Computer-Aided Reasoning for Software

CSE507

Practical Applications of SAT

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Emina Torlak
emina@cs.washington.edu

Today

Past 2 lectures

- The theory and mechanics of SAT solving

Today

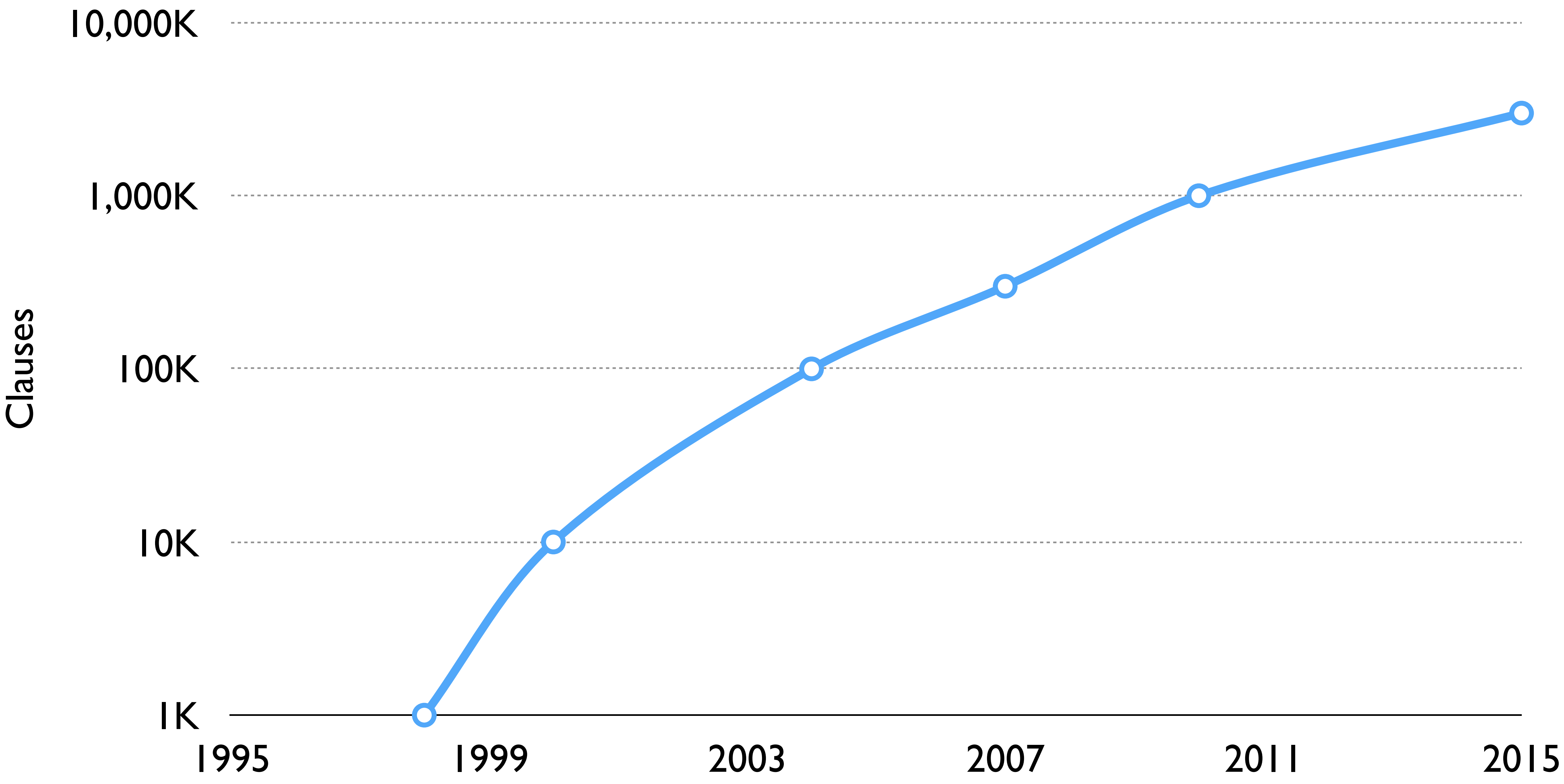
- Practical applications of SAT
- Variants of the SAT problem
- Motivating the next lecture on SMT

But first …

- A brief Q&A session for Homework I

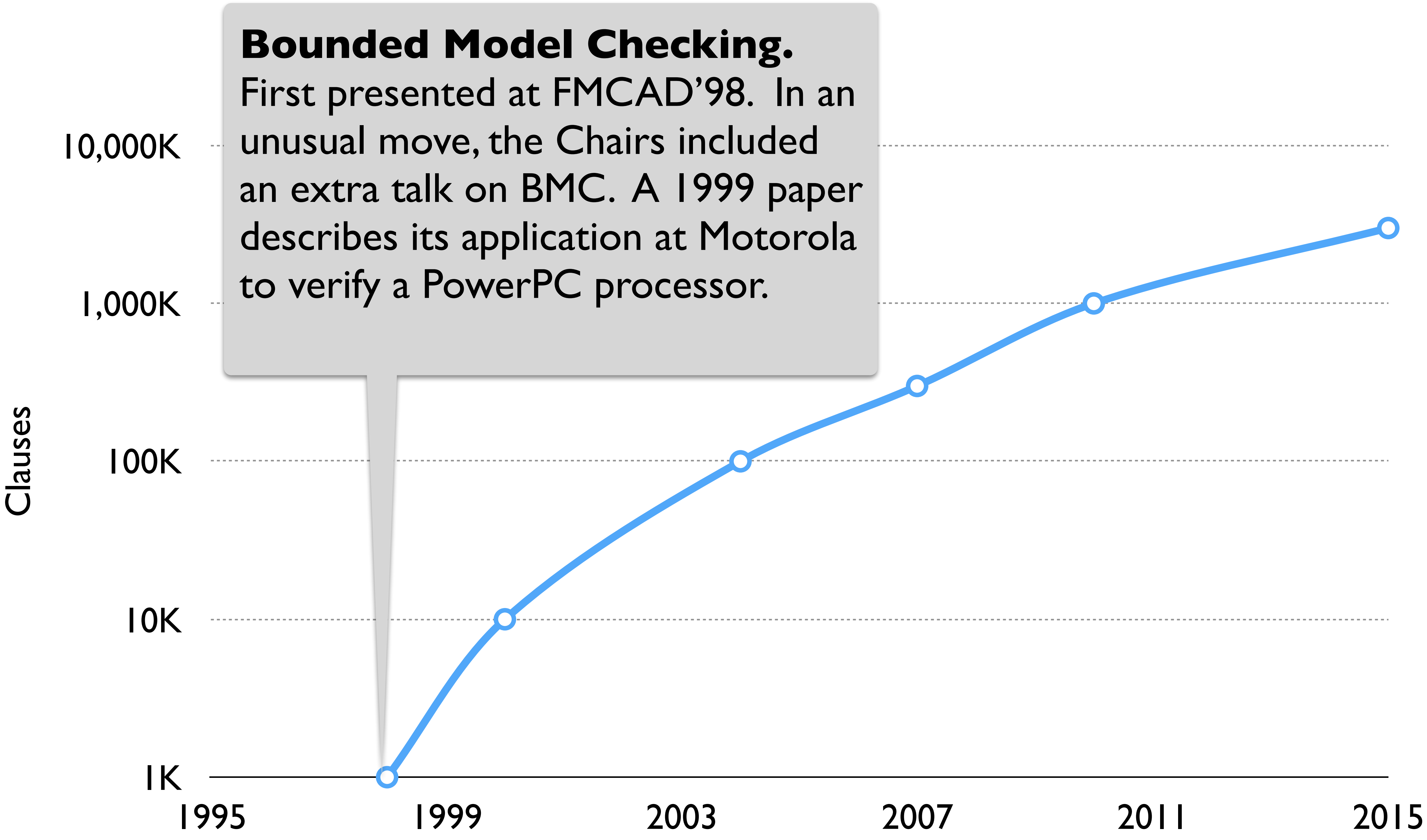
topics

A brief history of SAT solving and applications



Based on a slide from Vijay Ganesh

A brief history of SAT solving and applications



Bounded Model Checking. First presented at FMCAD'98. In an unusual move, the Chairs included an extra talk on BMC. A 1999 paper describes its application at Motorola to verify a PowerPC processor.

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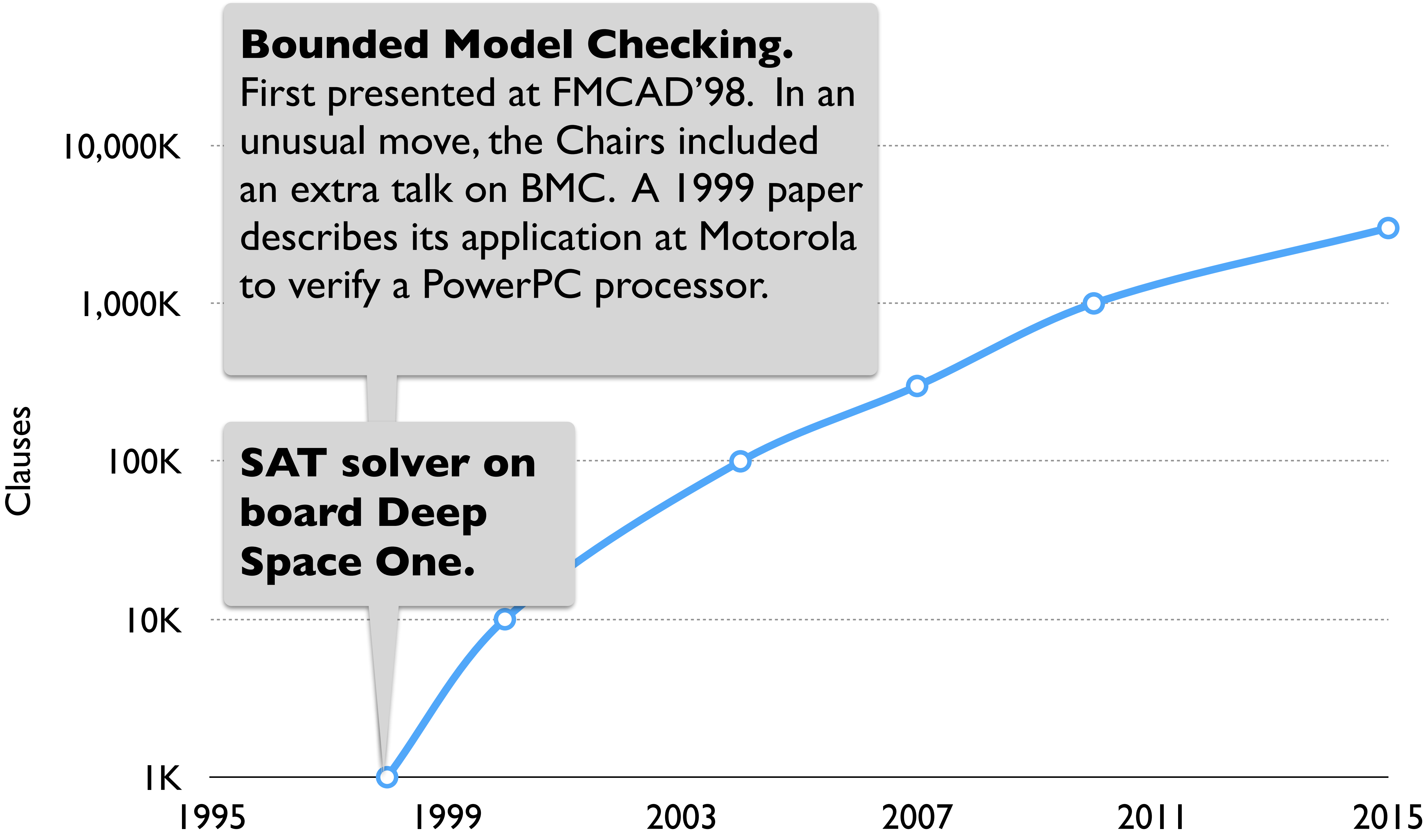

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SAT solver on board Deep Space One.

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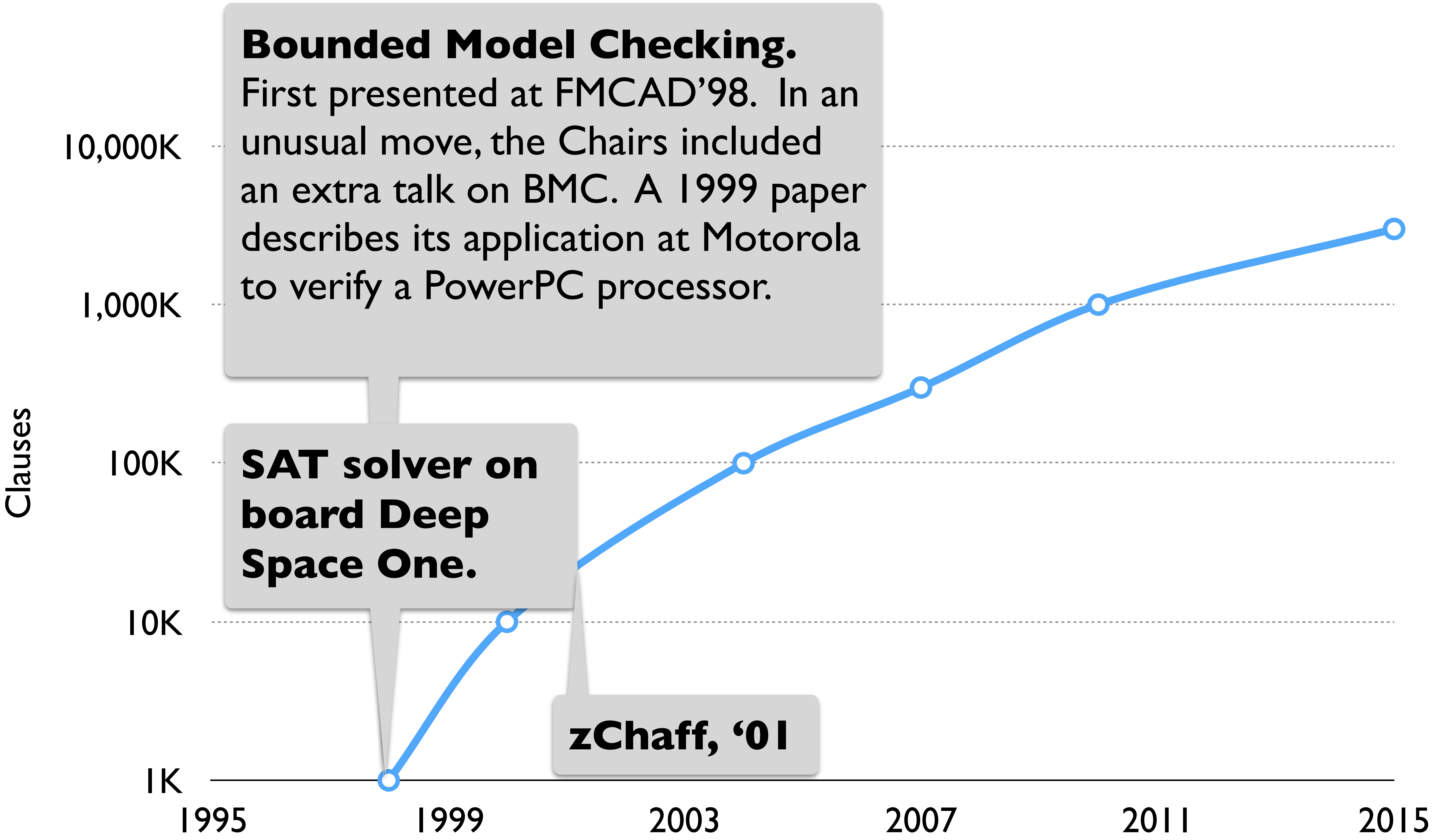

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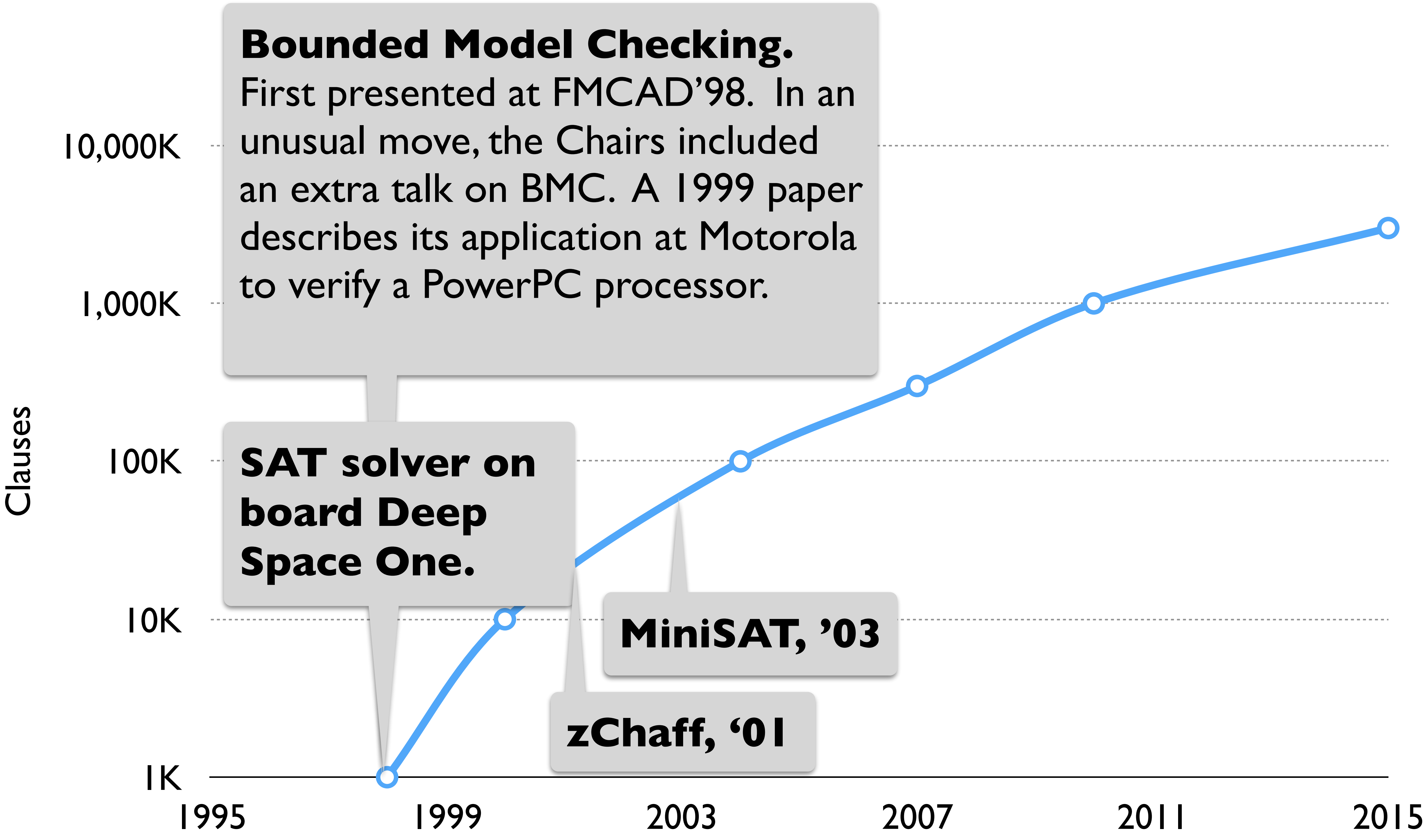

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MiniSAT, '03

zChaff, '01

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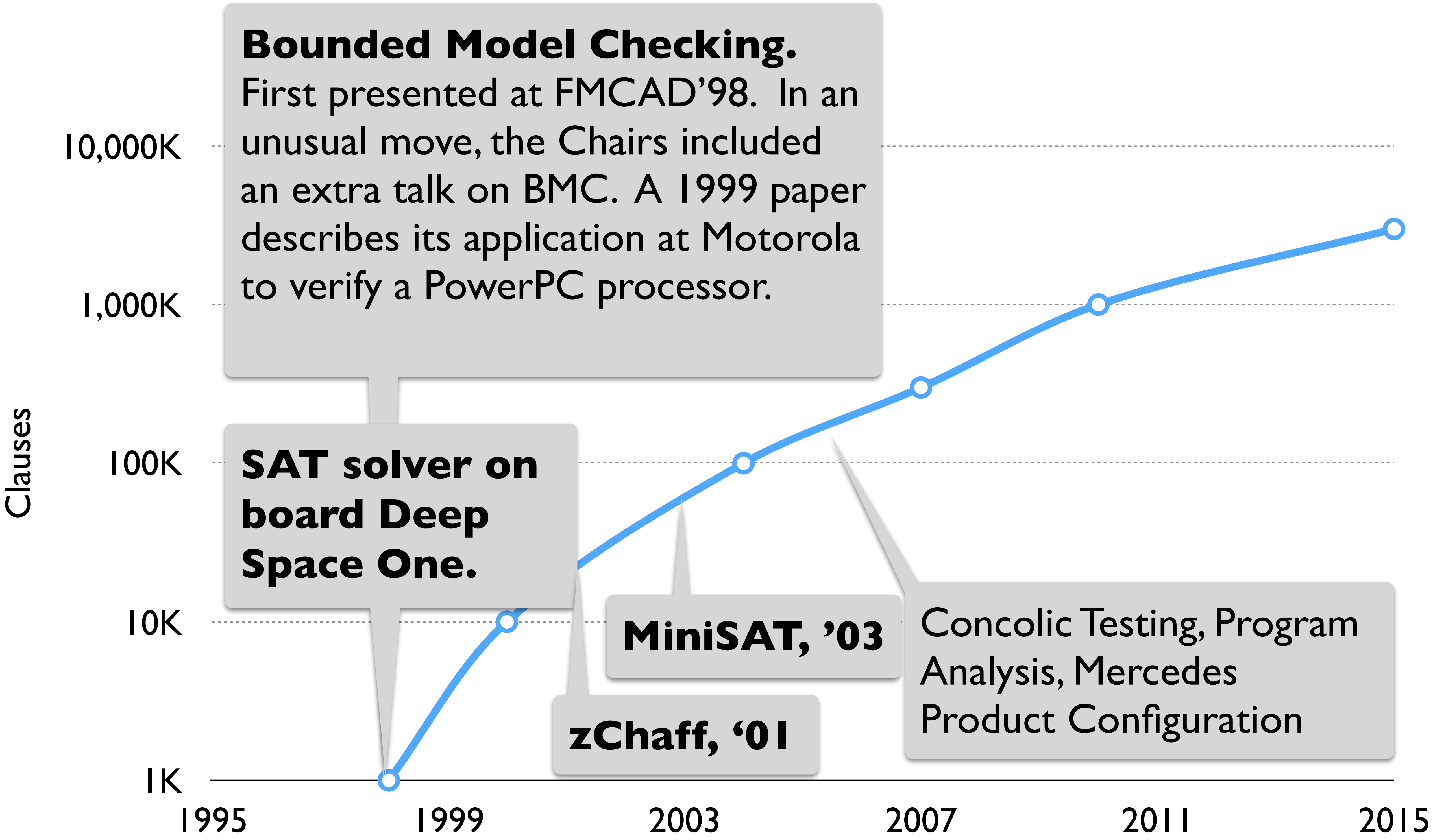

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Concolic Testing, Program Analysis, Mercedes Product Configuration

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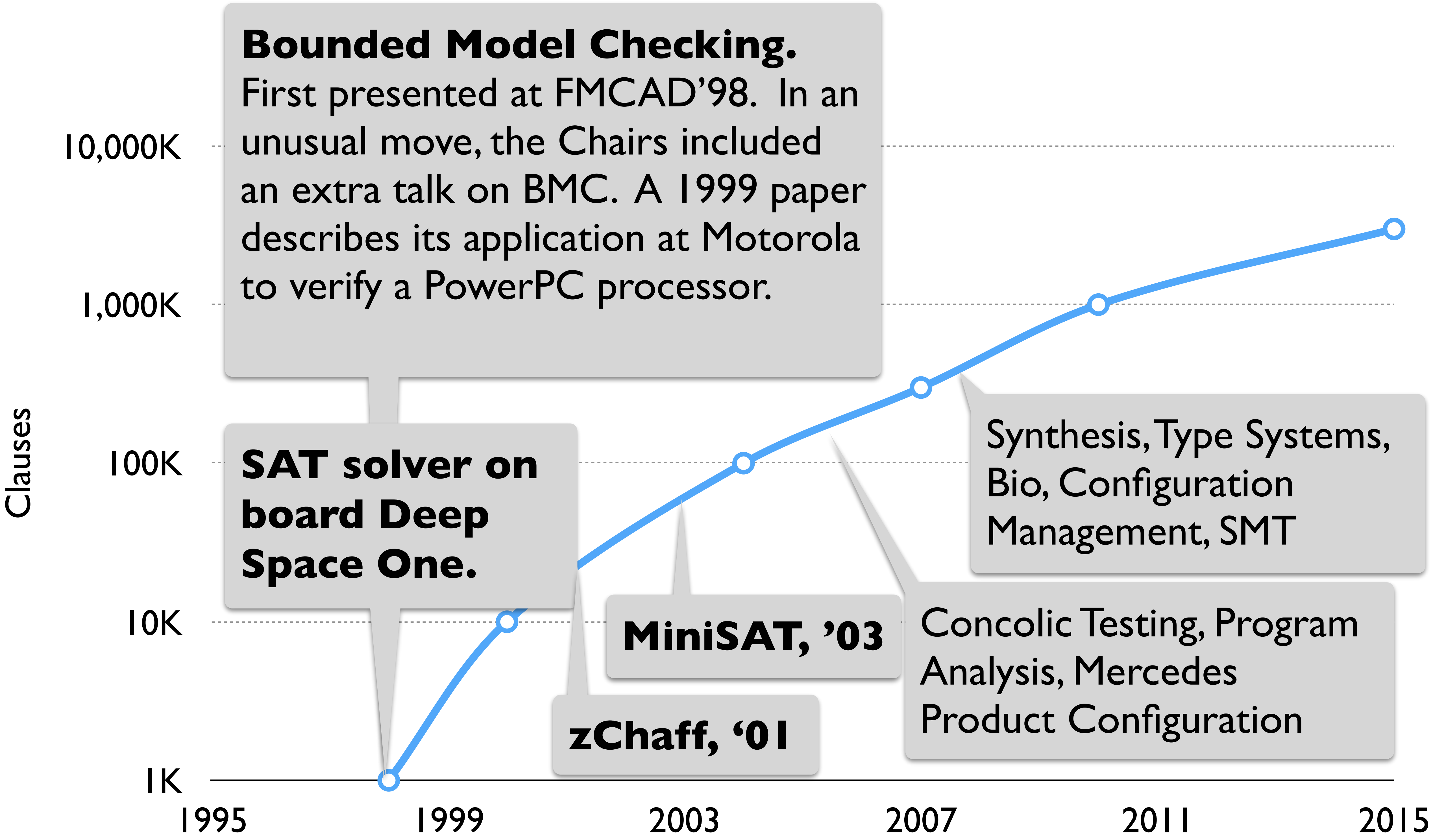

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Concolic Testing, Program Analysis, Mercedes Product Configuration

Synthesis, Type Systems, Bio, Configuration Management, SMT

Based on a slide from Vijay Ganesh

today

Bounded Model Checking (BMC) & Configuration Management

Bounded Model Checking (in general)

Given a system and a property, BMC checks if the property is satisfied by all executions of the system with ≤k steps, on all inputs of size ≤n.

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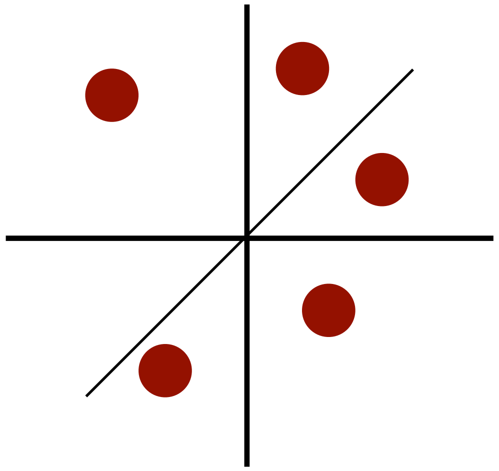
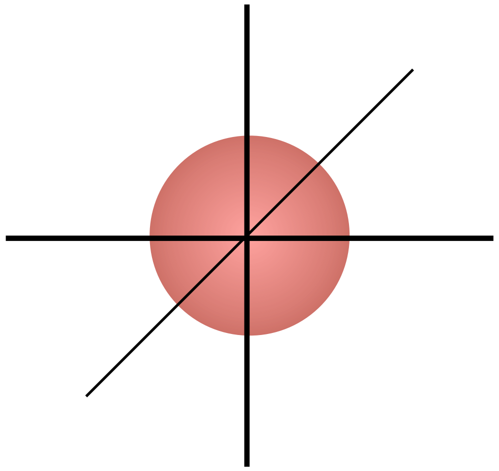
Given a system and a property, BMC checks if the property is satisfied by all executions of the system with ≤k steps, on all inputs of size ≤n.

We will focus on **safety properties** (i.e., making sure a bad state, such as an assertion violation, is not reached).

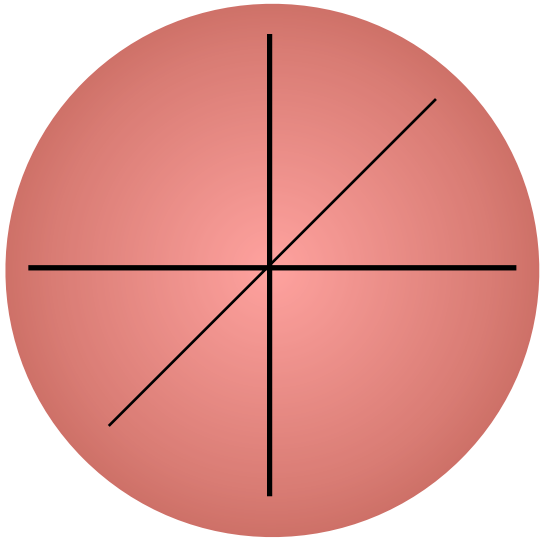
Bounded Model Checking (in general)



Testing: checks a few executions of arbitrary size



BMC: checks all executions of size ≤k



Verification: checks all executions of every size

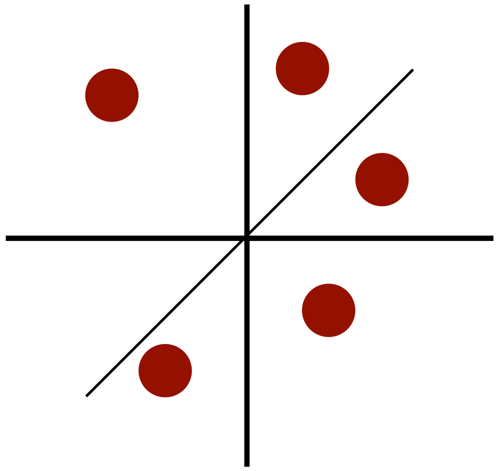
low confidence

high confidence

low human labor

high human labor

Bounded Model Checking (in general)



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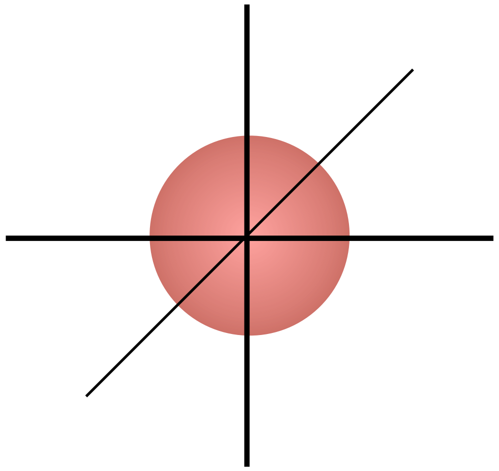
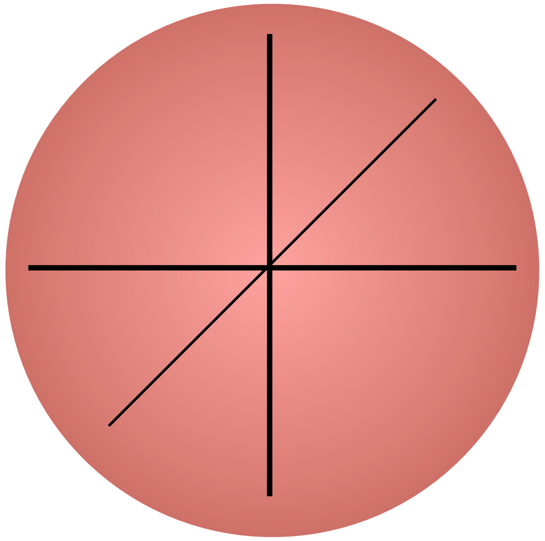


BMC: checks all executions of size ≤k



Verification: checks all executions of every size

low confidence

low human labor

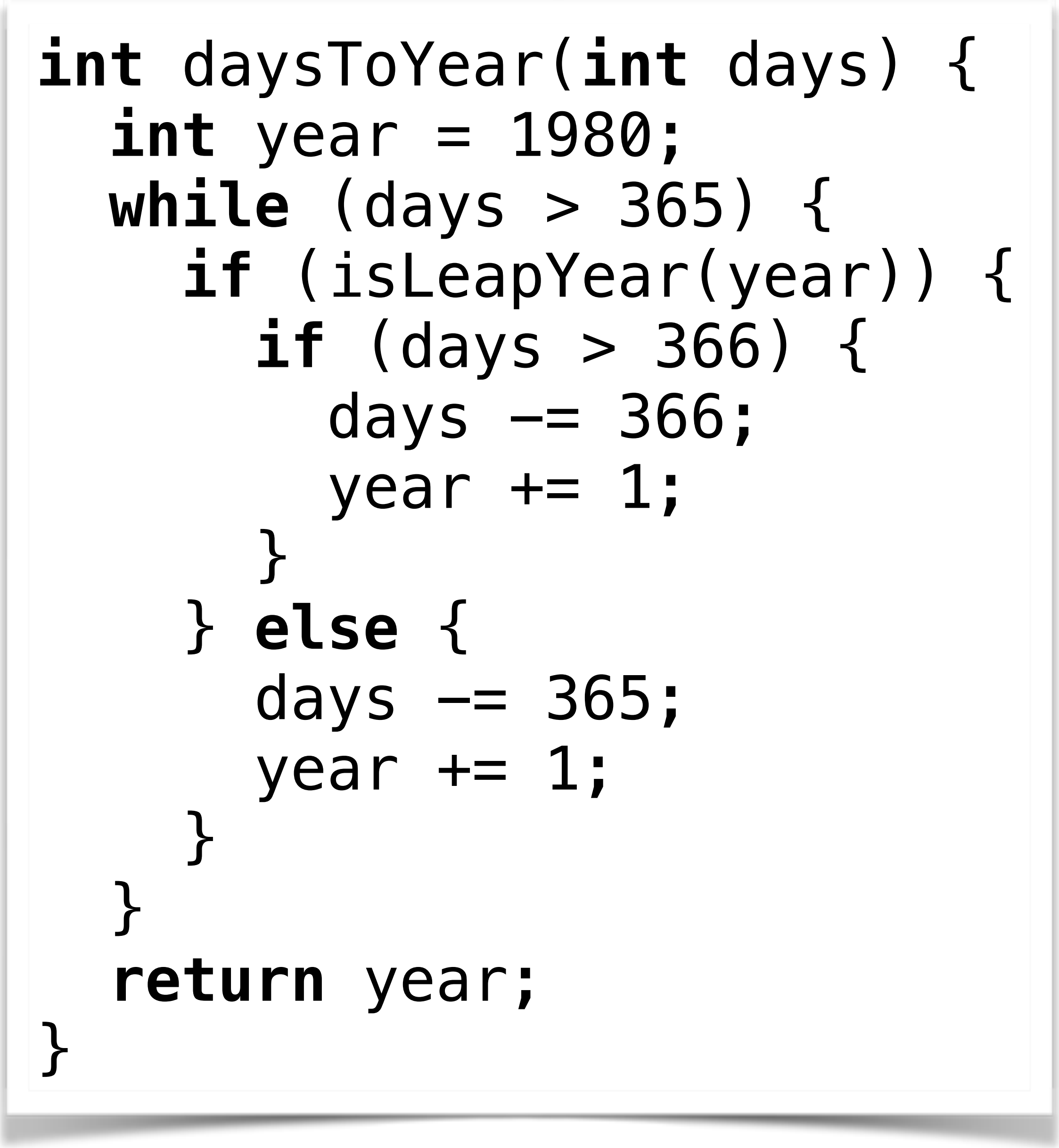
The **small scope hypothesis** says that many bugs can be triggered with small inputs and executions.

high confidence

high human labor

BMC by example

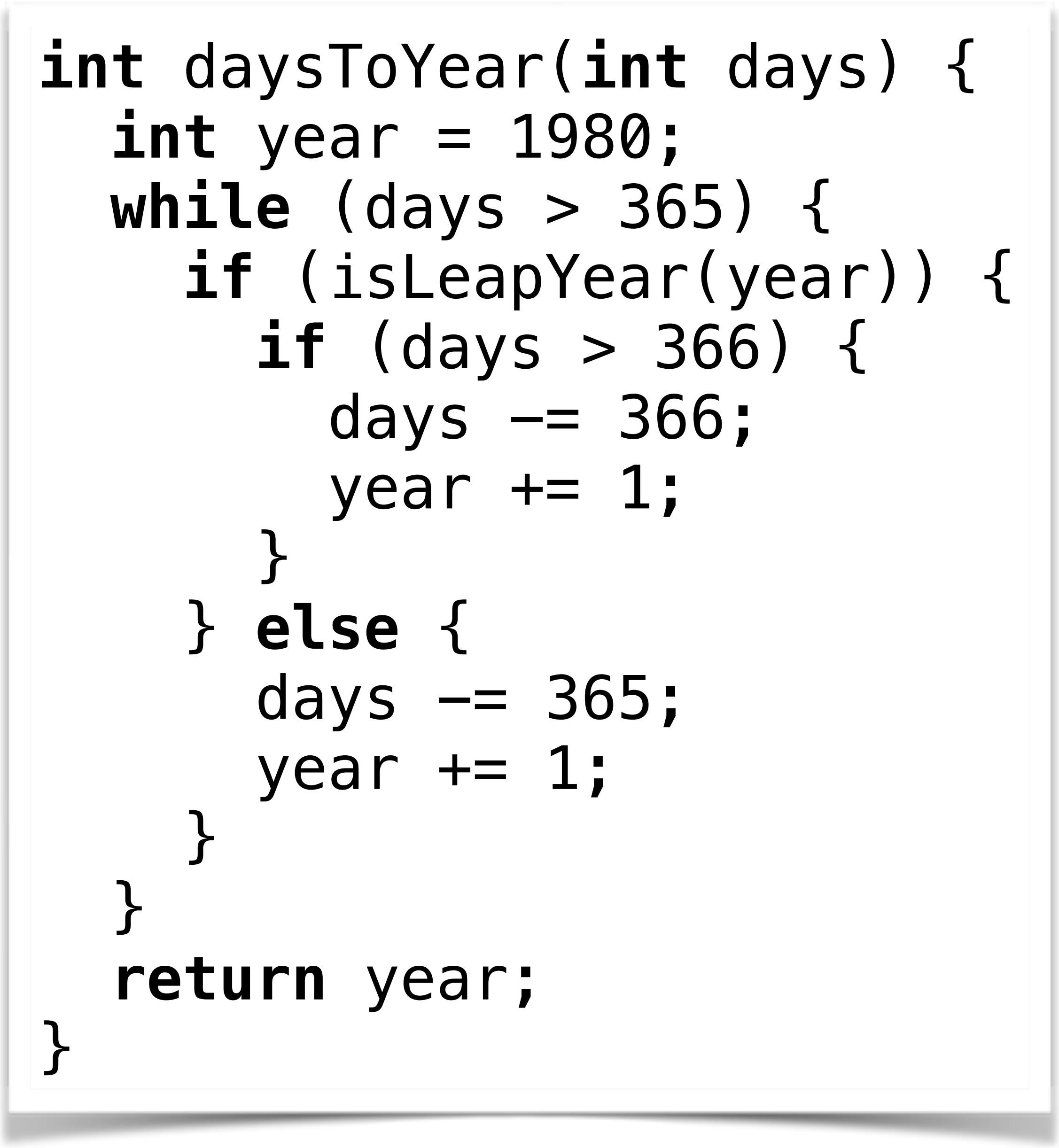
BMC by example



```
int daysToYear(int days) {
  int year = 1980;
  while (days > 365) {
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
  }
  return year;
}
```

The Zune Bug: on December 31, 2008, all first generation Zune players from Microsoft became unresponsive because of this code. What's wrong?

BMC by example



```
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  while (days > 365) {
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        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
  }
  return year;
}
```

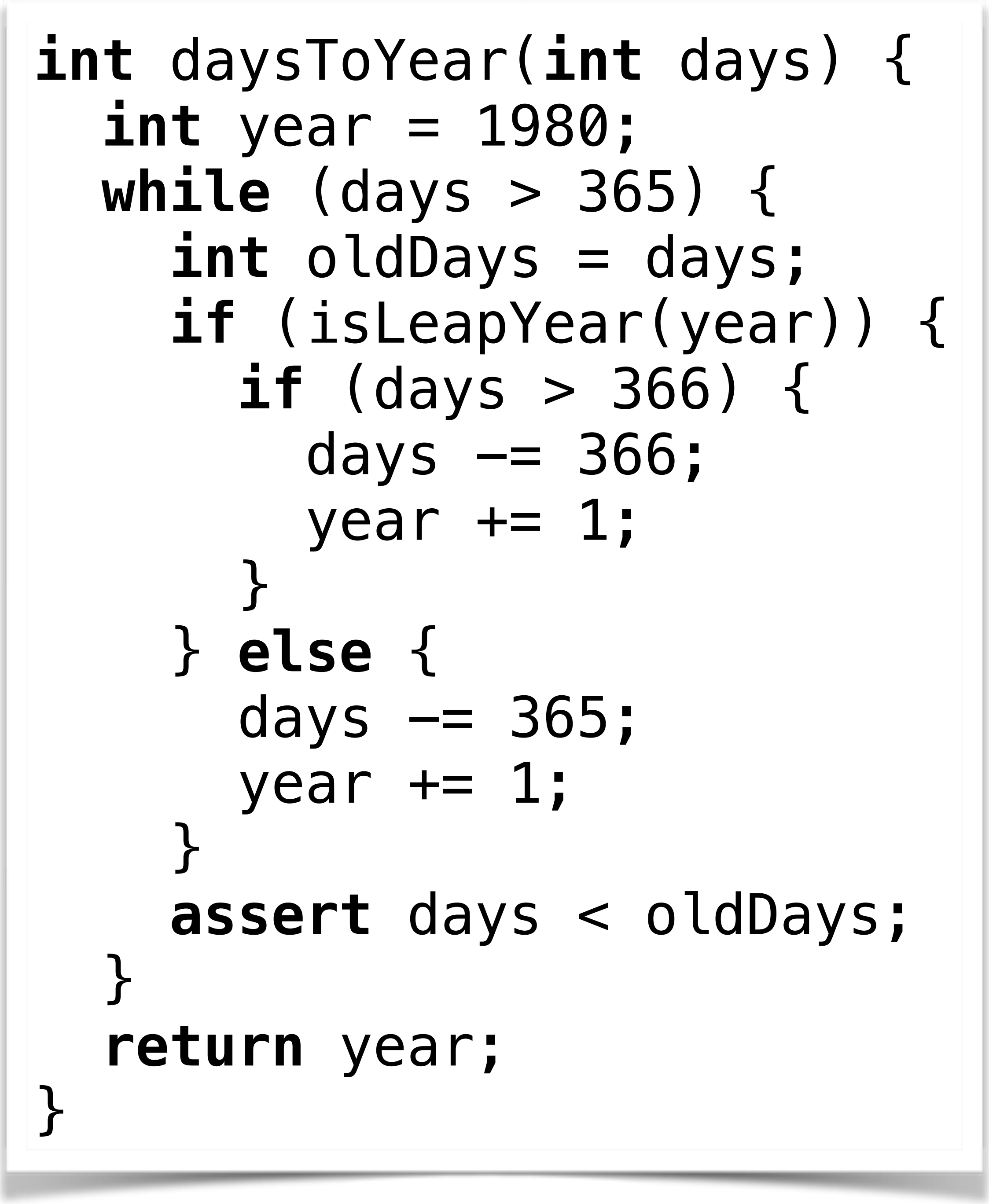
Infinite loop triggered on the last day of every leap year.

BMC by example

```
int daysToYear(int days) {
  int year = 1980;
  while (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
  }
  return year;
}
```

A desired safety property: the value of the days variable decreases in every loop iteration.

BMC step 1 of 4: finitize loops & inline calls



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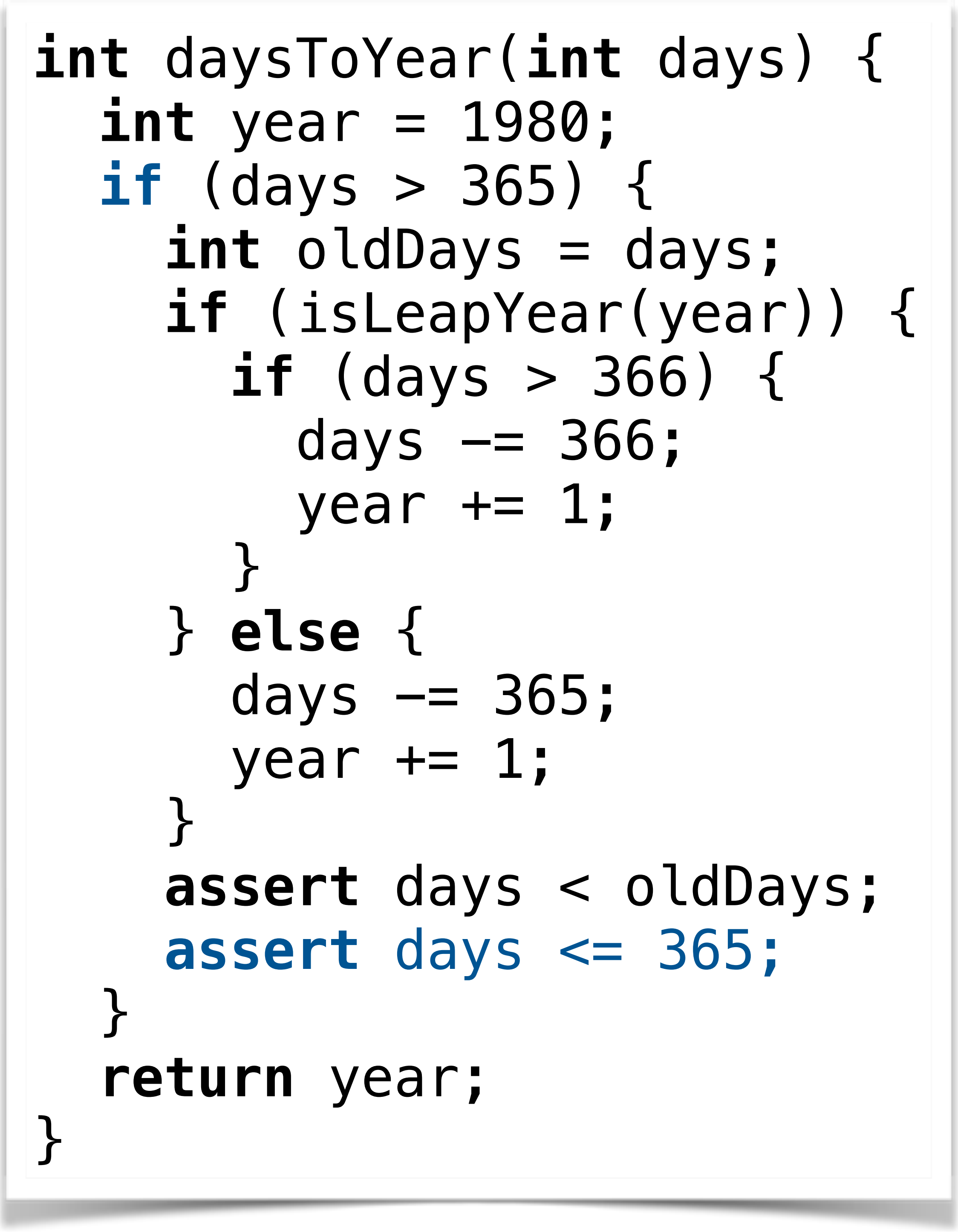
  while (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
  }
  return year;
}
```

BMC step 1 of 4: finitize loops & inline calls

```
int daysToYear(int days) {
  int year = 1980;
  if (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
    assert days <= 365;
  }
  return year;
}
```

- Unwind all loops k times (e.g., k=1), and add an **unwinding assertion** after each.

BMC step 1 of 4: finitize loops & inline calls



```
int daysToYear(int days) {
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  if (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
    assert days <= 365;
  }
  return year;
}
```

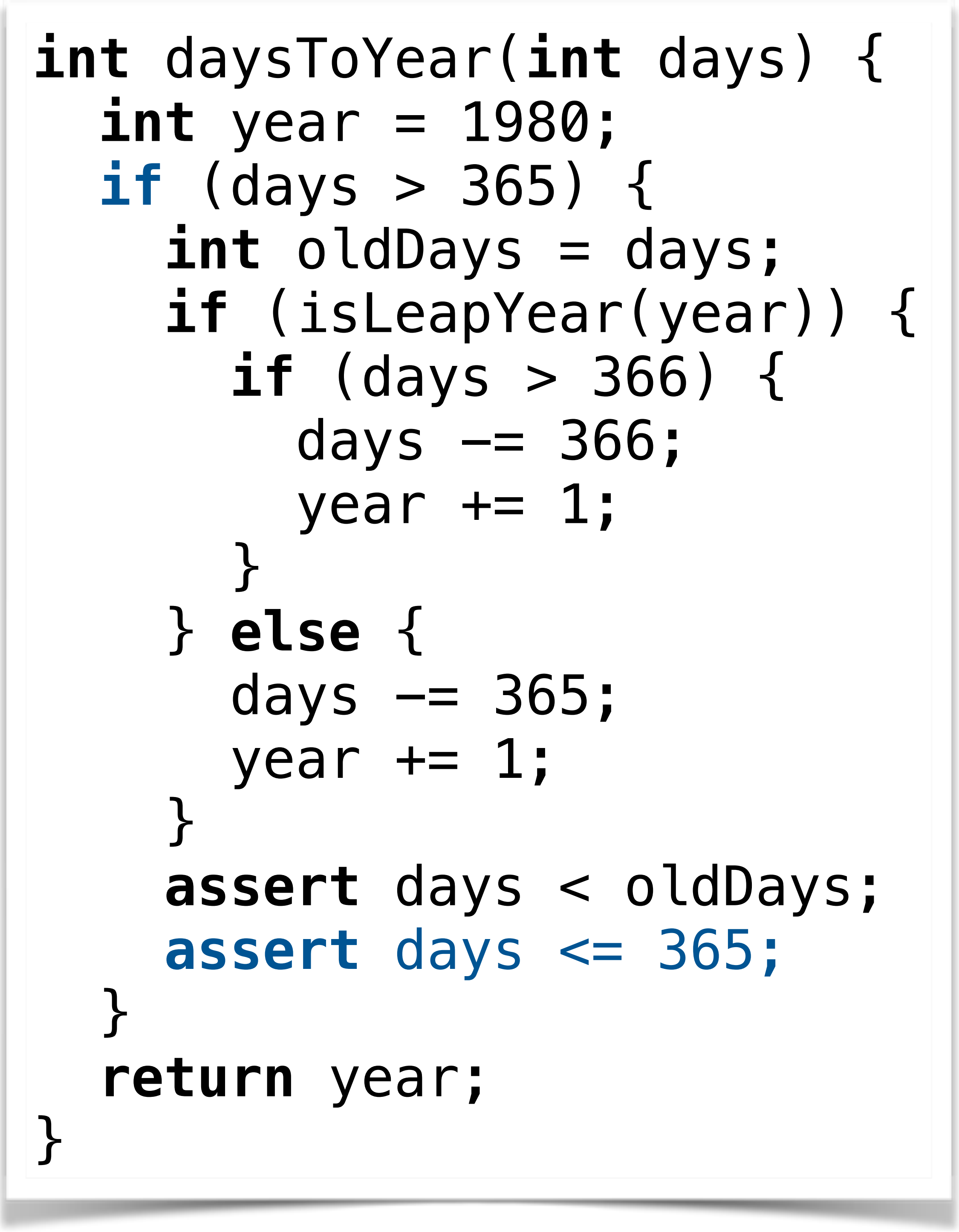
- Unwind all loops k times (e.g., k=1), and add an **unwinding assertion** after each.
- If a CEX violates a program assertion, we have found a buggy behavior of length ≤k.

BMC step 1 of 4: finitize loops & inline calls

```
int daysToYear(int days) {
  int year = 1980;
  if (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
    assert days <= 365;
  }
  return year;
}
```

- Unwind all loops k times (e.g., k=1), and add an **unwinding assertion** after each.
- If a CEX violates a program assertion, we have found a buggy behavior of length ≤k.
- If a CEX violates an unwinding assertion, the program has no buggy behavior of length ≤k, but it may have a longer one.

BMC step 1 of 4: finitize loops & inline calls



```
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    int oldDays = days;
    if (isLeapYear(year)) {
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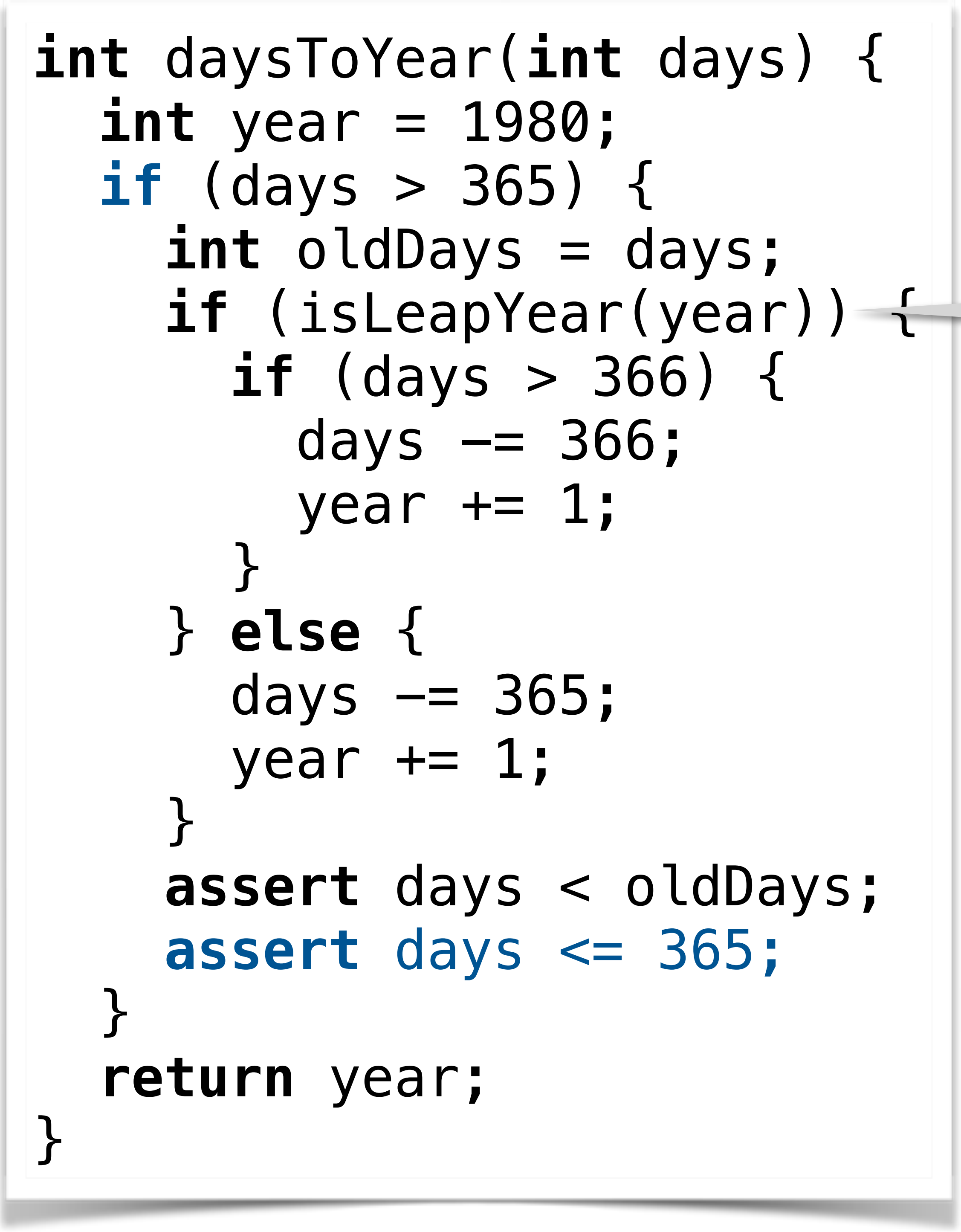
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
    assert days <= 365;
  }
  return year;
}
```

- Unwind all loops k times (e.g., k=1), and add an **unwinding assertion** after each.
- If a CEX violates a program assertion, we have found a buggy behavior of length ≤k.
- If a CEX violates an unwinding assertion, the program has no buggy behavior of length ≤k, but it may have a longer one.
- If there is no CEX, the program is correct for all k!

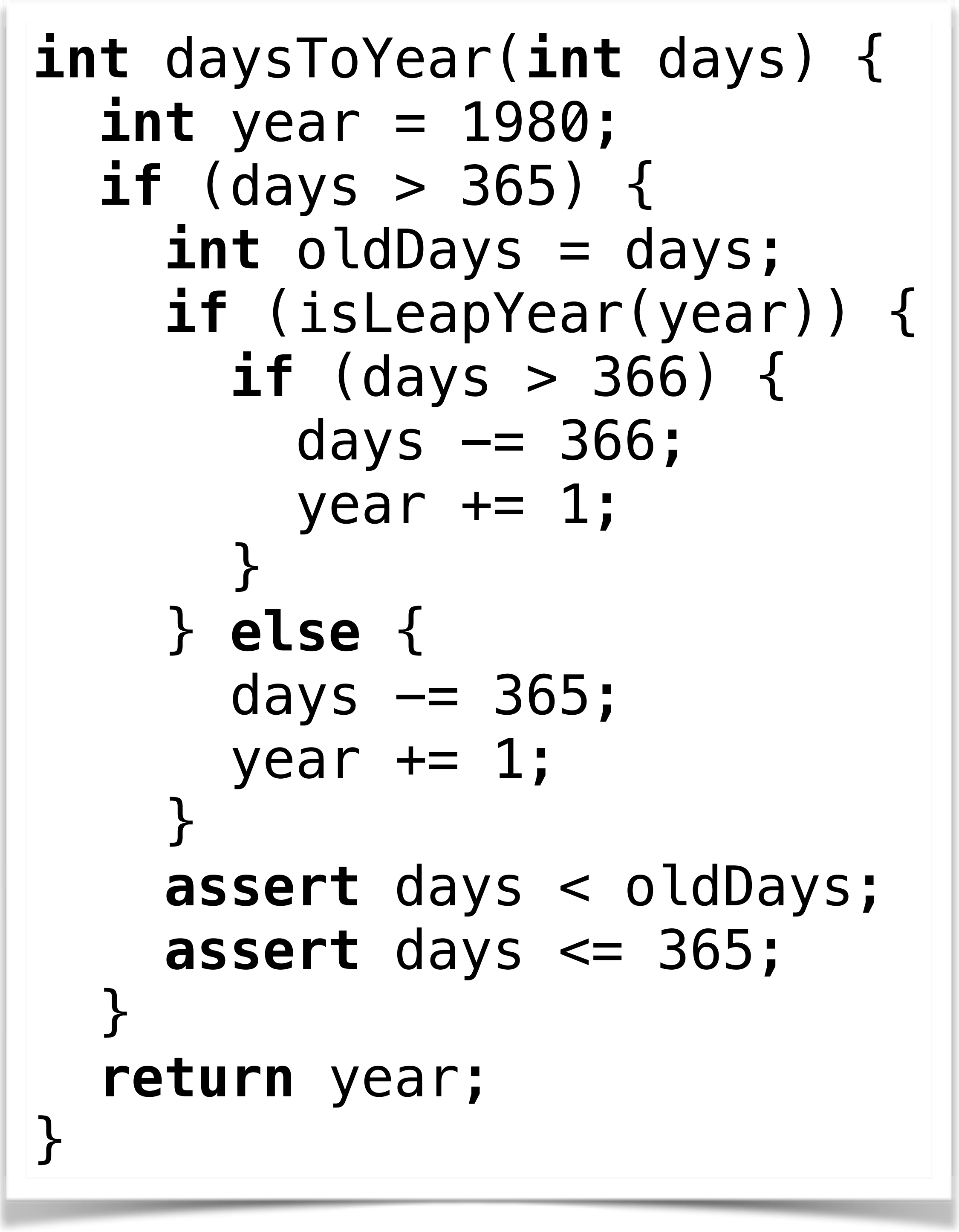
BMC step 1 of 4: finitize loops & inline calls



```
int daysToYear(int days) {
  int year = 1980;
  if (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
    assert days <= 365;
  }
  return year;
}
```

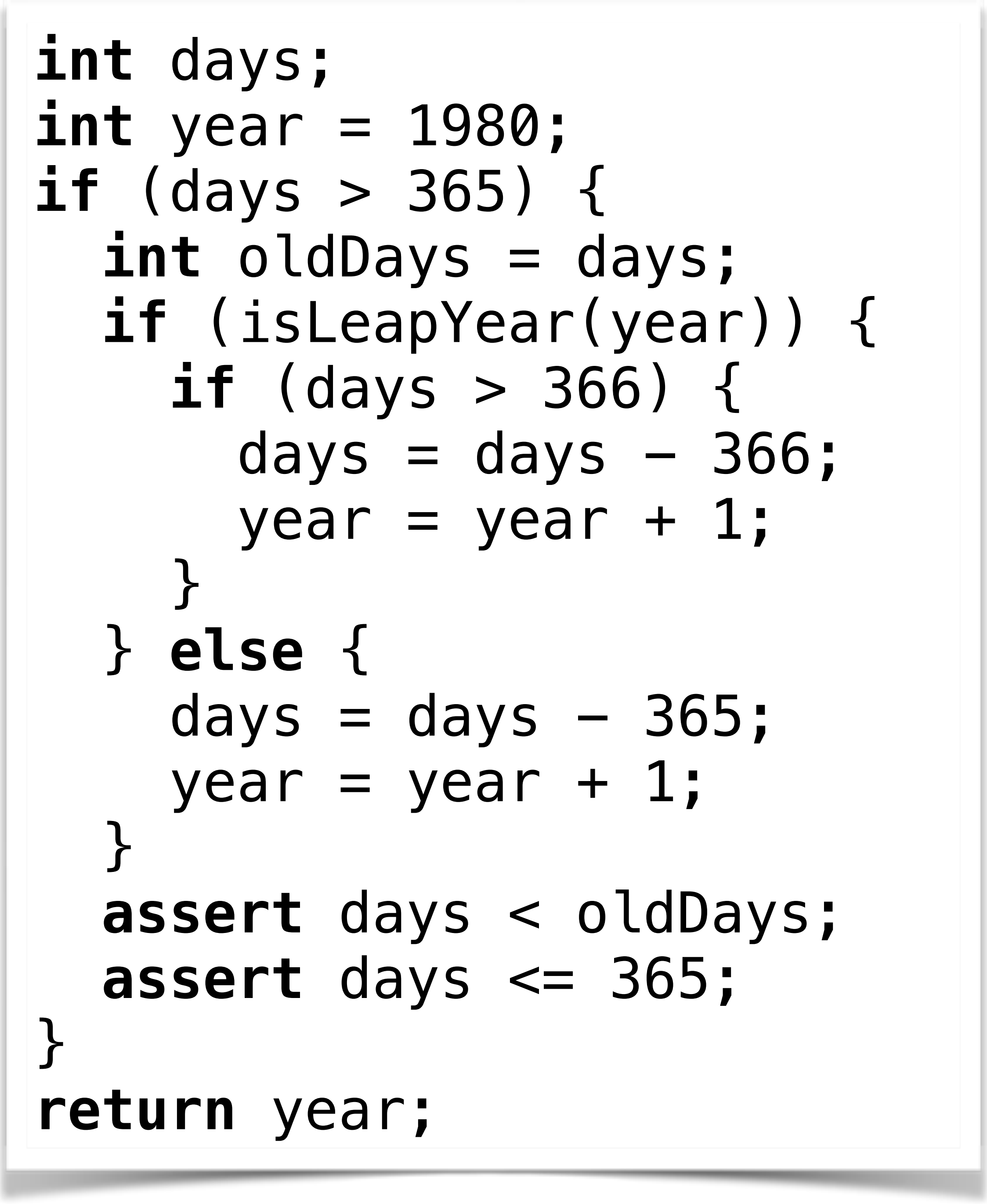
Assume call to isLeapYear is inlined (replaced with the procedure body). We’ll keep it for readability.

BMC step 2 of 4: eliminate side effects



```
int daysToYear(int days) {
  int year = 1980;
  if (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
    assert days <= 365;
  }
  return year;
}
```

BMC step 2 of 4: eliminate side effects



```
int days;
int year = 1980;
if (days > 365) {
  int oldDays = days;
  if (isLeapYear(year)) {
    if (days > 366) {
      days = days - 366;
      year = year + 1;
    }
  } else {
    days = days - 365;
    year = year + 1;
  }
  assert days < oldDays;
  assert days <= 365;
}
return year;
```

BMC step 2 of 4: eliminate side effects

```
int days;
int year = 1980;
if (days > 365) {
  int oldDays = days;
  if (isLeapYear(year)) {
    if (days > 366) {
      days = days - 366;
      year = year + 1;
    }
  } else {
    days = days - 365;
    year = year + 1;
  }
  assert days < oldDays;
  assert days <= 365;
}
return year;
```

Convert to **Static Single Assignment** (SSA) form:

- Replace each assignment to a variable v with a definition of a fresh variable v_i.
- Change uses of variables so that they refer to the correct definition (version).
- Make conditional dependences explicit with gated φ nodes.

BMC step 2 of 4: eliminate side effects

```
int days0;
int year0 = 1980;
if (days0 > 365) {
  int oldDays0 = days0;
  if (isLeapYear(year0)) {
    if (days0 > 366) {
      days1 = days0 - 366;
      year1 = year0 + 1;
    }
  } else {
    days3 = days0 - 365;
    year3 = year0 + 1;
  }
  assert days4 < oldDays0;
  assert days4 <= 365;
}
return year5;
```

Convert to **Static Single Assignment** (SSA) form:

- Replace each assignment to a variable v with a definition of a fresh variable v_i.
- Change uses of variables so that they refer to the correct definition (version).
- Make conditional dependences explicit with gated φ nodes.

BMC step 2 of 4: eliminate side effects

```
int days0;
int year0 = 1980;
boolean g0 = (days0 > 365);
int oldDays0 = days0;
boolean g1 = isLeapYear(year0);
boolean g2 = days0 > 366;
days1 = days0 - 366;
year1 = year0 + 1;
days2 = φ(g1 && g2, days1, days0);
year2 = φ(g1 && g2, year1, year0);
days3 = days0 - 365;
year3 = year0 + 1;
days4 = φ(g1, days2, days3);
year4 = φ(g1, year2, year3);
assert days4 < oldDays0;
assert days4 <= 365;
year5 = φ(g0, year4, year0);
return year5;
```

Convert to **Static Single Assignment** (SSA) form:

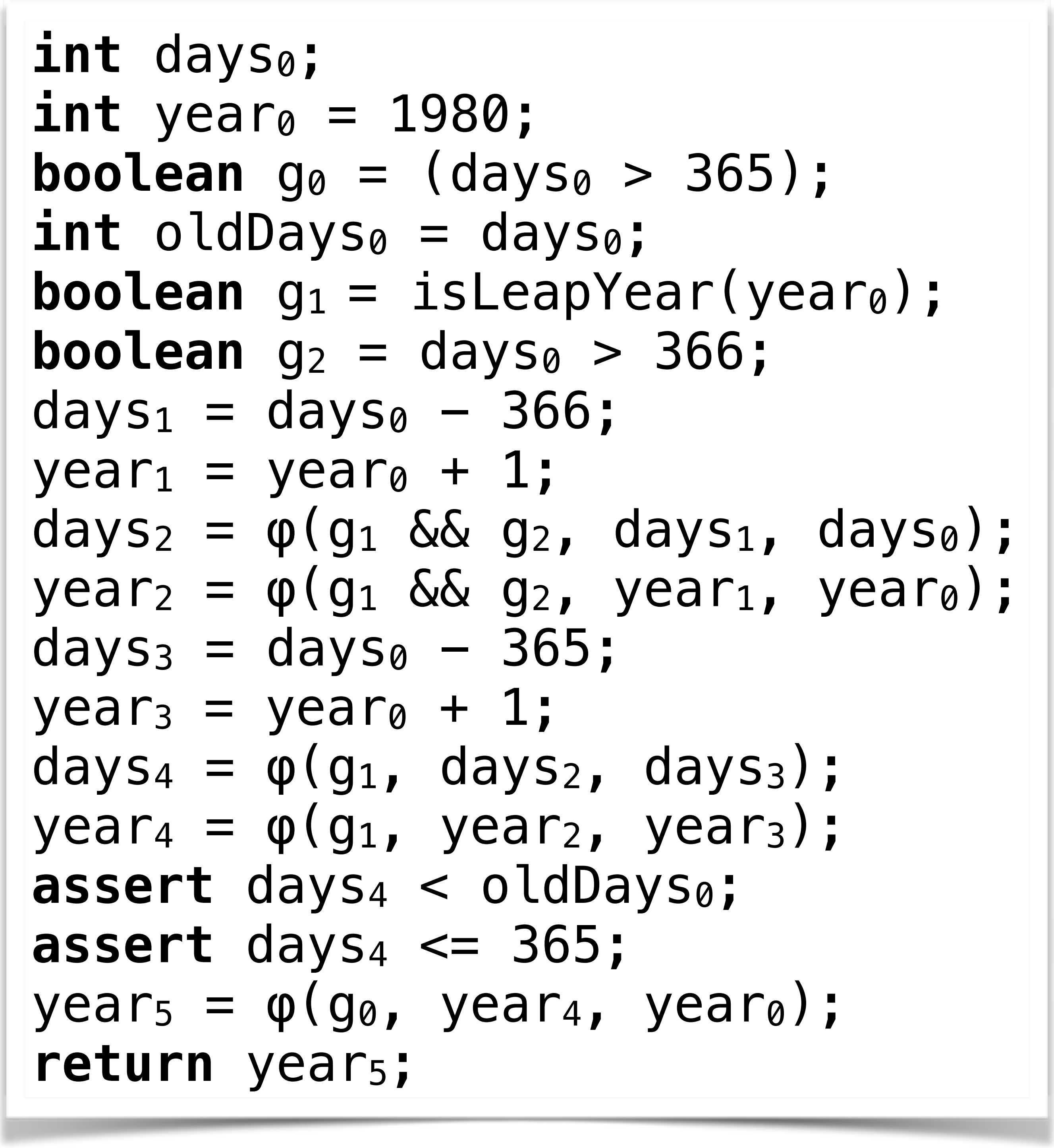
- Replace each assignment to a variable v with a definition of a fresh variable v_i.
- Change uses of variables so that they refer to the correct definition (version).
- Make conditional dependences explicit with gated φ nodes.

BMC step 2 of 4: eliminate side effects

```
int days₀;
int year₀ = 1980;
if (days₀ > 365) {
  int oldDays₀ = days₀;
  if (isLeapYear(year₀)) {
    if (days₀ > 366) {
      days₁ = days₀ − 366;
      year₁ = year₀ + 1;
    }
  } else {
    days₃ = days₀ − 365;
    year₃ = year₀ + 1;
  }
  assert days₄ < oldDays₀;
  assert days₄ <= 365;
}
return year₄;
```

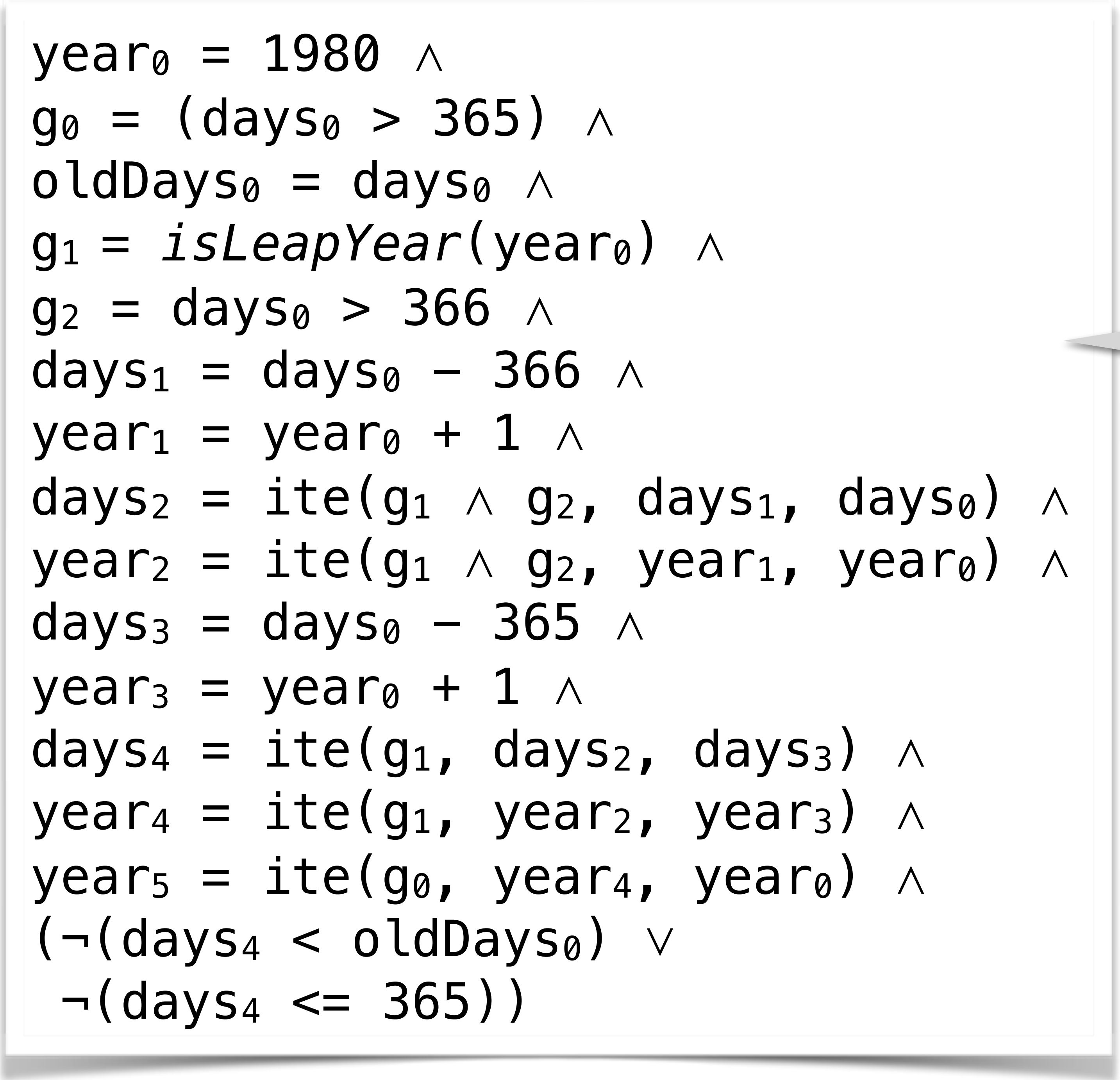
```
int days₀;
int year₀ = 1980;
boolean g₀ = (days₀ > 365);
int oldDays₀ = days₀;
boolean g₁ = isLeapYear(year₀);
boolean g₂ = days₀ > 366;
days₁ = days₀ − 366;
year₁ = year₀ + 1;
days₂ = φ(g₁ && g₂, days₁, days₀);
year₂ = φ(g₁ && g₂, year₁, year₀);
days₃ = days₀ − 365;
year₃ = year₀ + 1;
days₄ = φ(g₁, days₂, days₃);
year₄ = φ(g₁, year₂, year₃);
assert days₄ < oldDays₀;
assert days₄ <= 365;
year₅ = φ(g₀, year₄, year₀);
return year₅;
```

BMC step 3 of 4: convert into equations



```
int days_0;
int year_0 = 1980;
boolean g_0 = (days_0 > 365);
int oldDays_0 = days_0;
boolean g_1 = isLeapYear(year_0);
boolean g_2 = days_0 > 366;
days_1 = days_0 - 366;
year_1 = year_0 + 1;
days_2 = φ(g_1 && g_2, days_1, days_0);
year_2 = φ(g_1 && g_2, year_1, year_0);
days_3 = days_0 - 365;
year_3 = year_0 + 1;
days_4 = φ(g_1, days_2, days_3);
year_4 = φ(g_1, year_2, year_3);
assert days_4 < oldDays_0;
assert days_4 <= 365;
year_5 = φ(g_0, year_4, year_0);
return year_5;
```

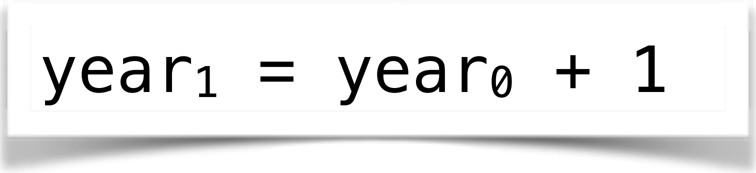
BMC step 3 of 4: convert into equations



$$
\begin{array}{l}
\mathtt{year}_0 = 1980 \land \\
\mathtt{g}_0 = (\mathtt{days}_0 > 365) \land \\
\mathtt{oldDays}_0 = \mathtt{days}_0 \land \\
\mathtt{g}_1 = \mathit{isLeapYear}(\mathtt{year}_0) \land \\
\mathtt{g}_2 = \mathtt{days}_0 > 366 \land \\
\mathtt{days}_1 = \mathtt{days}_0 - 366 \land \\
\mathtt{year}_1 = \mathtt{year}_0 + 1 \land \\
\mathtt{days}_2 = \mathtt{ite}(\mathtt{g}_1 \land \mathtt{g}_2, \mathtt{days}_1, \mathtt{days}_0) \land \\
\mathtt{year}_2 = \mathtt{ite}(\mathtt{g}_1 \land \mathtt{g}_2, \mathtt{year}_1, \mathtt{year}_0) \land \\
\mathtt{days}_3 = \mathtt{days}_0 - 365 \land \\
\mathtt{year}_3 = \mathtt{year}_0 + 1 \land \\
\mathtt{days}_4 = \mathtt{ite}(\mathtt{g}_1, \mathtt{days}_2, \mathtt{days}_3) \land \\
\mathtt{year}_4 = \mathtt{ite}(\mathtt{g}_1, \mathtt{year}_2, \mathtt{year}_3) \land \\
\mathtt{year}_5 = \mathtt{ite}(\mathtt{g}_0, \mathtt{year}_4, \mathtt{year}_0) \land \\
(\neg(\mathtt{days}_4 < \mathtt{oldDays}_0) \lor \\
\ \neg(\mathtt{days}_4 <= 365))
\end{array}
$$

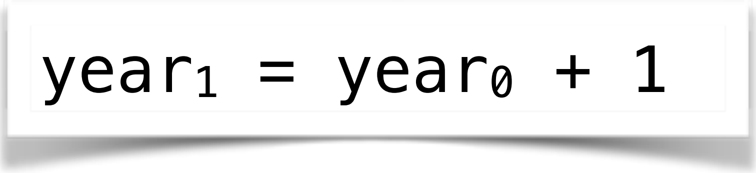
A solution to these equations is a sound **counterexample**: an interpretation for all logical variables that satisfies the program semantics (for up to k unwindings) but violates at least one of the assertions.

BMC step 4 of 4: convert into CNF



$\texttt{year}_1 = \texttt{year}_0 + 1$

BMC step 4 of 4: convert into CNF



```
year₁ = year₀ + 1
```

$$\text{year}_0 = \underset{31}{0}\underset{30}{0}\underset{29}{0} \ldots \underset{2}{0}\underset{1}{0}\underset{0}{0}$$

Represent numbers as arrays of bits …

BMC step 4 of 4: convert into CNF

$year_1 = year_0 + 1$

$$year_0 = \underset{31}{0}\underset{30}{0}\underset{29}{0} \ldots \underset{2}{0}\underset{1}{0}\underset{0}{0}$$

Represent numbers as arrays of bits, and create one propositional variable per bit for each number.

$year_{0:31}$

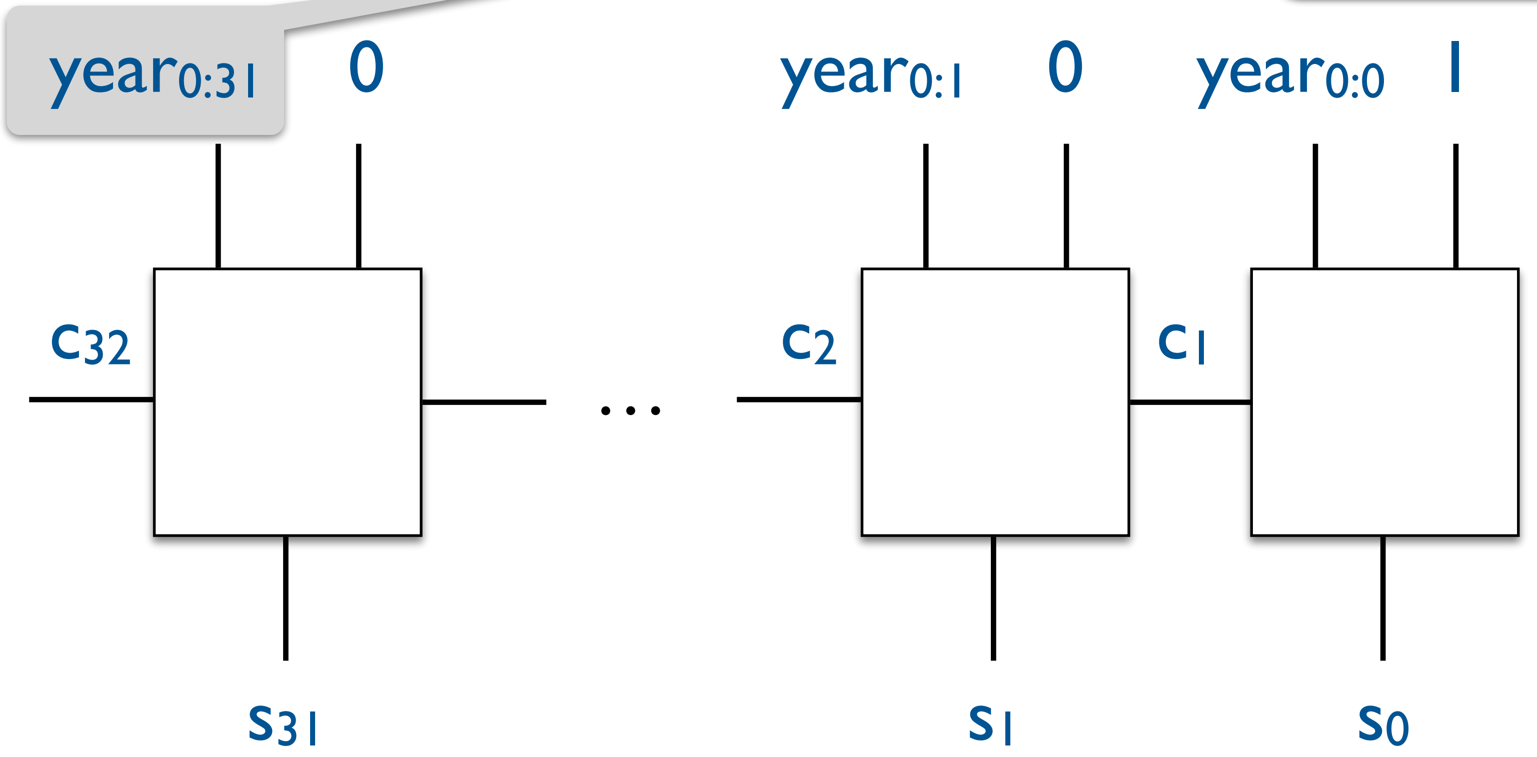
BMC step 4 of 4: convert into CNF

$year_1 = year_0 + 1$

$year_0$ = 000 … 000

31 30 29 2 1 0

Represent numbers as arrays of bits, and create one propositional variable per bit for each number.



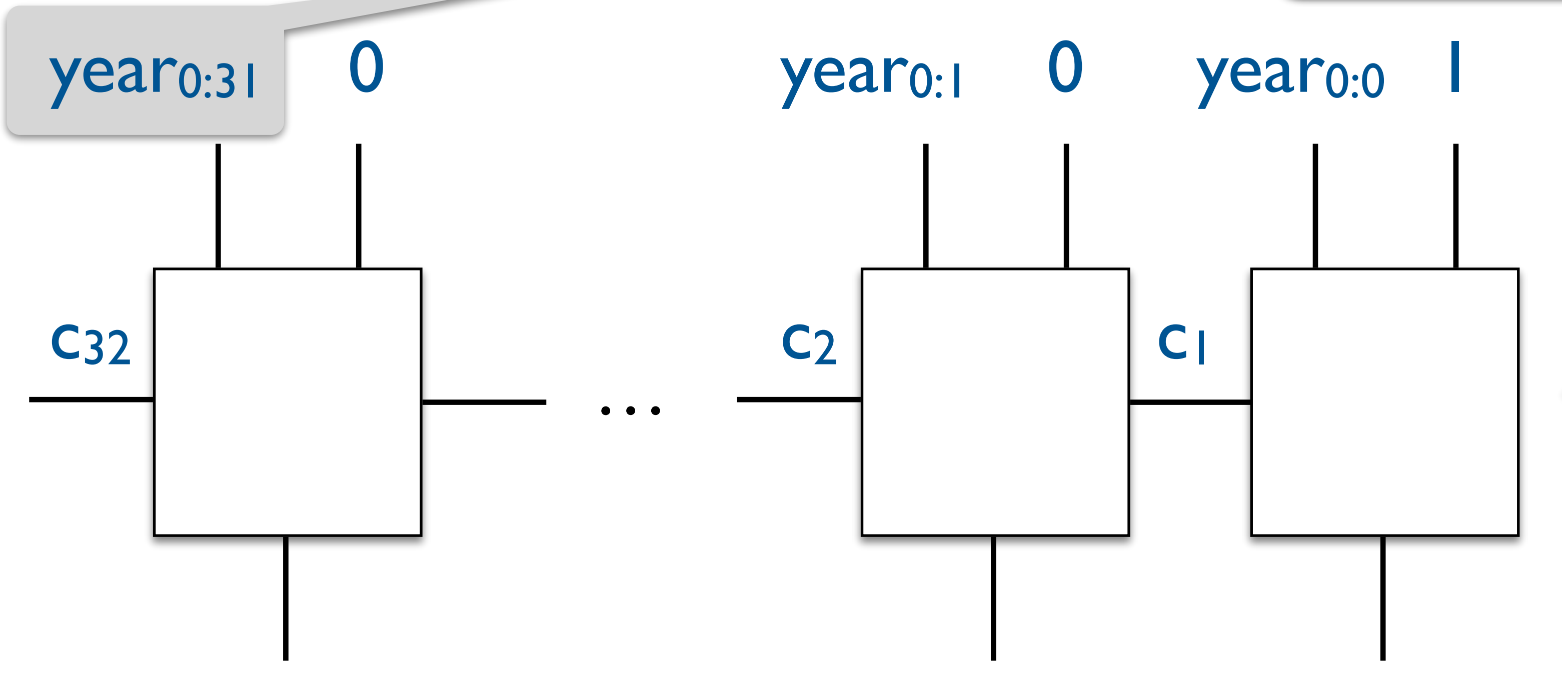
Construct an adder circuit for $year_0 + 1$.

BMC step 4 of 4: convert into CNF

```
year₁ = year₀ + 1
```

$$year_0 = \underset{31}{0}\underset{30}{0}\underset{29}{0} \ldots \underset{2}{0}\underset{1}{0}\underset{0}{0}$$

Represent numbers as arrays of bits, and create one propositional variable per bit for each number.

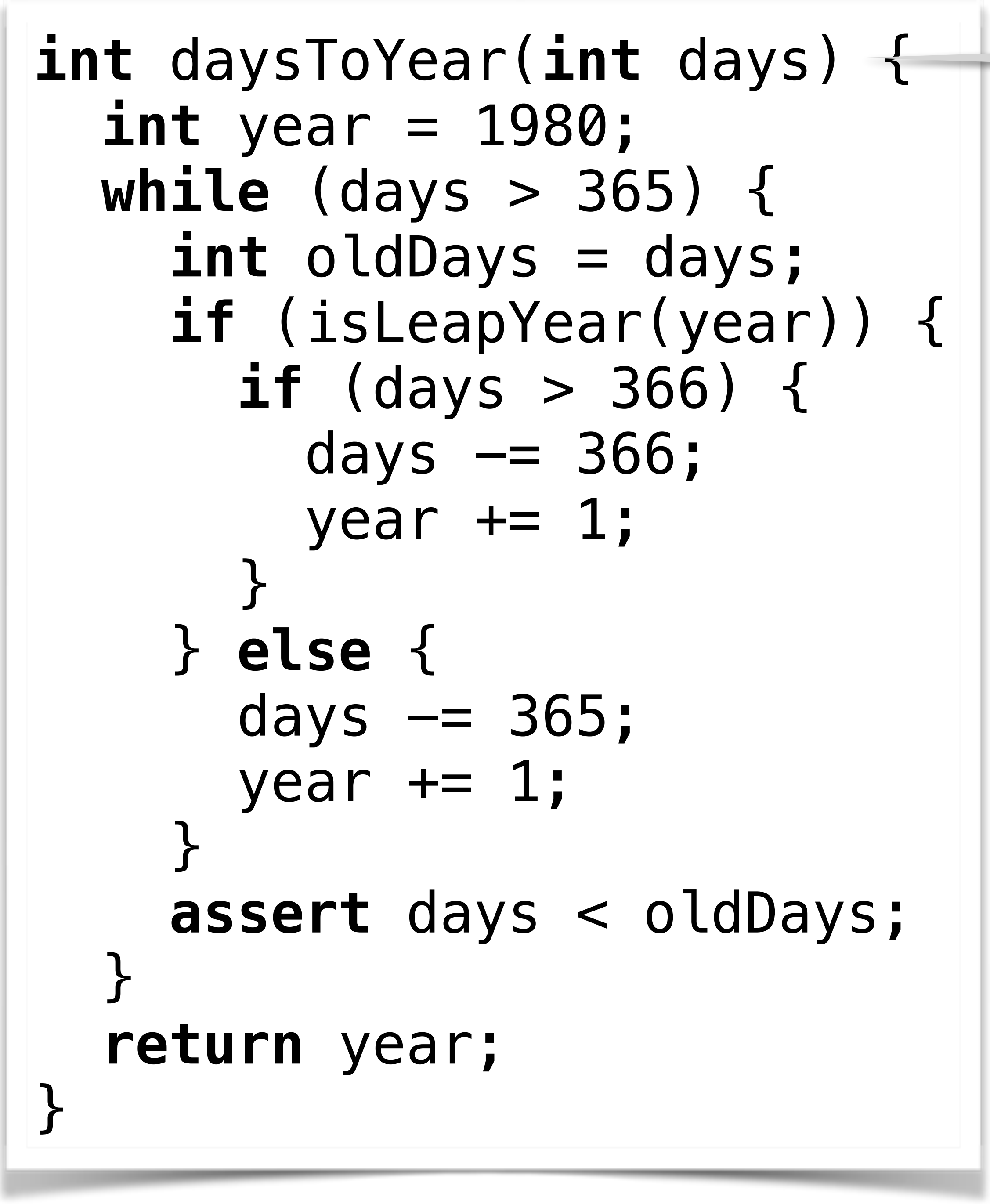


Construct an adder circuit for $year_0 + 1$.

$$year_{1:31} \iff s_{31} \land \ldots \land year_{1:1} \iff s_1 \quad \land \quad s_0 \iff year_{1:0}$$

Introduce new clauses to constrain bits in $year_1$ to match bits in the sum.

BMC counterexample for k=1



```
int daysToYear(int days) {
  int year = 1980;
  while (days > 365) {
    int oldDays = days;
    if (isLeapYear(year)) {
      if (days > 366) {
        days -= 366;
        year += 1;
      }
    } else {
      days -= 365;
      year += 1;
    }
    assert days < oldDays;
  }
  return year;
}
```

days = 366

today

Bounded Model Checking (BMC) & Configuration Management

Configuration Management

Given a configuration, consisting of a set of components, their dependencies, and conflicts:

- Decide if a new component can be added to the configuration.
- Add the component while optimizing some linear function.
- If the component cannot be added, find a way to add it by removing as few conflicting components from the current configuration as possible.

Configuration Management

Given a configuration, consisting of a set of components, their dependencies, and conflicts:

- Decide if a new component can be added to the configuration.
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SAT

maven

eclipse

SuSE

Configuration Management

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SAT

Pseudo-Boolean Constraints

Configuration Management

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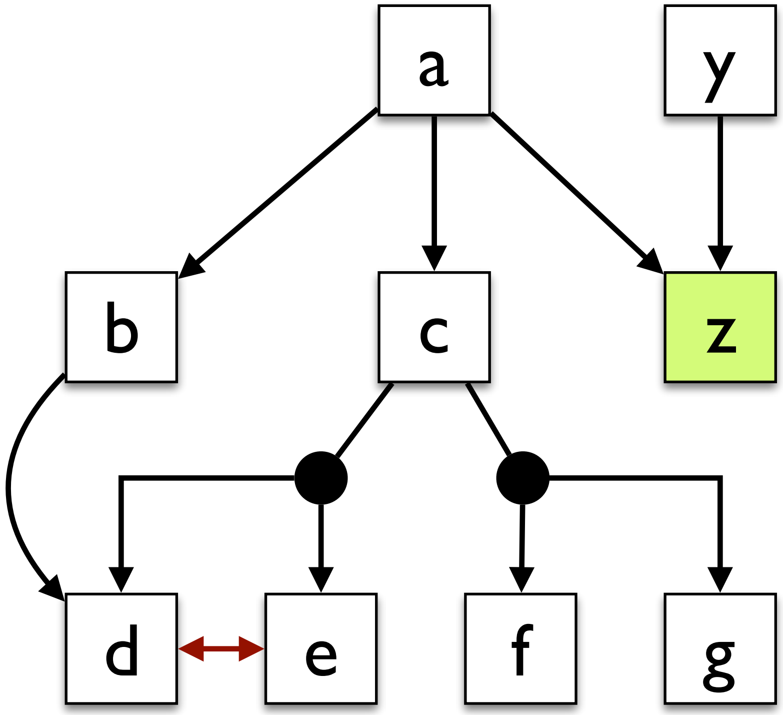
SAT

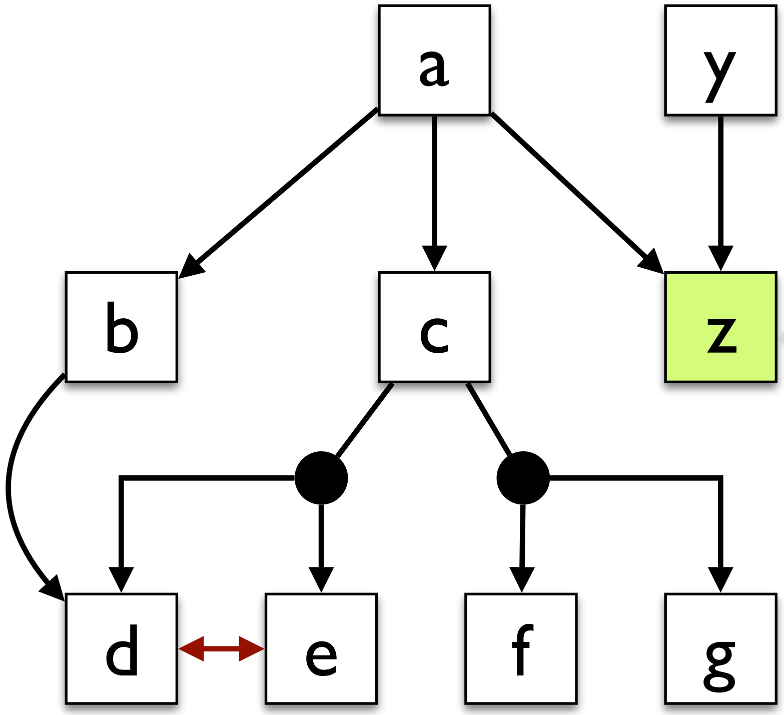
Pseudo-Boolean Constraints

Partial (Weighted) MaxSAT

Deciding if a component can be installed

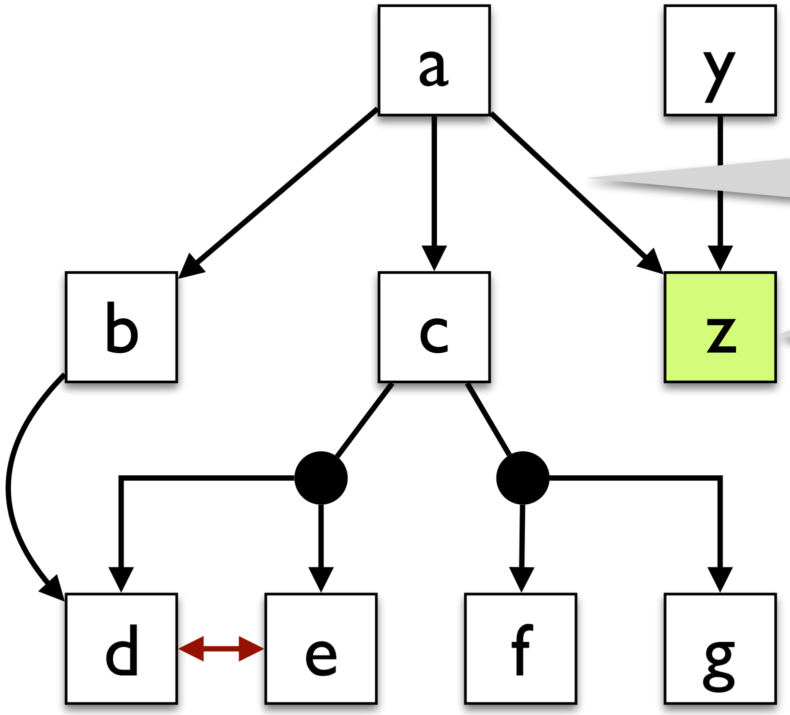


Deciding if a component can be installed



z already installed.

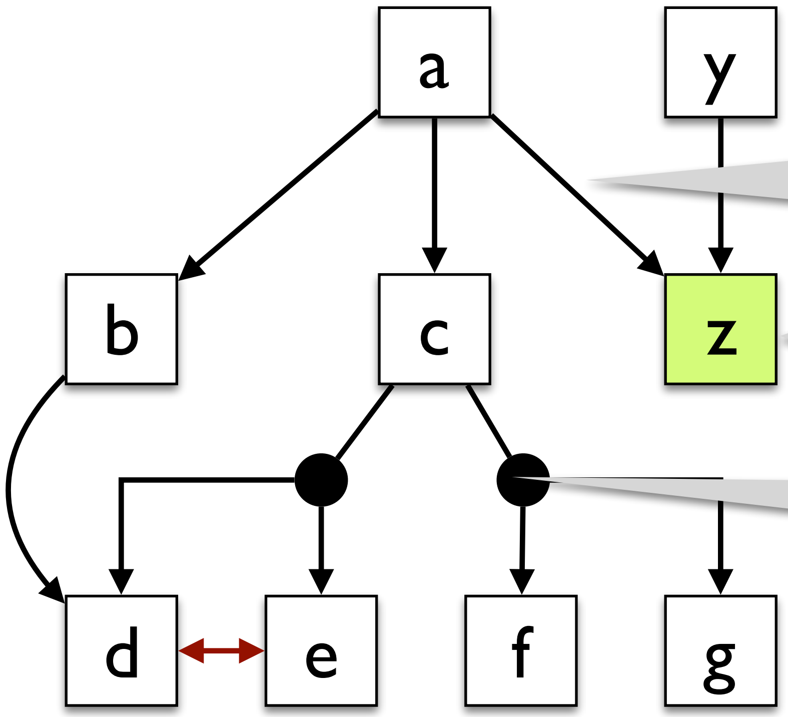
Deciding if a component can be installed



a depends on b, c, z.

z already installed.

Deciding if a component can be installed

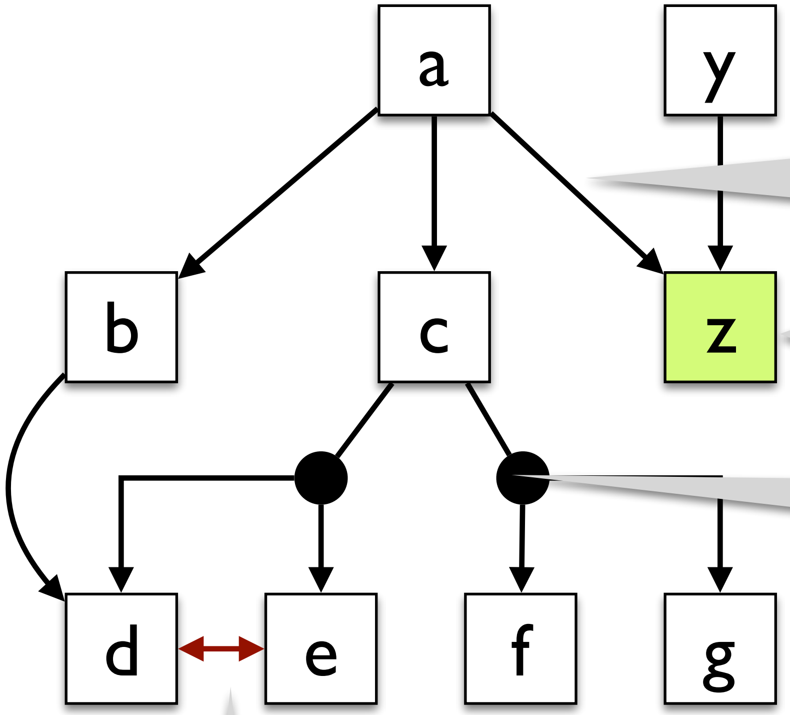


a depends on b, c, z.

z already installed.

c needs f or g.

Deciding if a component can be installed



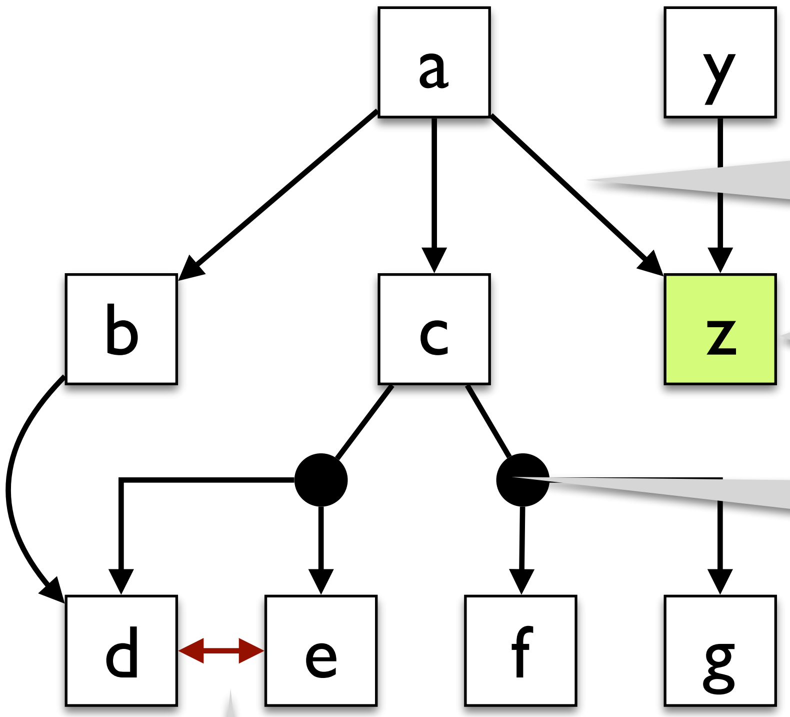
a depends on b, c, z.

z already installed.

c needs f or g.

Conflict: d and e cannot both be installed.

Deciding if a component can be installed



a depends on b, c, z.

z already installed.

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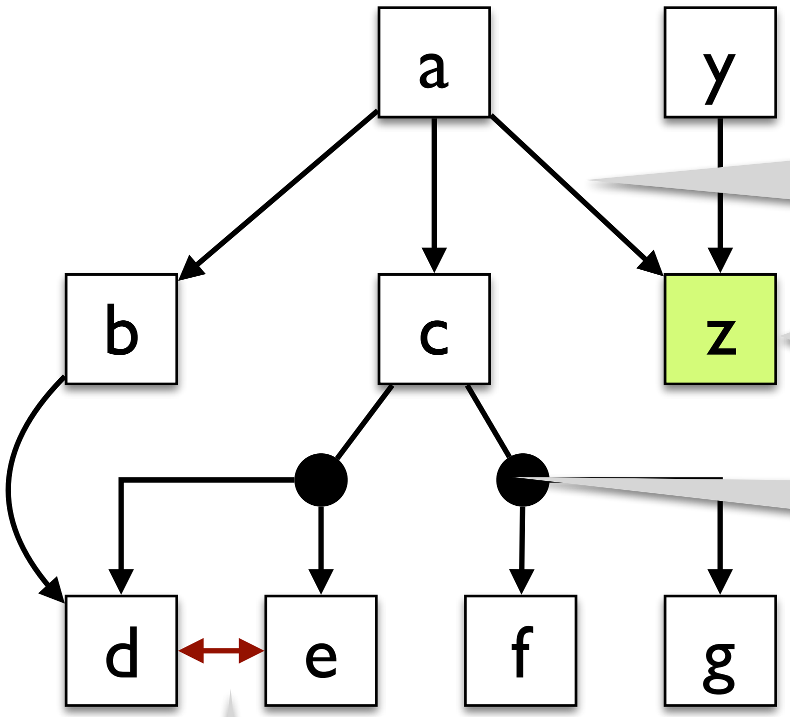
Conflict: d and e cannot both be installed.

To install a, CNF constraints are:

Deciding if a component can be installed



a depends on b, c, z.

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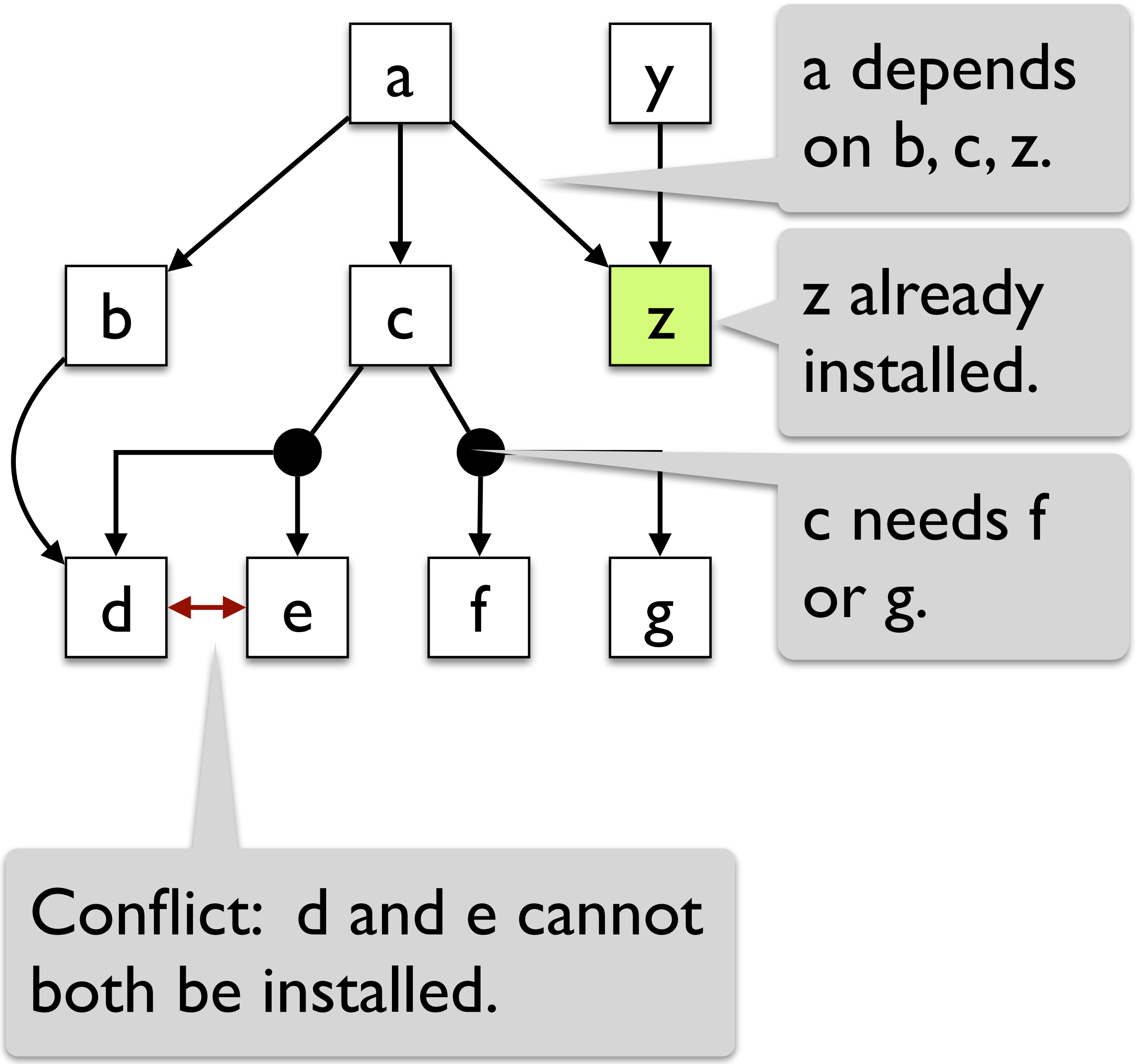
Conflict: d and e cannot both be installed.

To install a, CNF constraints are:

$(\neg a \vee b) \wedge (\neg a \vee c) \wedge (\neg a \vee z) \wedge$

Deciding if a component can be installed



a depends on b, c, z.

z already installed.

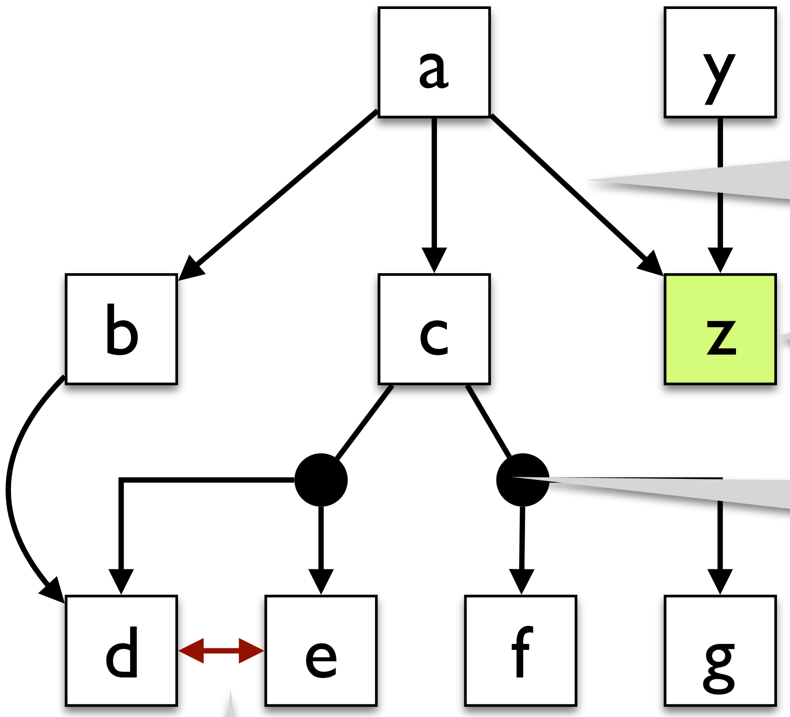
c needs f or g.

Conflict: d and e cannot both be installed.

To install a, CNF constraints are:

$(\neg a \lor b) \land (\neg a \lor c) \land (\neg a \lor z) \land$
$(\neg b \lor d) \land$

Deciding if a component can be installed



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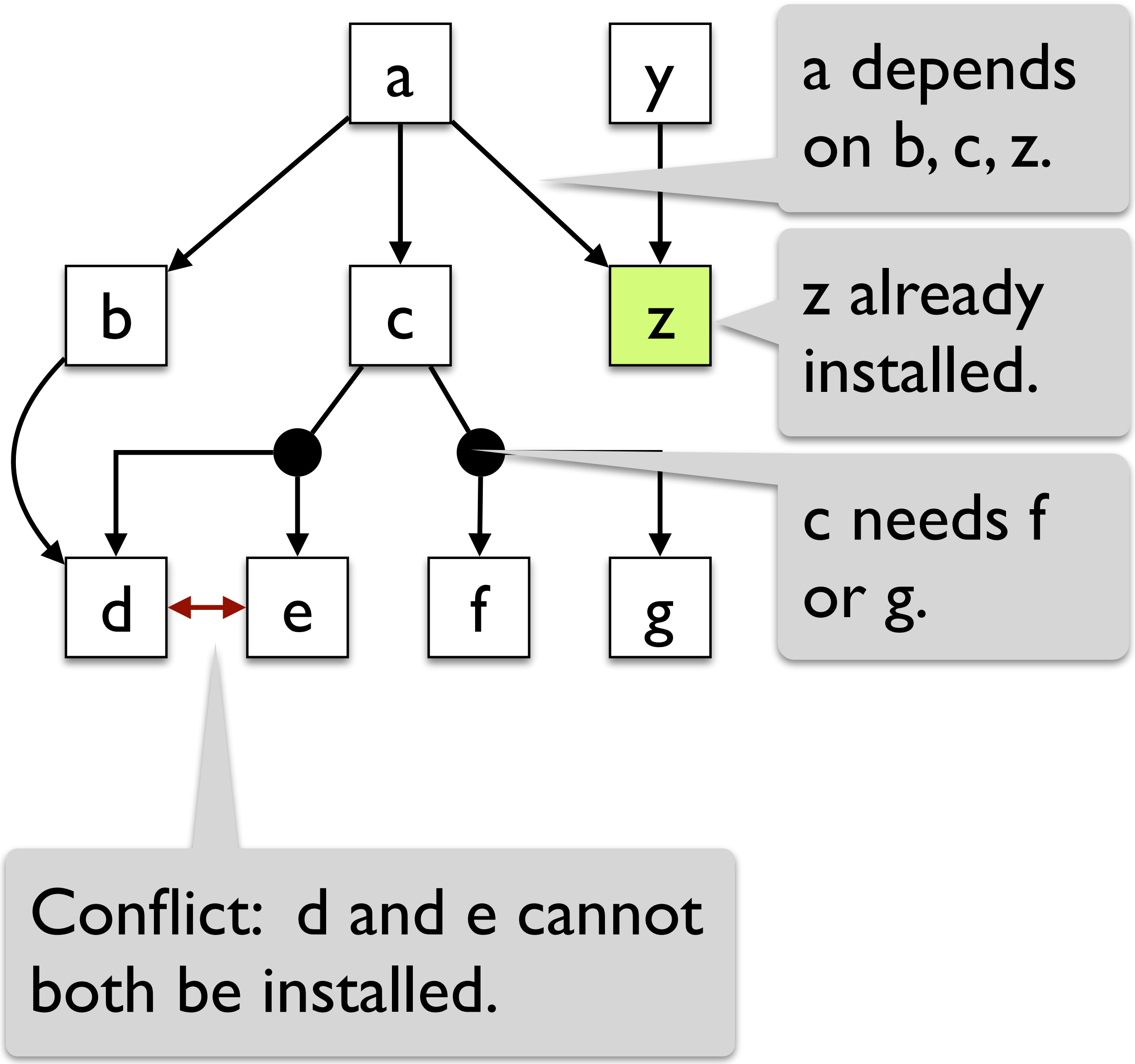
Conflict: d and e cannot both be installed.

To install a, CNF constraints are:

$(\neg a \lor b) \land (\neg a \lor c) \land (\neg a \lor z) \land$
$(\neg b \lor d) \land$
$(\neg c \lor d \lor e) \land (\neg c \lor f \lor g) \land$

Deciding if a component can be installed



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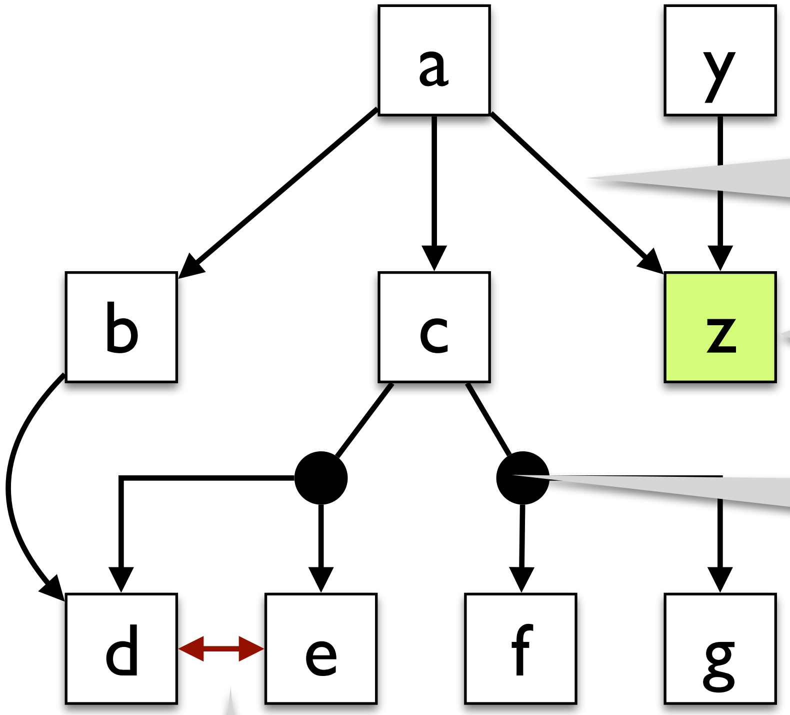
Conflict: d and e cannot both be installed.

To install a, CNF constraints are:

$(\neg a \lor b) \land (\neg a \lor c) \land (\neg a \lor z) \land$
$(\neg b \lor d) \land$
$(\neg c \lor d \lor e) \land (\neg c \lor f \lor g) \land$
$(\neg d \lor \neg e) \land$

Deciding if a component can be installed



a depends on b, c, z.

z already installed.

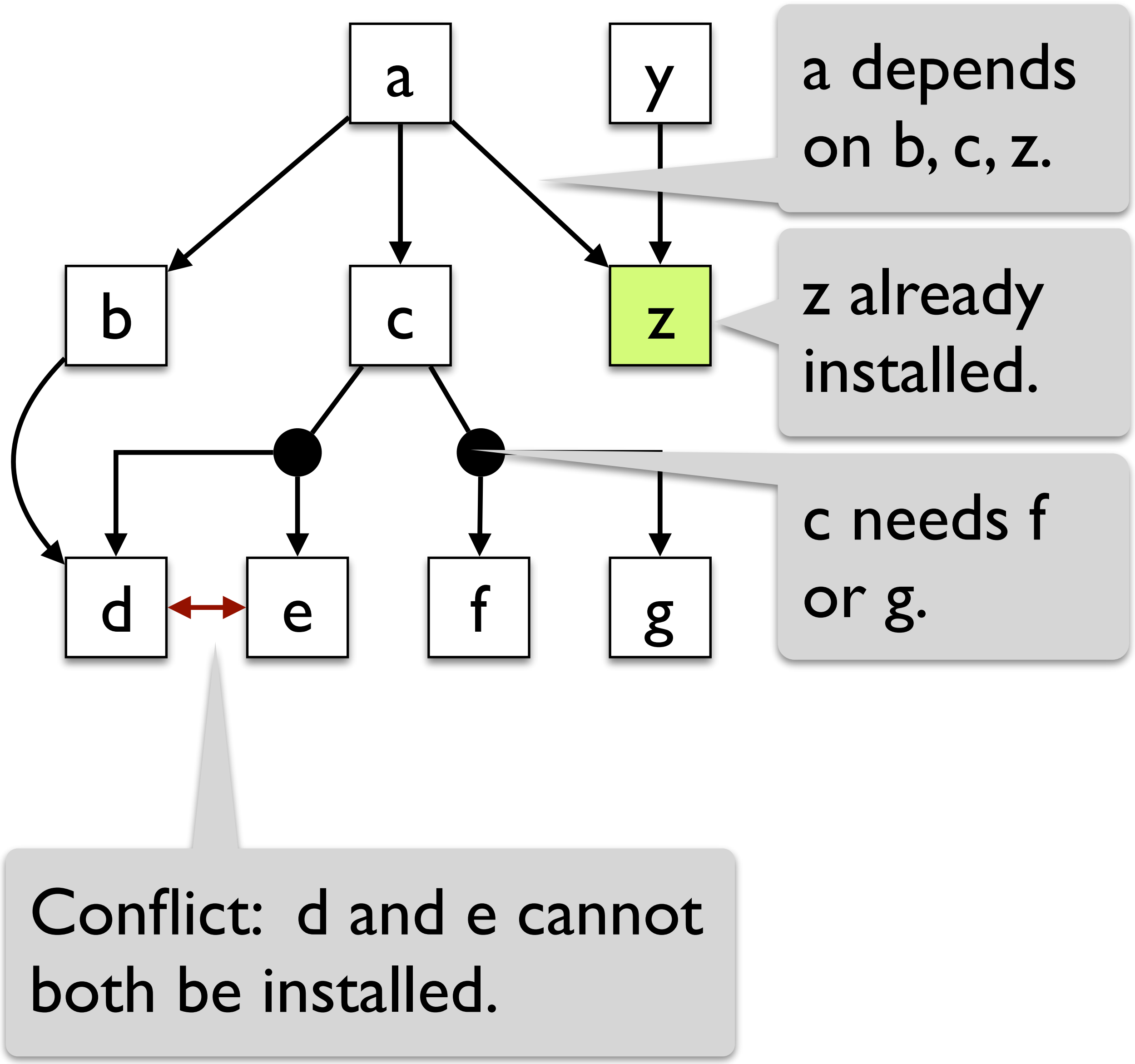
c needs f or g.

Conflict: d and e cannot both be installed.

To install a, CNF constraints are:

$(\neg a \vee b) \wedge (\neg a \vee c) \wedge (\neg a \vee z) \wedge$
$(\neg b \vee d) \wedge$
$(\neg c \vee d \vee e) \wedge (\neg c \vee f \vee g) \wedge$
$(\neg d \vee \neg e) \wedge$
$(\neg y \vee z) \wedge$

Deciding if a component can be installed



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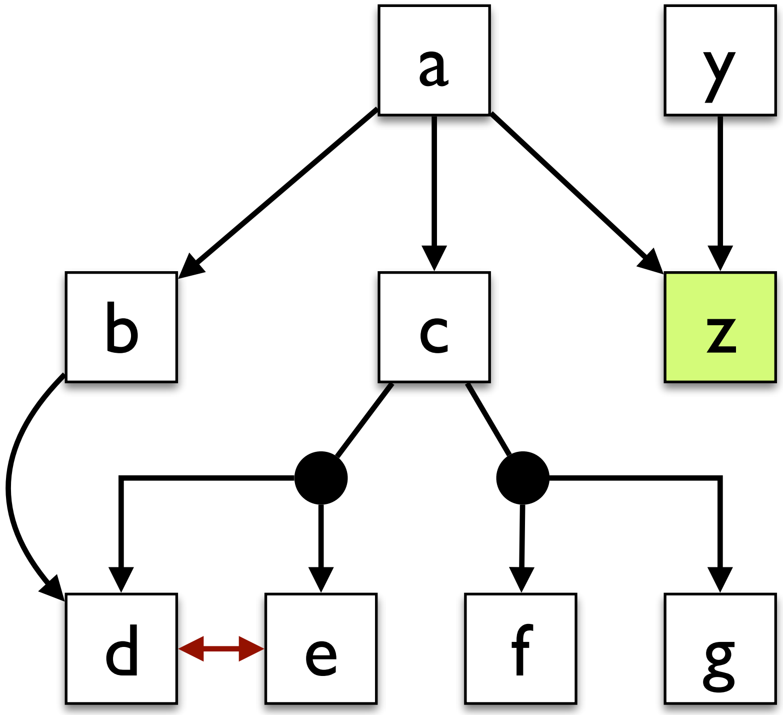
c needs f or g.

Conflict: d and e cannot both be installed.

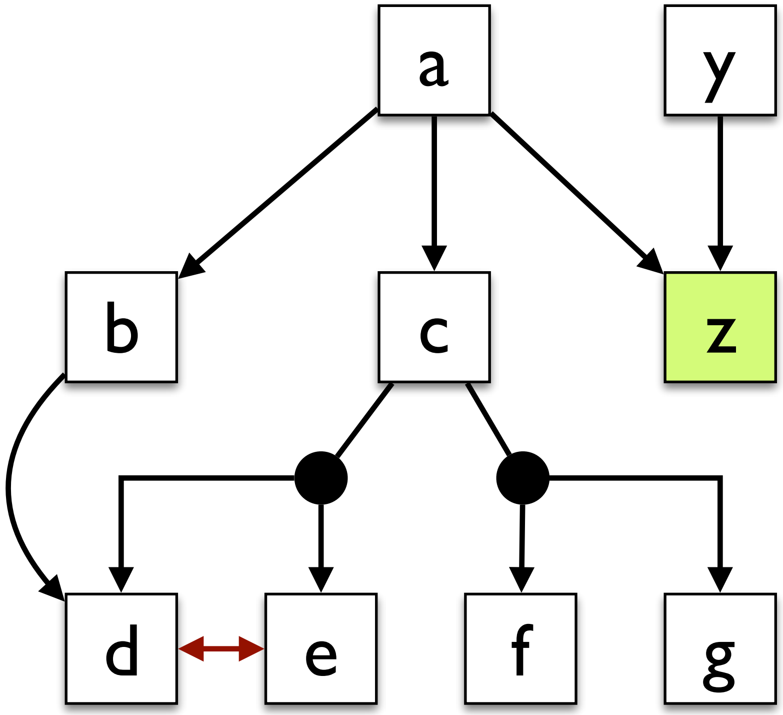
To install a, CNF constraints are:

$$(\neg a \vee b) \wedge (\neg a \vee c) \wedge (\neg a \vee z) \wedge$$
$$(\neg b \vee d) \wedge$$
$$(\neg c \vee d \vee e) \wedge (\neg c \vee f \vee g) \wedge$$
$$(\neg d \vee \neg e) \wedge$$
$$(\neg y \vee z) \wedge$$
$$a \wedge z$$

Optimal installation



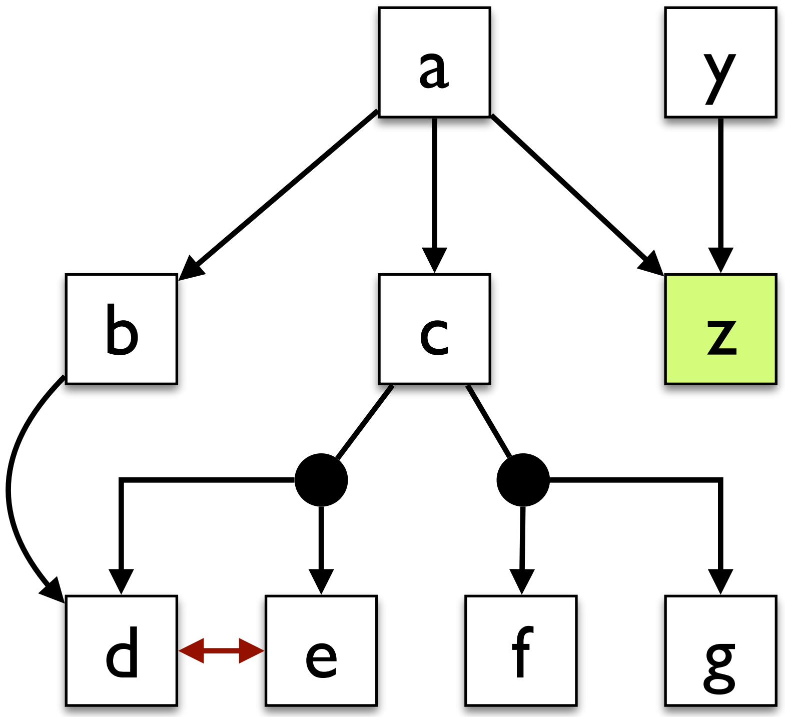
Optimal installation



Assume f and g are 5MB and 2MB each, and all other components are 1MB. To install a, while minimizing total size, pseudo-boolean constraints are:

Pseudo-boolean solvers accept a linear function to minimize, in addition to a (weighted) CNF.

Optimal installation



Assume f and g are 5MB and 2MB each, and all other components are 1MB. To install a, while minimizing total size, pseudo-boolean constraints are:

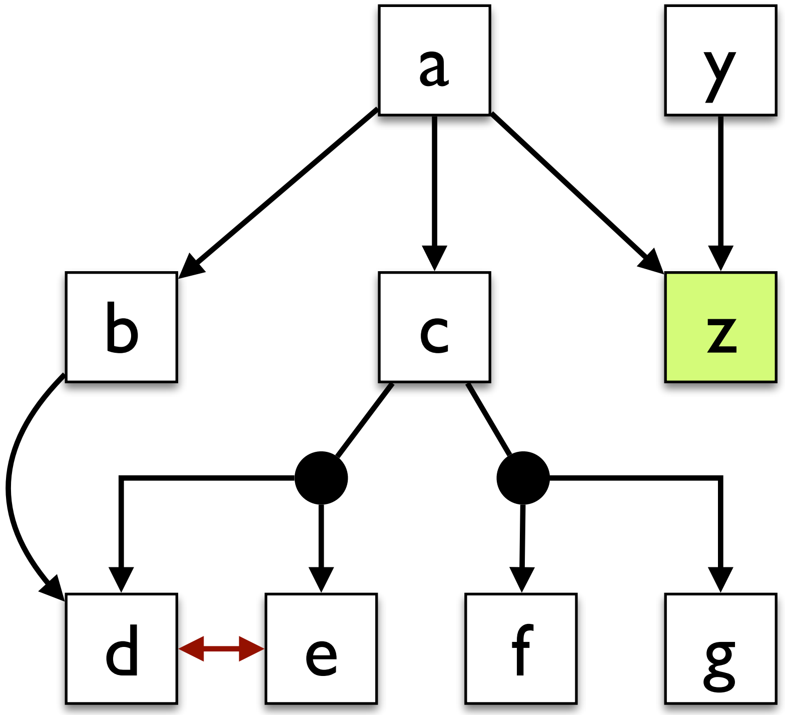
min $c_1x_1 + \ldots + c_nx_n$

$a_{11}x_1 + \ldots + a_{1n}x_n \geq b_1$

$\ldots$

$a_{k1}x_1 + \ldots + a_{kn}x_n \geq b_k$

Optimal installation



min $c_1x_1 + \ldots + c_nx_n$

$a_{11}x_1 + \ldots + a_{1n}x_n \geq b_1$

…

$a_{k1}x_1 + \ldots + a_{kn}x_n \geq b_k$

Assume f and g are 5MB and 2MB each, and all other components are 1MB. To install a, while minimizing total size, pseudo-boolean constraints are:

min $a + b + c + d + e + 5f + 2g + y + 0z$

$(-a + b \geq 0) \wedge (-a + c \geq 0) \wedge (-a + z \geq 0) \wedge$

$(-b + d \geq 0) \wedge$

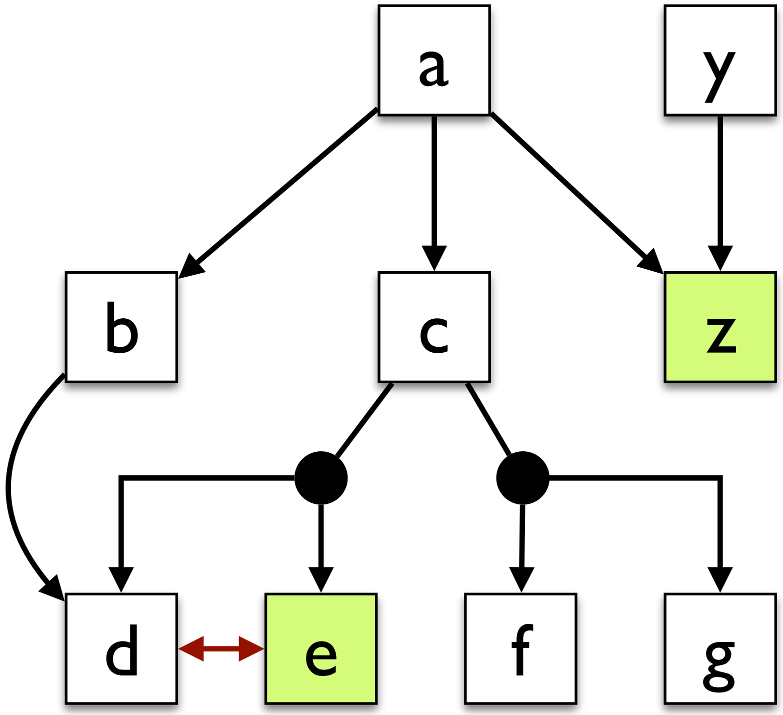
$(-c + d + e \geq 0) \wedge (-c + f + g \geq 0) \wedge$

$(-d + -e \geq -1) \wedge$

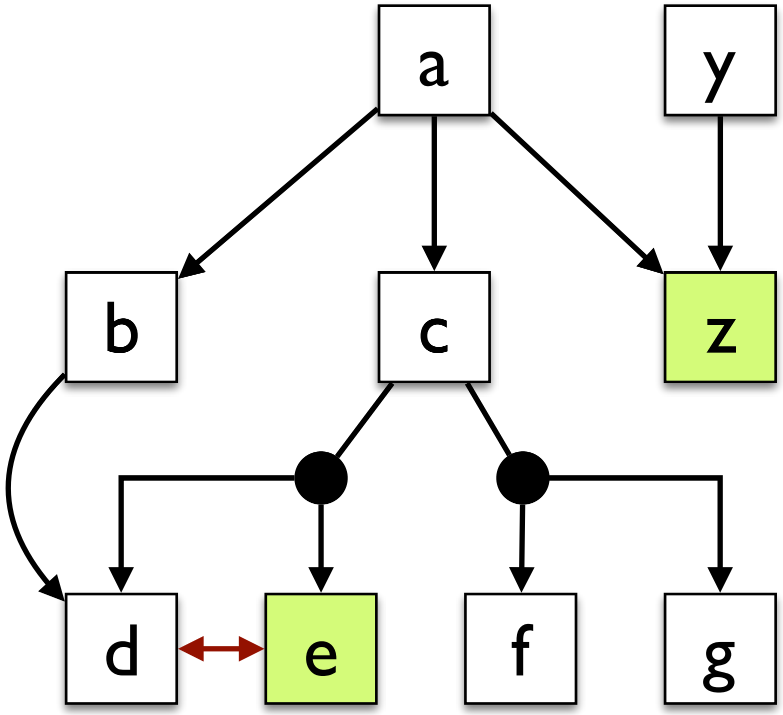
$(-y + z \geq 0) \wedge$

$(a \geq 1) \wedge (z \geq 1)$

Installation in the presence of conflicts

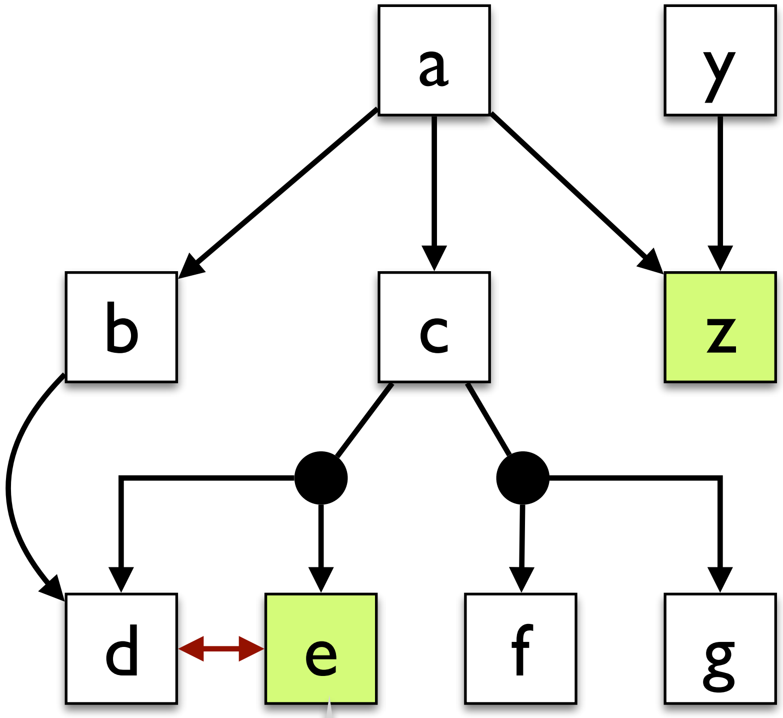


Installation in the presence of conflicts



a cannot be installed because it requires b, which requires d, which conflicts with e.

Installation in the presence of conflicts



To install a, while minimizing the number of removed components, Partial MaxSAT constraints are:

hard: (¬a ∨ b) ∧ (¬a ∨ c) ∧ (¬a ∨ z) ∧
(¬b ∨ d) ∧
(¬c ∨ d ∨ e) ∧ (¬c ∨ f ∨ g) ∧
(¬d ∨ ¬e) ∧ (¬y ∨ z) ∧ a

soft: e ∧ z

Partial MaxSAT solver takes as input a set of **hard** clauses and a set of **soft** clauses, and it produces an assignment that satisfies all hard clauses and the greatest number of soft clauses.

Summary

Today

- SAT solvers have been used successfully in many applications & domains
- But reducing problems to SAT is a lot like programming in assembly …
- We need higher-level logics!

Next lecture

- On to richer logics: introduction to Satisfiability Modulo Theories (SMT)