Semantics and Verification of Software

Lecture 23: Dataflow Analysis VI (MOP vs. Fixpoint Solution & Wrap-Up)

Thomas Noll

Lehrstuhl für Informatik 2
(Software Modeling and Verification)

RWTH Aachen University

noll@cs.rwth-aachen.de

http://www-i2.informatik.rwth-aachen.de/i2/svsw10/

Summer Semester 2010

Outline

The MOP Solution I

- Other solution method for dataflow systems
- MOP = Meet Over all Paths
- Analysis information for block B^l = least upper bound over all paths leading to l

Definition (Paths)

Let $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ be a dataflow system. For every $l \in L$, the set of paths up to l is given by

$$Path(l) := \{[l_1, \ldots, l_{k-1}] \mid k \geq 1, l_1 \in E, \\ (l_i, l_{i+1}) \in F \text{ for every } 1 \leq i \leq k, l_k = l\}.$$

For a path $p = [l_1, \ldots, l_{k-1}] \in Path(l)$, we define the transfer function $\varphi_p : D \to D$ by

$$\varphi_p := \varphi_{l_{k-1}} \circ \ldots \circ \varphi_{l_1} \circ \mathsf{id}_D$$

(so that $\varphi_{[]} = \mathsf{id}_D$).

The MOP Solution II

Definition (MOP solution)

Let $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ be a dataflow system where $L = \{l_1, \ldots, l_n\}$. The MOP solution for S is determined by

$$\mathsf{mop}(S) := (\mathsf{mop}(l_1), \ldots, \mathsf{mop}(l_n)) \in D^n$$

where, for every $l \in L$,

$$\mathsf{mop}(l) := \bigsqcup \{\varphi_p(\iota) \mid p \in Path(l)\}.$$

Remark:

- $Path(l)$ is generally infinite

$\Longrightarrow$ not clear how to compute $\mathsf{mop}(l)$

- In fact: MOP solution generally undecidable

Undecidability of the MOP Solution

Theorem (Undecidability of MOP solution)

The MOP solution for Constant Propagation is undecidable.

Proof.

Based on undecidability of Modified Post Correspondence Problem:
Let Γ be some alphabet, $n \in \mathbb{N}$, and $u_1, \ldots, u_n, v_1, \ldots, v_n \in \Gamma^+$.
Does there exist $i_1, \ldots, i_m \in \{1, \ldots, n\}$ with $m \geq 1$ and $i_1 = 1$ such that $u_{i_1} u_{i_2} \ldots u_{i_m} = v_{i_1} v_{i_2} \ldots v_{i_m}$?

(on the board) □

Outline

Formalizing Constant Propagation Analysis I

The dataflow system $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ is given by

- set of labels $L := L_c$,
- extremal labels $E := \{\mathsf{init}(c)\}$ (forward problem),
- flow relation $F := \mathsf{flow}(c)$ (forward problem),
- complete lattice $(D, \sqsubseteq)$ where
  - $D := \{\delta \mid \delta : Var_c \to \mathbb{Z} \cup \{\bot, \top\}\}$
    - $\delta(x) = z \in \mathbb{Z}$: x has constant value z
    - $\delta(x) = \bot$: x undefined
    - $\delta(x) = \top$: x overdefined (i.e., different possible values)
  - $\sqsubseteq \subseteq D \times D$ defined by pointwise extension of $\bot \sqsubseteq z \sqsubseteq \top$ (for every $z \in \mathbb{Z}$)

Example

$Var_c = \{\mathtt{w}, \mathtt{x}, \mathtt{y}, \mathtt{z}\}$,

$$\delta_1 = (\underbrace{\bot}_{\mathtt{w}}, \underbrace{1}_{\mathtt{x}}, \underbrace{2}_{\mathtt{y}}, \underbrace{\top}_{\mathtt{z}}),\ \delta_2 = (\underbrace{3}_{\mathtt{w}}, \underbrace{1}_{\mathtt{x}}, \underbrace{4}_{\mathtt{y}}, \underbrace{\top}_{\mathtt{z}})$$

$$\Longrightarrow\ \delta_1 \sqcup \delta_2 = (\underbrace{3}_{\mathtt{w}}, \underbrace{1}_{\mathtt{x}}, \underbrace{\top}_{\mathtt{y}}, \underbrace{\top}_{\mathtt{z}})$$

Formalizing Constant Propagation Analysis II

Dataflow system $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ (continued):

- extremal value $\iota := \delta_\top \in D$ where $\delta_\top(x) := \top$ for every $x \in Var_c$,
- transfer functions $\{\varphi_l \mid l \in L\}$ defined by

$$\varphi_l(\delta) := \begin{cases} \delta & \text{if } B^l = \texttt{skip} \text{ or } B^l \in BExp \\ \delta[x \mapsto \mathfrak{A}[\![a]\!]\delta] & \text{if } B^l = (x \texttt{ := } a) \end{cases}$$

where

$$\mathfrak{A}[\![x]\!]\delta := \delta(x) \qquad \mathfrak{A}[\![z]\!]\delta := z$$

$$\mathfrak{A}[\![a_1 \ op \ a_2]\!]\delta := \begin{cases} z_1 \ op \ z_2 & \text{if } z_1, z_2 \in \mathbb{Z} \\ \bot & \text{if } z_1 = \bot \text{ or } z_2 = \bot \\ \top & \text{otherwise} \end{cases}$$

for $z_1 := \mathfrak{A}[\![a_1]\!]\delta$ and $z_2 := \mathfrak{A}[\![a_2]\!]\delta$

Outline

MOP vs. Fixpoint Solution I

Theorem 23.1 (MOP vs. Fixpoint Solution)

Let $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ be a dataflow system. Then

$$\mathsf{mop}(S) \sqsubseteq \mathsf{fix}(\Phi_S)$$

Reminder: by Definition 21.2,

$$\Phi_S : D^n \to D^n : (d_{l_1}, \ldots, d_{l_n}) \mapsto (d'_{l_1}, \ldots, d'_{l_n})$$

where $L = \{l_1, \ldots, l_n\}$ and, for each $1 \leq i \leq n$,

$$d'_{l_i} := \begin{cases} \iota & \text{if } l_i \in E \\ \bigsqcup\{\varphi_{l'}(d_{l'}) \mid (l', l_i) \in F\} & \text{otherwise} \end{cases}$$

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on the board □

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Proof.

on the board □

The next example shows that both solutions can indeed be different.

MOP vs. Fixpoint Solution II

Example 23.2 (Constant Propagation)

$c :=$ `if` $[$`z > 0`$]^1$ `then`
  $[$`x := 2;`$]^2$
  $[$`y := 3;`$]^3$
`else`
  $[$`x := 3;`$]^4$
  $[$`y := 2;`$]^5$
$[$`z := x+y;`$]^6$
$[\ldots]^7$

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Transfer functions
(for $\delta = (\delta(\mathtt{x}), \delta(\mathtt{y}), \delta(\mathtt{z})) \in D$):

$\varphi_1((a,b,c)) = (a,b,c)$
$\varphi_2((a,b,c)) = (2,b,c)$
$\varphi_3((a,b,c)) = (a,3,c)$
$\varphi_4((a,b,c)) = (3,b,c)$
$\varphi_5((a,b,c)) = (a,2,c)$
$\varphi_6((a,b,c)) = (a,b,a+b)$

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1. Fixpoint solution:

$$
\begin{aligned}
\mathsf{CP}_1 &= \iota && = (\top,\top,\top)\\
\mathsf{CP}_2 &= \varphi_1(\mathsf{CP}_1) && = (\top,\top,\top)\\
\mathsf{CP}_3 &= \varphi_2(\mathsf{CP}_2) && = (2,\top,\top)\\
\mathsf{CP}_4 &= \varphi_1(\mathsf{CP}_1) && = (\top,\top,\top)\\
\mathsf{CP}_5 &= \varphi_4(\mathsf{CP}_4) && = (3,\top,\top)\\
\mathsf{CP}_6 &= \varphi_3(\mathsf{CP}_3) \sqcup \varphi_5(\mathsf{CP}_5) &&\\
&= (2,3,\top) \sqcup (3,2,\top) && = (\top,\top,\top)\\
\mathsf{CP}_7 &= \varphi_6(\mathsf{CP}_6) && = (\top,\top,\top)
\end{aligned}
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\end{aligned}$$

2. MOP solution:

$$\begin{aligned}
\mathsf{mop}(7) &= \varphi_{[1,2,3,6]}(\top,\top,\top) \sqcup\\
&\qquad \varphi_{[1,4,5,6]}(\top,\top,\top)\\
&= (2,3,5) \sqcup (3,2,5)\\
&= (\top,\top,5)
\end{aligned}$$

Distributive Transfer Functions I

A sufficient criterion for the coincidence of MOP and Fixpoint Solution is the distributivity of the transfer functions.

Definition 23.3 (Distributivity)

- Let $(D, \sqsubseteq)$ and $(D', \sqsubseteq')$ be complete lattices, and let $F : D \to D'$. F is called distributive (w.r.t. $(D, \sqsubseteq)$ and $(D', \sqsubseteq')$) if, for every $d_1, d_2 \in D$,

$$F(d_1 \sqcup_D d_2) = F(d_1) \sqcup_{D'} F(d_2).$$

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$$F(d_1 \sqcup_D d_2) = F(d_1) \sqcup_{D'} F(d_2).$$
- A dataflow system $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ is called distributive if every $\varphi_l : D \to D$ $(l \in L)$ is so.

Distributive Transfer Functions II

Example 23.4

1. The Available Expressions dataflow system is distributive:

$$\begin{aligned}\varphi_l(A_1 \sqcup A_2) &= ((A_1 \cap A_2) \setminus \mathsf{kill}_{\mathsf{AE}}(B^l)) \cup \mathsf{gen}_{\mathsf{AE}}(B^l) \\ &= ((A_1 \setminus \mathsf{kill}_{\mathsf{AE}}(B^l)) \cup \mathsf{gen}_{\mathsf{AE}}(B^l)) \cap \\ &\quad ((A_2 \setminus \mathsf{kill}_{\mathsf{AE}}(B^l)) \cup \mathsf{gen}_{\mathsf{AE}}(B^l)) \\ &= \varphi_l(A_1) \sqcup \varphi_l(A_2)\end{aligned}$$

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2. The Live Variables dataflow system is distributive (similar)
3. The Constant Propagation dataflow system is not distributive:

$$\begin{aligned}(\top, \top, \top) &= \varphi_{\texttt{z:=x+y}}((2, 3, \top) \sqcup (3, 2, \top)) \\ &\neq \varphi_{\texttt{z:=x+y}}((2, 3, \top)) \sqcup \varphi_{\texttt{z:=x+y}}((3, 2, \top)) \\ &= (\top, \top, 5)\end{aligned}$$

Coincidence of MOP and Fixpoint Solution

Theorem 23.5 (MOP vs. Fixpoint Solution)

Let $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ be a distributive dataflow system. Then

$$\mathsf{mop}(S) = \mathsf{fix}(\Phi_S)$$

Coincidence of MOP and Fixpoint Solution

Theorem 23.5 (MOP vs. Fixpoint Solution)

Let $S = (L, E, F, (D, \sqsubseteq), \iota, \varphi)$ *be a distributive dataflow system. Then*

$$\mathsf{mop}(S) = \mathsf{fix}(\Phi_S)$$

Proof.

- by showing that $\Phi_S(\mathsf{mop}(S)) = \mathsf{mop}(S)$ ...
  (see [Nielson/Nielson/Hankin 2005, p. 81])
- ... and using $\mathsf{mop}(S) \sqsubseteq \mathsf{fix}(\Phi_S)$ (Theorem 23.1)

□

Outline

Semantics of Functional Languages I

- Program = list of function definitions

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- Simplest setting: first-order function definitions of the form

$$f(x_1, \ldots, x_n) = t$$

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  - term t over (base and defined) function calls and $x_1, \ldots, x_n$

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  - term t over (base and defined) function calls and $x_1, \ldots, x_n$
- Operational semantics (only function calls)
  - call-by-value case:
$$\frac{t_1 \to z_1 \quad \ldots \quad t_n \to z_n \quad t[x_1 \mapsto z_1, \ldots, x_n \mapsto z_n] \to z}{f(t_1, \ldots, t_n) \to z}$$
  - call-by-name case:
$$\frac{t[x_1 \mapsto t_1, \ldots, x_n \mapsto t_n] \to z}{f(t_1, \ldots, t_n) \to z}$$

Semantics of Functional Languages II

- Denotational semantics
  - program = equation system (for functions)
  - induces call-by-value and call-by-name functional
  - monotonic and continuous w.r.t. graph inclusion
  - semantics := least fixpoint (Tarski/Knaster Theorem)
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- Extensions: higher-order types, data types, ...
- see [Winskel 1996, Sct. 9] and *Functional Programming* course [Giesl]

Semantics of Concurrent Languages

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  $$\text{Program} : \text{Input} \to \text{Output}$$

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- (Operational) Semantics: labelled transition systems defined by transition rules of the form

$$\frac{}{\alpha.P \xrightarrow{\alpha} P} \quad \frac{P \xrightarrow{\alpha} P'}{P + Q \xrightarrow{\alpha} P'} \quad \frac{P \xrightarrow{\alpha} P'}{P \parallel Q \xrightarrow{\alpha} P' \parallel Q} \quad \frac{P \xrightarrow{\alpha} P' \quad Q \xrightarrow{\bar{\alpha}} Q'}{P \parallel Q \xrightarrow{\tau} P' \parallel Q'} \quad \ldots$$

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- see course on *Modelling Concurrent and Probabilistic Systems* in Summer 2009 [Katoen, Noll] and [Winskel 1996, Sct. 14]

Outline

Courses Winter 2010/11

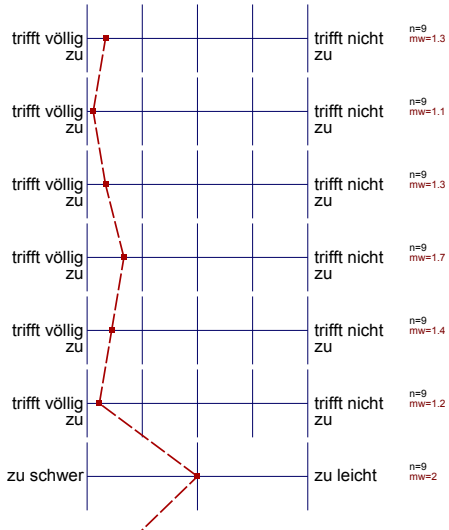
- Course Advanced Model Checking [Katoen]
- Practical Course Model Checking [Katoen, Sher, Yue]
- Course Compiler Construction [Noll] ("Hiwi" jobs available!)

Outline

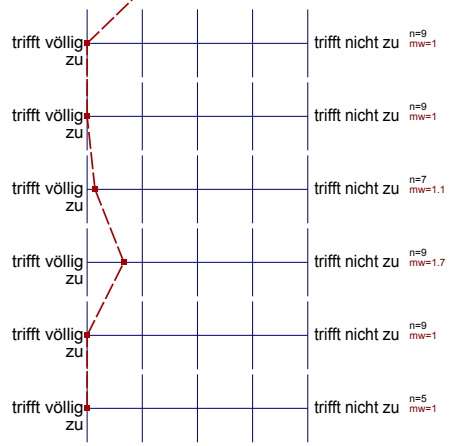
Profillinie

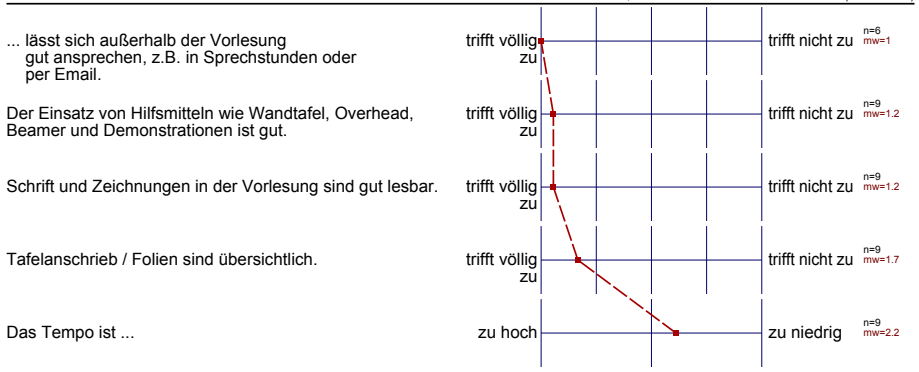
Teilbereich:	Informatik
Name der/des	Priv.doz. Dr.rer.nat. Thomas Noll
Titel der Lehrveranstaltung: (Name der Umfrage)	Semantik und Verifikation von Software (10ss-29423) (Vorlesung)

Konzept der Vorlesung



Vermittlung und Verhalten

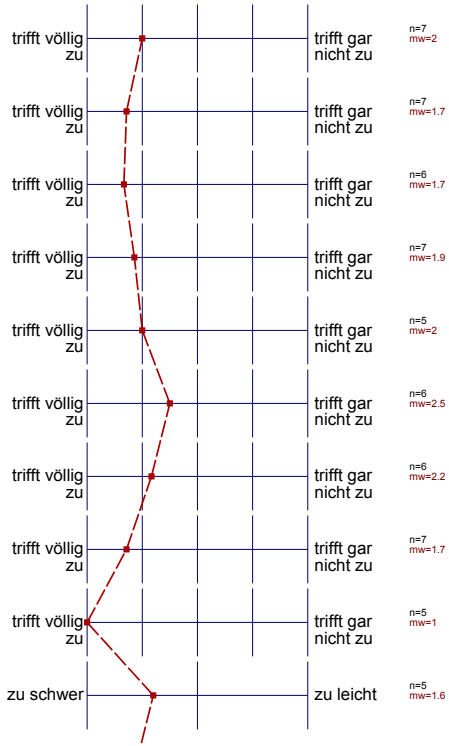



... lässt sich außerhalb der Vorlesung gut ansprechen, z.B. in Sprechstunden oder per Email.
trifft völlig zu
trifft nicht zu
n=6
mw=1
Der Einsatz von Hilfsmitteln wie Wandtafel, Overhead, Beamer und Demonstrationen ist gut.
trifft völlig zu
trifft nicht zu
n=9
mw=1.2
Schrift und Zeichnungen in der Vorlesung sind gut lesbar.
trifft völlig zu
trifft nicht zu
n=9
mw=1.2
Tafelanschrieb / Folien sind übersichtlich.
trifft völlig zu
trifft nicht zu
n=9
mw=1.7
Das Tempo ist ...
zu hoch
zu niedrig
n=9
mw=2.2

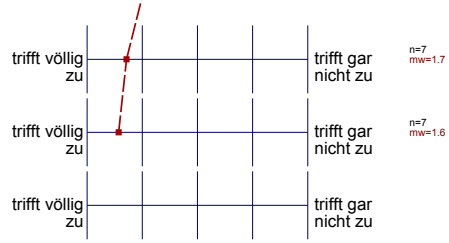
Profillinie

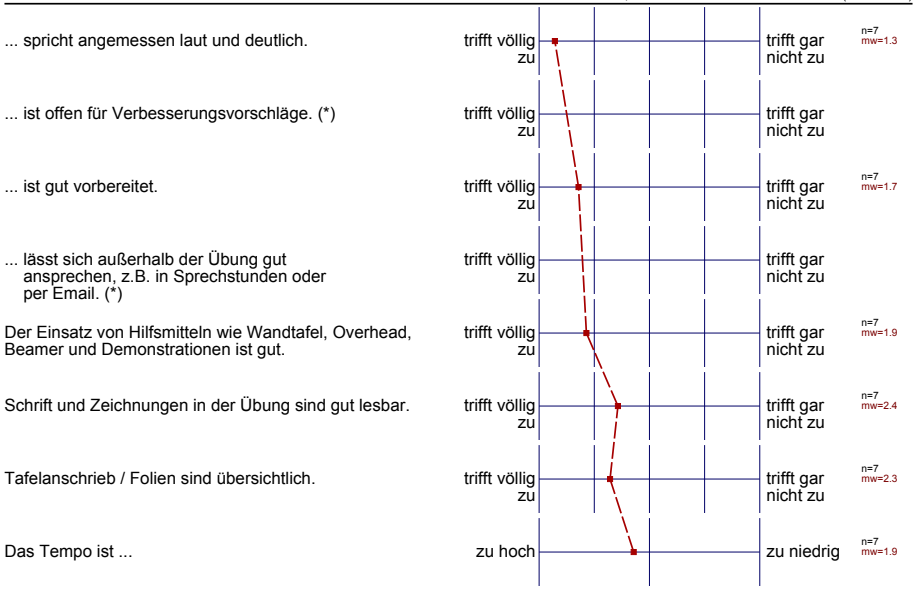
Teilbereich: Informatik
Name der/des: Priv.doz. Dr.rer.nat. Thomas Noll
Titel der Lehrveranstaltung: (Name der Umfrage): Semantik und Verifikation von Software (10ss-29422) (Übung)

Konzept der Übung



Vermittlung und Verhalten





(*) Hinweis: Wenn die Anzahl der Antworten auf eine Frage zu gering ist, wird für die Frage keine Auswertung angezeigt.