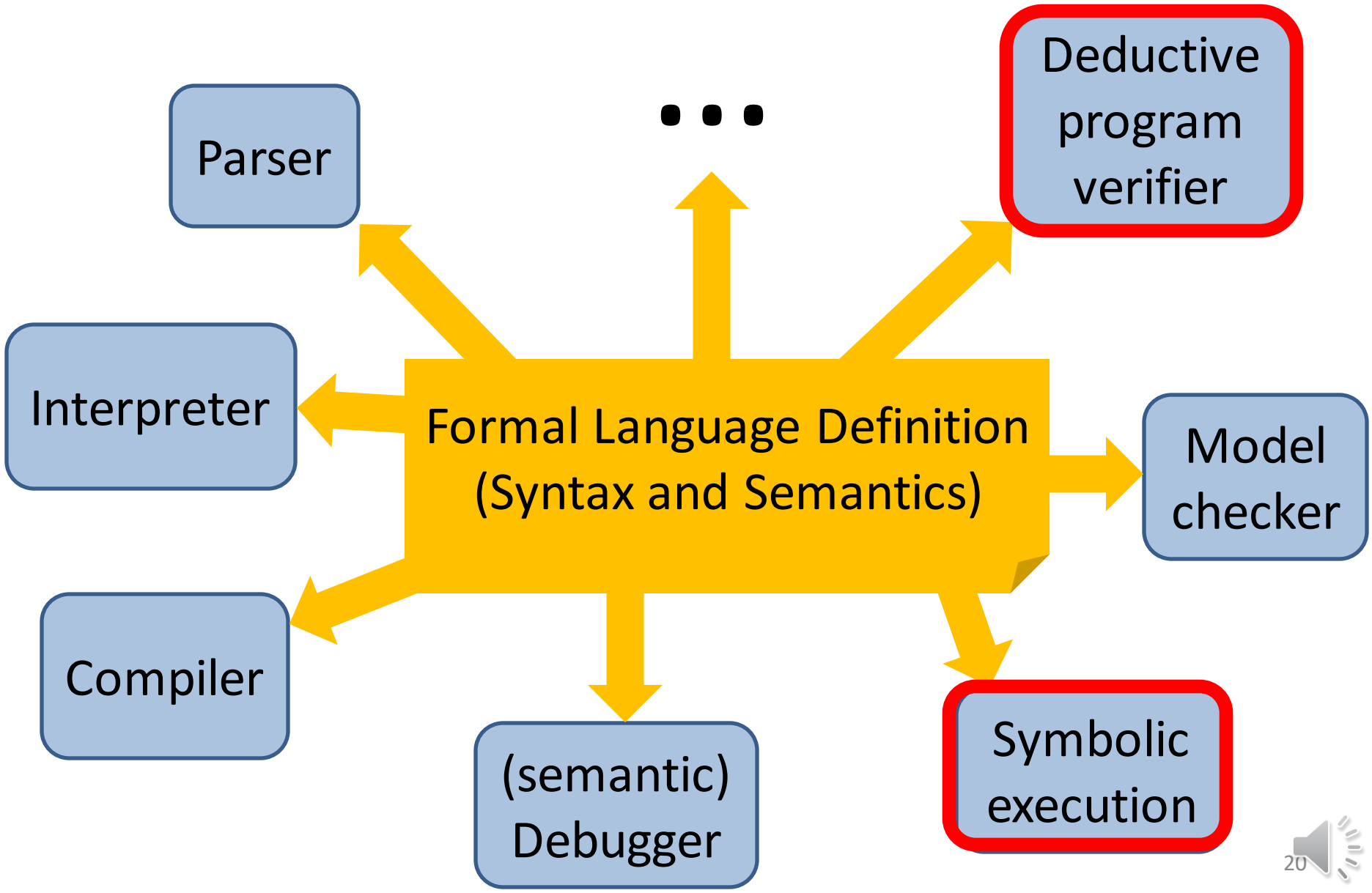
From RV-Match to Blockchain

- RV-Match currently commercialized within

- The same technology, K, used for defining blockchain languages: EVM, IELE, Plutus, …



Ideal Language Framework Vision [K]

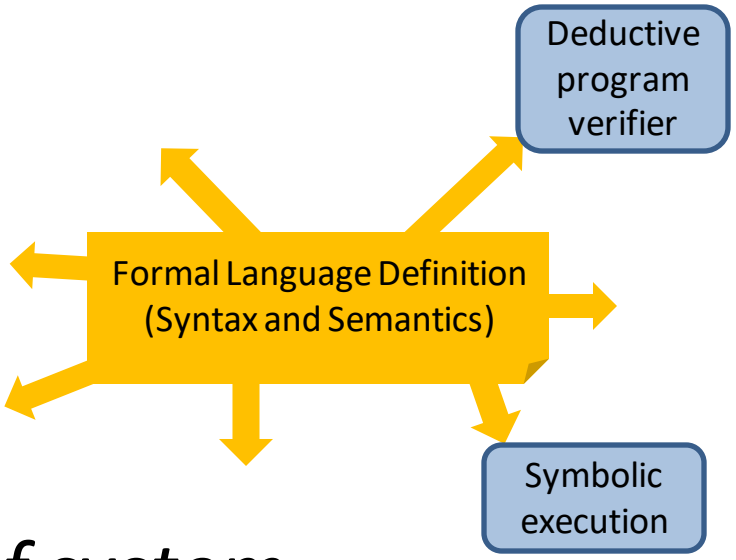


State-of-the-Art

- Redefine the language using a different semantic approach (Hoare/separation/dynamic logic)
- Language specific, non-executable, error-prone

$$\frac{\mathcal{H} \vdash \{\psi \wedge \mathtt{e} \neq 0\}\, \mathtt{s}\, \{\psi\}}{\mathcal{H} \vdash \{\psi\}\, \mathtt{while(e)}\, \mathtt{s}\, \{\psi \wedge \mathtt{e} = 0\}}$$

What We Want



- Use directly the trusted executable semantics!
- *Language-independent proof system*
  - Takes operational semantics as axioms
  - Derives reachability properties
  - Sound and relatively complete for all languages!

Reachability Logic (Semantics of K)

[LICS'13, RTA'14, RTA'15,OOPLSA'16]

- "Rewrite" rules over configurations

$$\varphi \Rightarrow \varphi'$$

- Reachability rules capture Hoare triples [FM'12]

$$\{Pre\}\,Code\,\{Post\} \quad \equiv \quad \widehat{Code} \wedge \widehat{Pre} \Rightarrow \epsilon \wedge \widehat{Post}$$

Sum 1+2+…+n in IMP: Main

```
rule
    <k>
      int n, sum;
      n = N:Int;
      sum = 0;
      while (!(n <= 0)) {
        sum = sum + n;
        n = n + -1;
      }
    =>
      .K
    </k>
    <state>
      .Map
    =>
      n   |-> 0
      sum |-> ((N +Int 1) *Int N /Int 2)
    </state>
requires N >=Int 0
```

Sum 1+2+…+n in IMP: Invariant

```
rule
    <k>
      while (!(n <= 0)) {
        sum = sum + n;
        n = n + -1;
      }
    =>
      .K
    ...</k>
    <state>...
      n   |-> (N:Int => 0)
      sum |-> (S:Int => S +Int ((N +Int 1) *Int N /Int 2))
    ...</state>
requires N >=Int 0
```

OK Performance [OOPLSA'16]

Time (seconds) spent on applying semantic steps (symbolic execution)

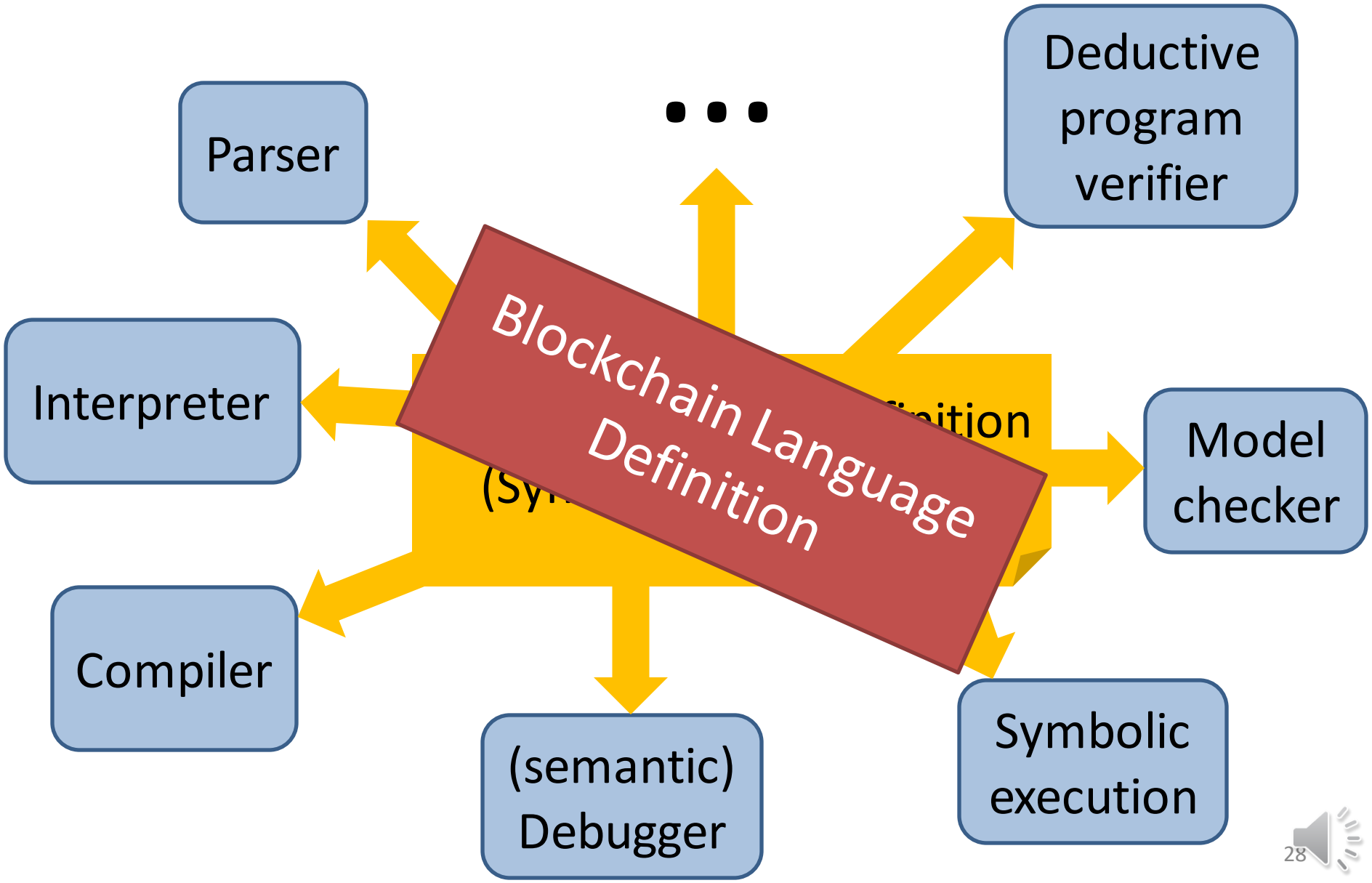
Time (seconds) spent on domain reasoning (like querying Z3)

Programs	KernelC				C				Java				JavaScript			
	Execution		Reasoning		Execution		Reasoning		Execution		Reasoning		Execution		Reasoning	
	Time	#Step	Time	#Query	Time	#Step	Time	#Query	Time	#Step	Time	#Query	Time	#Step	Time	#Query
BST find	0.6	192	1.2	95	10.4	1,028	3.6	246	1.9	322	2.8	244	4.5	1,736	1.8	93
BST insert	0.8	336	2.9	160	23.0	2,481	7.2	414	4.1	691	4.5	342	5.4	3,394	2.8	158
BST delete	1.4	582	5.6	420	55.1	4,540	16.6	938	9.8	1,274	15.1	1,125	15.6	5,052	5.6	373
AVL find	0.6	192	1.2	95	9.9	1,028	3.1	214	2.2	322	2.7	244	4.5	1,736	1.9	93
AVL insert	6.2	1,980	42.1	1,133	210.7	12,616	70.6	1,865	42.4	3,753	62.8	2,146	102.5	26,977	32.5	1,221
AVL delete	9.5	2,933	45.4	1,758	514.8	26,003	118.9	3,883	122.2	8,144	149.4	4,866	184.3	38,591	55.3	2,233
RBT find	0.6	192	1.1	95	11.5	1,064	3.0	214	2.1	322	2.9	244	4.9	1,736	1.9	93
RBT insert	7.6	2,331	48.1	1,392	722.0	30,924	181.8	4,394	39.9	4,240	75.7	2,547	84.9	28,082	29.6	1,381
RBT delete	10.6	3,891	33.7	2,033	1593.8	50,389	308.3	15,429	95.8	8,312	75.4	4,460	144.2	51,356	39.4	2,009
Treap find	0.6	200	1.4	118	11.2	1,064	3.2	214	2.0	322	2.9	244	4.6	1,736	1.9	116
Treap insert	1.4	753	4.5	247	52.4	4,954	15.3	724	12.7	1,469	10.4	563	13.7	7,738	5.2	243
Treap delete	2.0	831	9.4	509	73.9	5,512	16.5	656	12.0	1,694	16.4	1,021	24.8	8,333	8.4	460
List reverse	0.4	142	0.3	21	6.6	815	4.8	76	1.5	222	2.6	46	5.0	1,162	0.5	20
List append	0.4	171	0.5	45	7.4	909	7.4	128	1.8	239	5.5	106	4.5	1,392	0.8	46
Bubble sort	0.9	391	26.8	190	28.4	2,401	38.0	357	3.4	589	35.4	345	5.6	2,688	25.7	145
Insertion sort	1.1	468	24.5	300	26.6	2,555	35.3	451	4.1	731	27.0	371	8.3	3,119	36.5	213
Quick sort	1.1	604	31.6	269	31.0	3,601	48.2	518	7.1	958	40.0	413	15.0	5,046	33.1	252
Merge sort	1.7	970	55.0	478	81.6	6,589	89.0	1,070	14.1	1,566	72.9	737	22.8	7,021	43.2	480
Total	47.7	17,159	335.2	9,358	3470.5	158,473	970.6	31,791	379.3	35,170	604.5	20,064	654.9	196,895	326.3	9,629

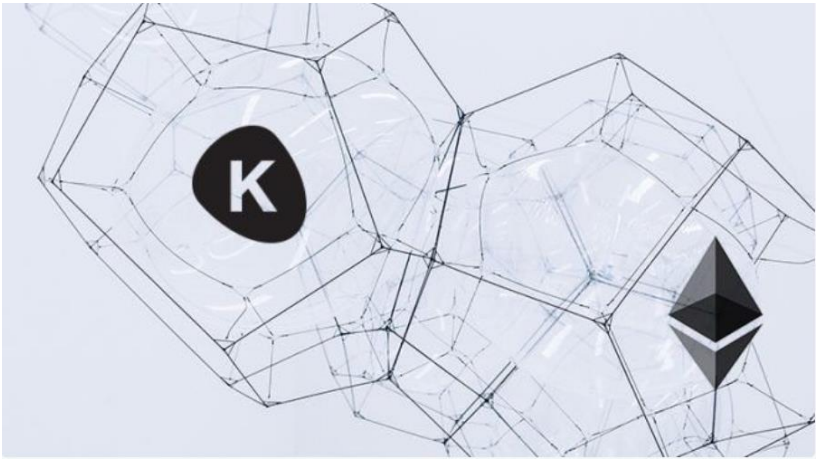
- Properties very challenging to verify automatically. We only found one such prover for C, based on a separation logic extension of VCC
  - Which takes 260 sec to verify AVL insert (ours takes 280 sec; see above)

K for the Blockchain

K Framework Vision



KEVM: Semantics of the Ethereum Virtual Machine (EVM) in K



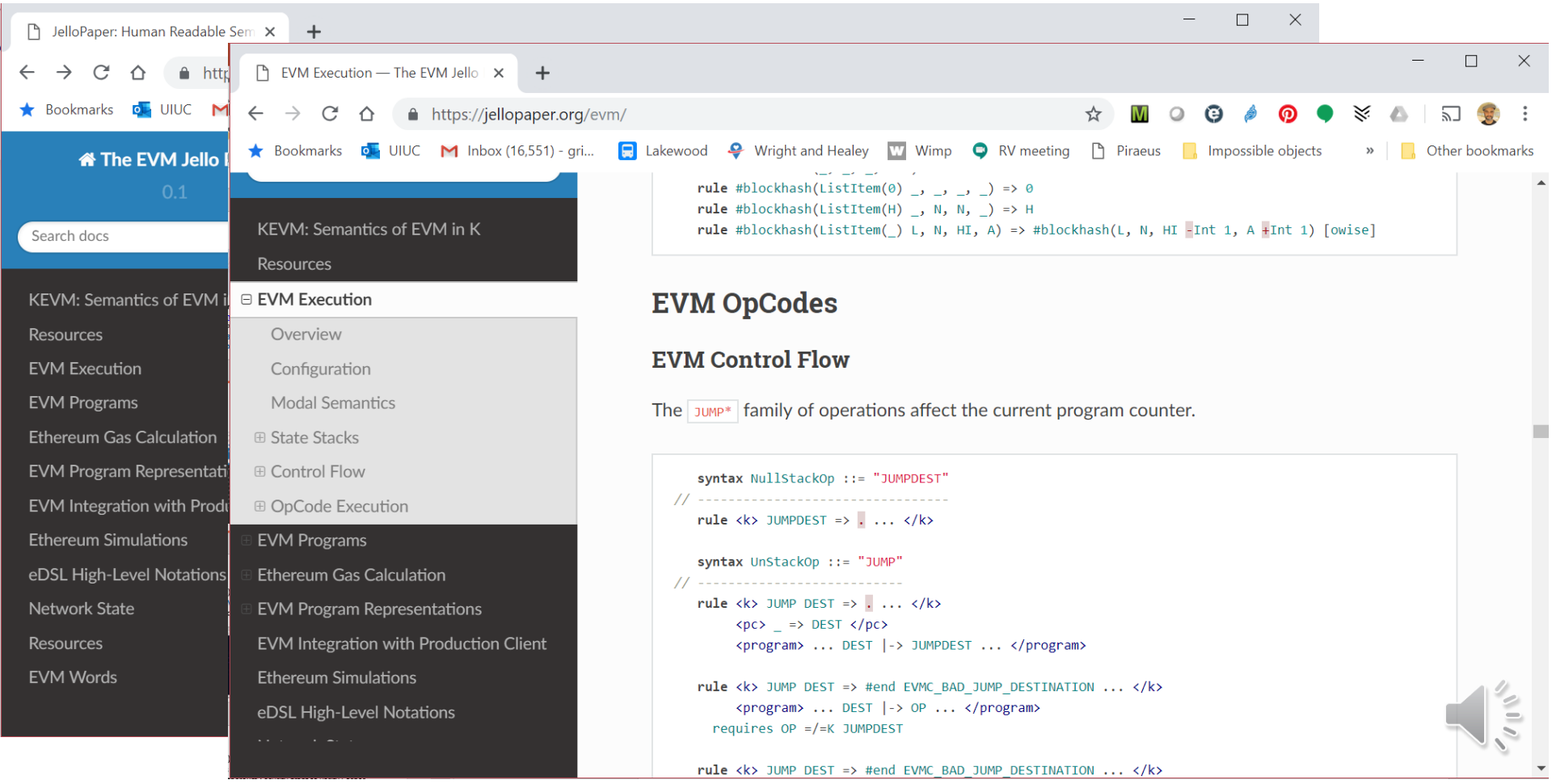
[CSL'18]

Complete semantics of EVM in K

- https://github.com/kframework/evm-semantics
- Passes 60,000+ tests of C++ reference implementation
- *8x (only!) slower than the C++ implementation; now 5x*

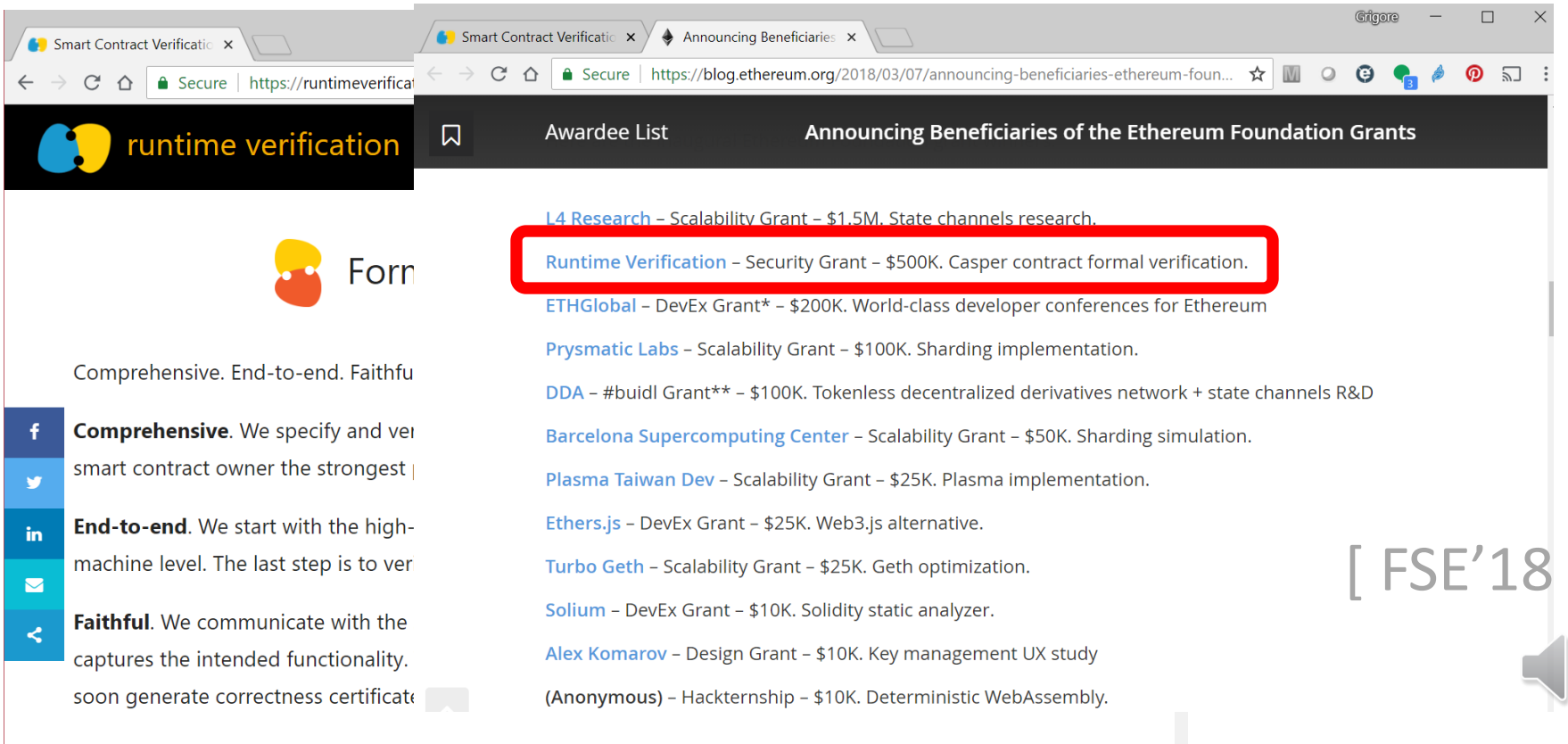
What Can We Do with KEVM?

1) *Formal documentation*: http://jellopaper.org



What Can We Do with KEVM?

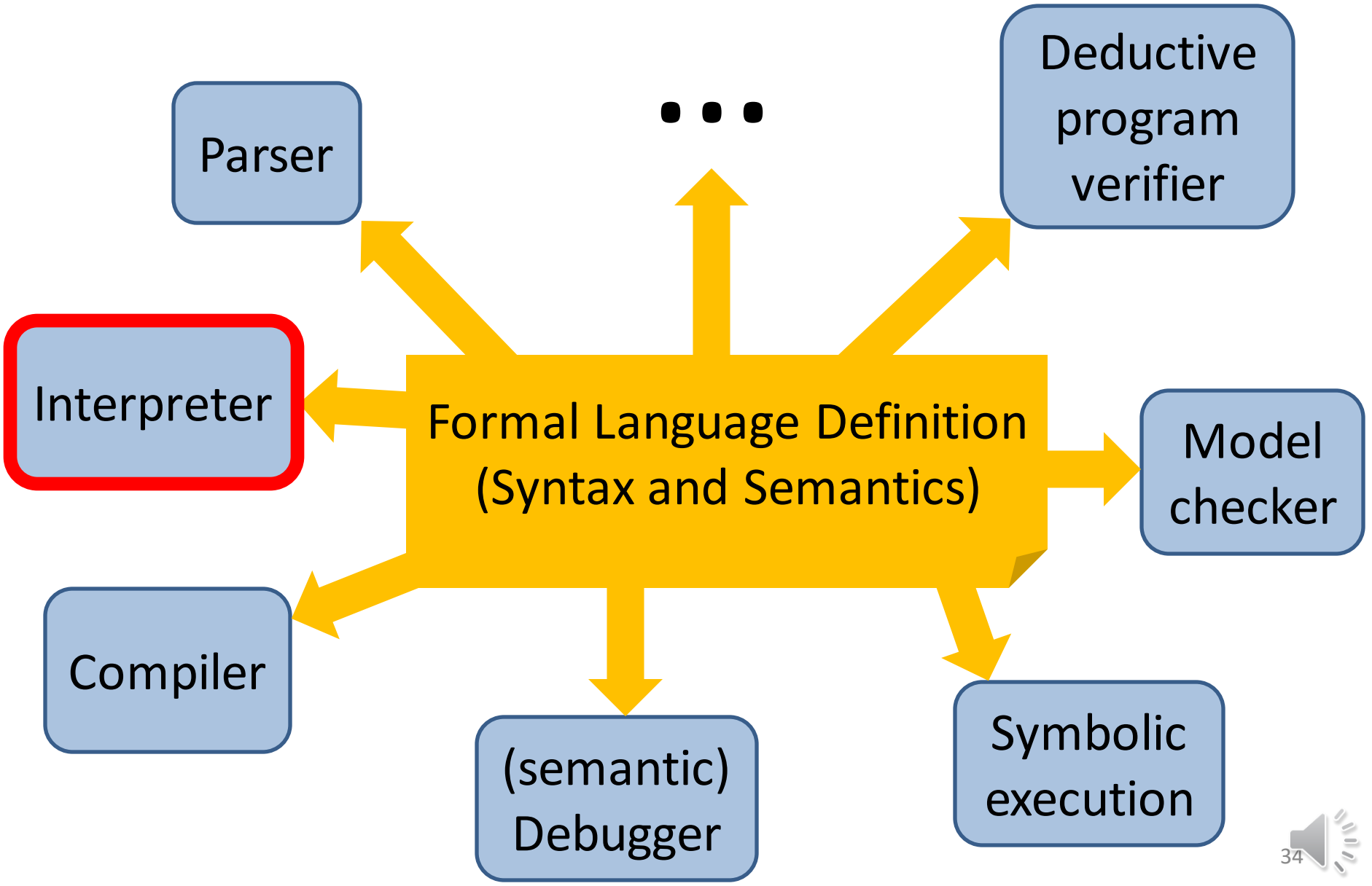
3) *Formally verify Ethereum smart contracts*! RV is doing that, commercially. RV also won first Ethereum Security grant to verify Casper.



[FSE'18]

Ongoing K Infrastructure Projects

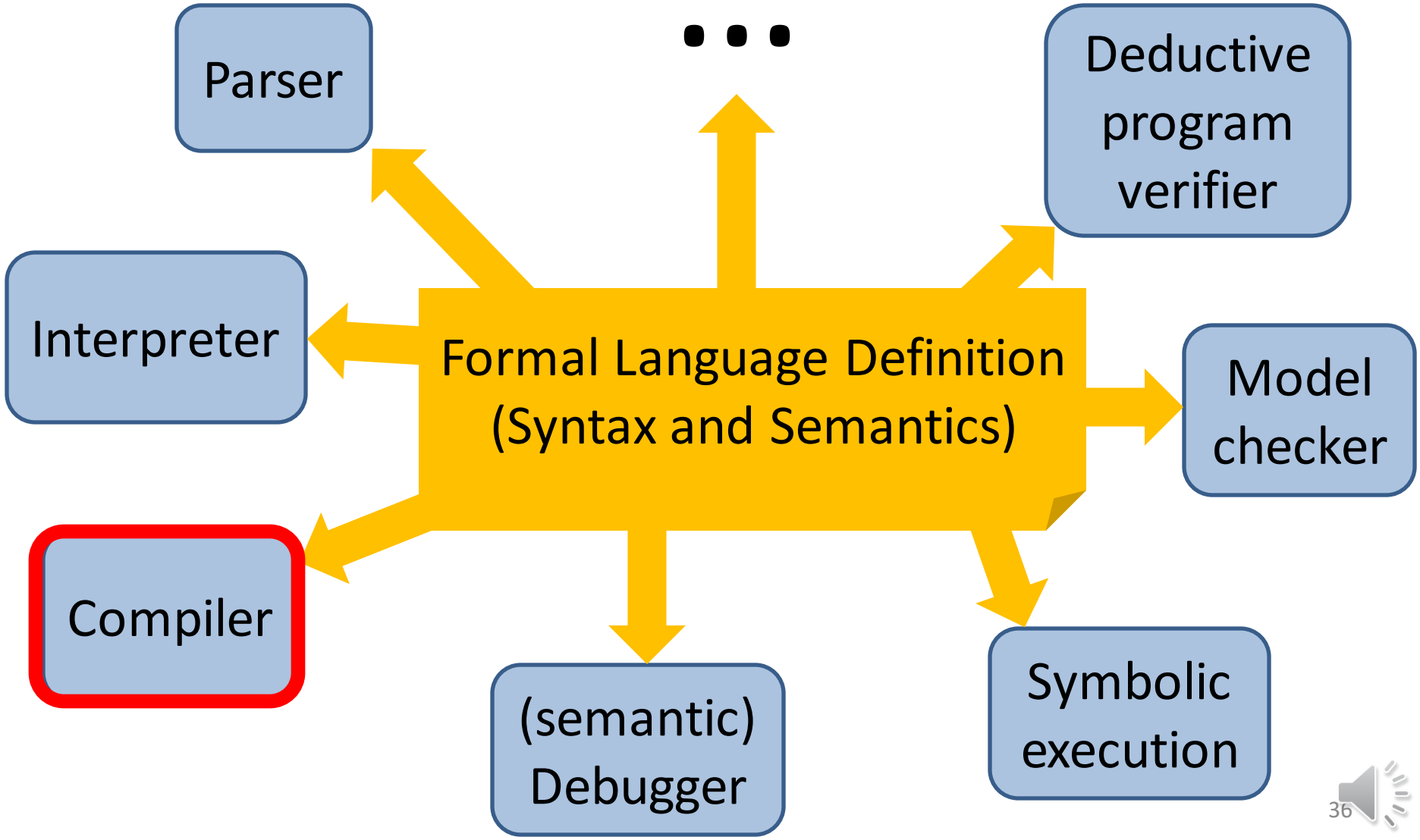
1. Fast LLVM Backend for K



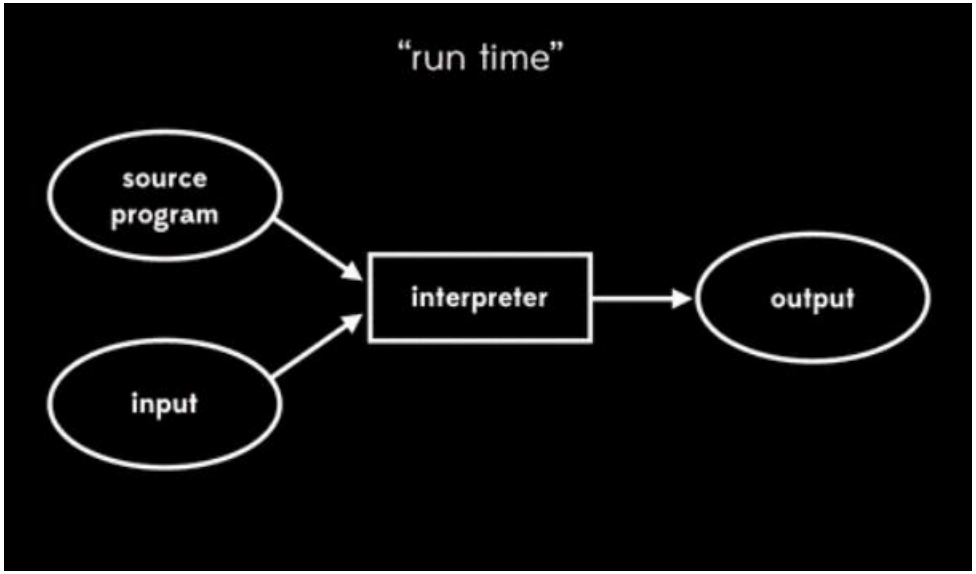
Fast LLVM Backend for K

- Current OCAML backend of K:
  - Fast enough to power RV-Match product and KEVM client
  - But still slower than hand-crafted interpreters
- LLVM backend for K under development:
  - Take advantage of LLVM's optimizations / pipeline
  - Expected to compete with hand-written interpreters!

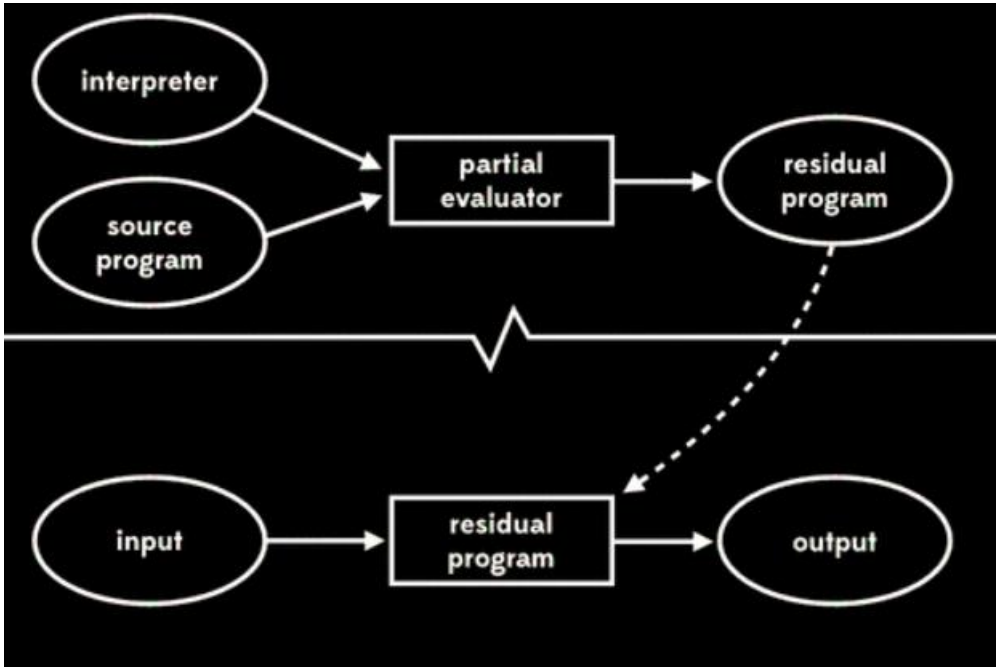
2. Semantics-Based Compilation



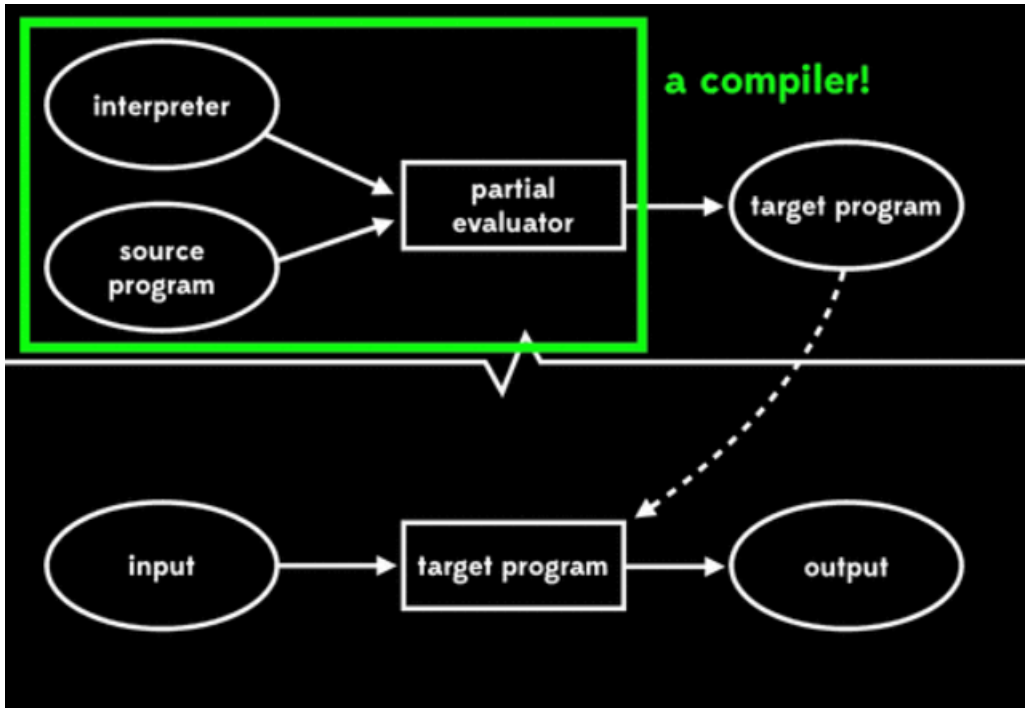
Futamura first projection



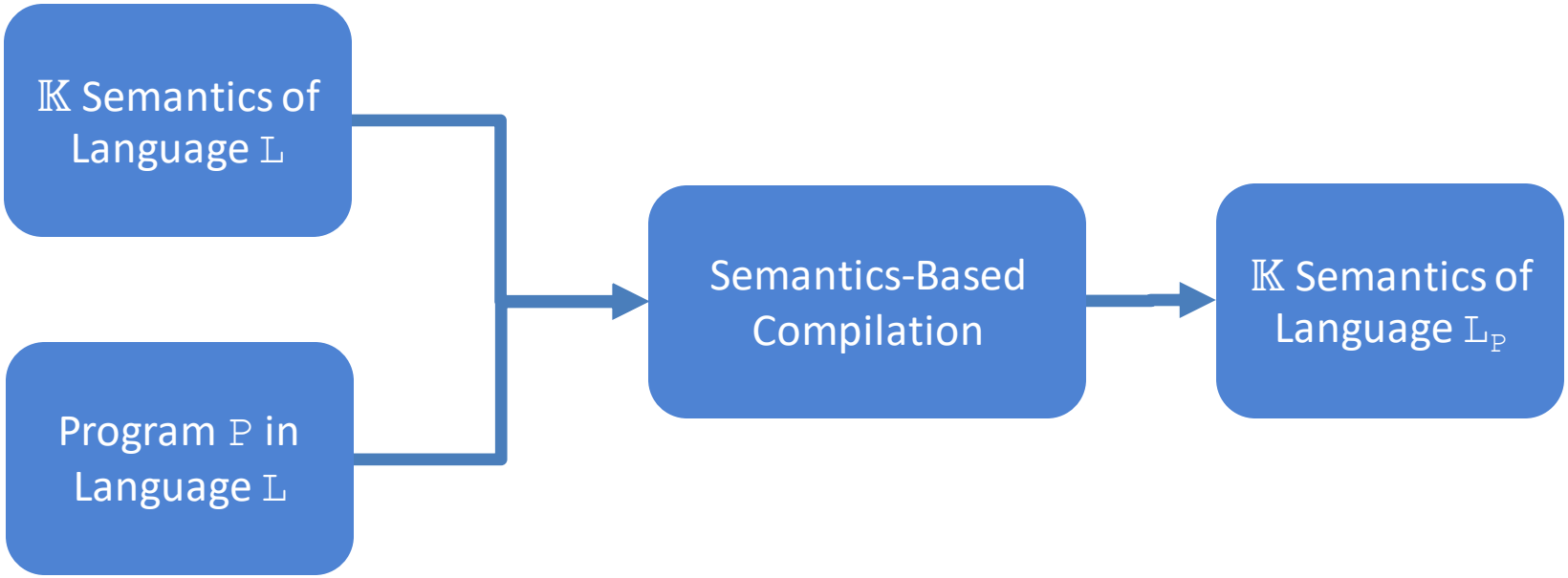
Futamura first projection



Futamura first projection



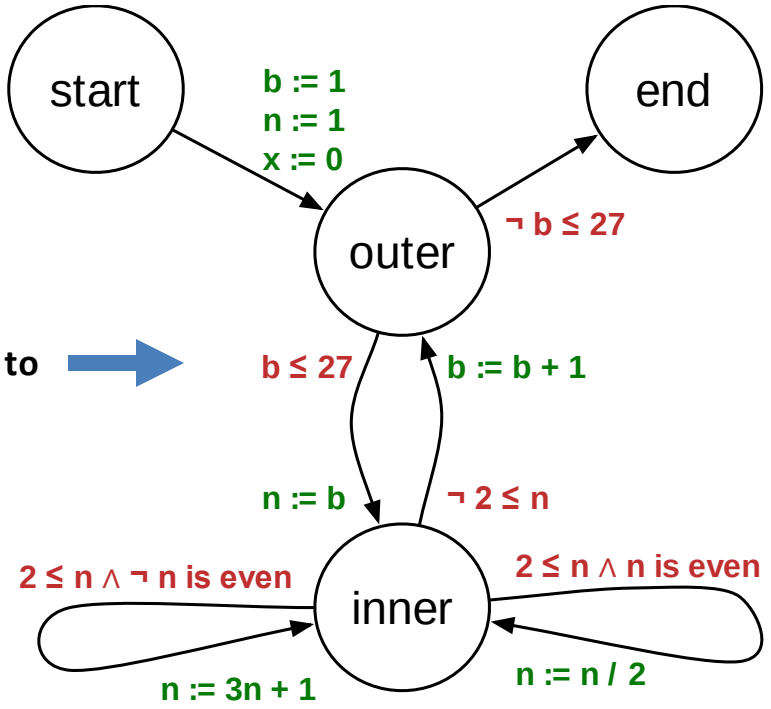
Semantics-Based Compilation (SBC)



Semantics-Based Compilation (SBC) Experiments with Early Prototype

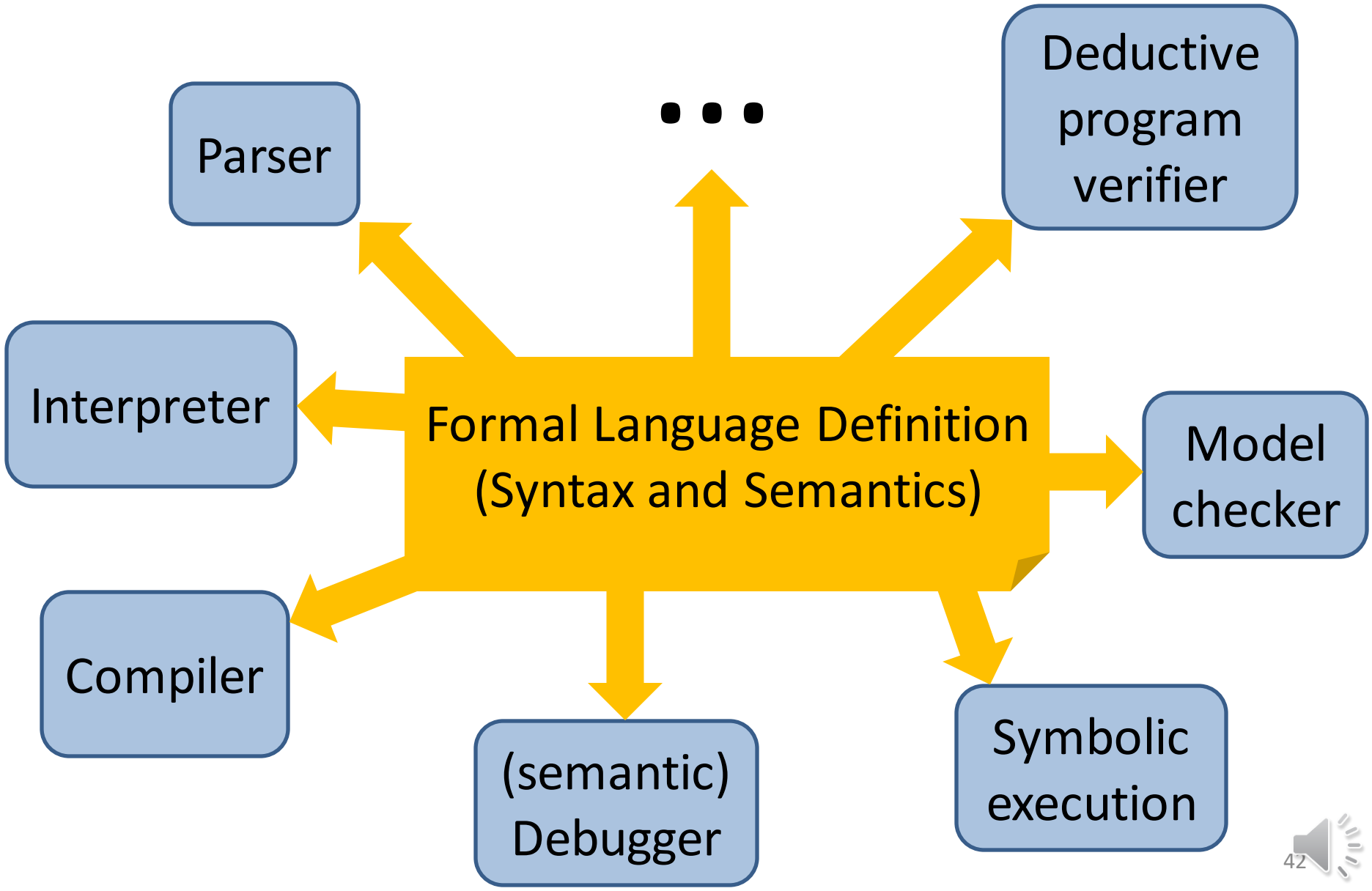
```
// start
int b , n , x ;
b = 1 ; n = 1 ; x = 0 ;

// outer
while (b <= 27) {
  n = b ;

  // inner
  while (2 <= n) {
    if (n <= ((n / 2) * 2))
{
      n = n / 2 ;
    } else {
      n = (3 * n) + 1 ;
    }
    x = x + 1 ;
  }
  b = b + 1 ;
}
// end
```

compiles to



Program	Original (s)	Compiled (s)	Speedup
sum.imp	70.6	7.3	9.7
collatz.imp	34.5	2.7	12.8
collatz-all.imp	77.4	5.7	13.6
krazy-loop.imp	67.6	3.3	20.5

Conclusion: It Can Be Done!



Backup