CS 4110

Programming Languages & Logics

Lecture 37

Typed Assembly Language

28 November 2012

Schedule

Monday

- Typed Assembly Language

Today

- Polymorphism
- Stack Types

Friday

- Compilation
- Course Review

TAL-0 Review

- Syntax
- Semantics
- Type System
  - $\Psi; \Gamma \vdash v : \tau$
  - $\Psi \vdash i : \Gamma \rightarrow \Gamma'$
  - $\tau \leq \tau'$
  - $\vdash H : \Psi$
  - $\vdash R : \Gamma$
  - $\vdash (H, R, B)$

TAL-0 Review

- Syntax
- Semantics
- Type System
  - $\Psi; \Gamma \vdash v : \tau$
  - $\Psi \vdash i : \Gamma \to \Gamma'$
  - $\tau \leq \tau'$
  - $\vdash H : \Psi$
  - $\vdash R : \Gamma$
  - $\vdash (H, R, B)$

Theorem (Type Safety)

If $\vdash \Sigma$ *and* $\Sigma \mapsto^{\star} \Sigma'$*, then* Σ' *is not stuck.*

Lemma (Progress and Preservation)

- *If* $\vdash \Sigma_1$ *then there exists a* Σ_2 *such that* $\Sigma_1 \mapsto \Sigma_2$
- *If* $\vdash \Sigma_1$ *and* $\Sigma_1 \mapsto \Sigma_2$ *then* $\vdash \Sigma_2$

TAL-1: Polymorphism

Syntax

- Add type variables α and universal types $\forall \alpha . \tau$
- Allow code label types to be polymorphic
  $\forall \alpha, \beta . \{r_1 : \alpha, r_2 : \beta, r_3 : \{r_1 : \beta, r_2 : \alpha\} \to \{\}\} \to \{\}$
- Add type application $v\,[\tau]$
- Write $v\,[\tau_1, \ldots, \tau_k]$ for $v\,[\tau_1] \cdots [\tau_k]$

Polymorphism Example

$swap$: $\forall \alpha, \beta. \{r_1 : \alpha, r_2 : \beta, r_{31} : \{r_1 : \beta, r_2 : \alpha\} \rightarrow \{\}\} \rightarrow \{\}$

```
    mov r3,r1
    mov r1,r2
    mov r2,r3
    jmp r31
```

$swap\_ints$: $\{r_1 : \text{int}, r_2 : \text{int}, r_{31} : \{r_1 : \text{int}, r_2 : \text{int}\} \rightarrow \{\}\} \rightarrow \{\}$

```
    jmp swap [int, int]
```

$swap\_int\_and\_label$: $\{r_1 : \text{int}, r_2 : \{r_2 : \text{int} \rightarrow \{\}\}$

```
    mov r31,L
    jmp swap [int, {r2:int} →{}]
```

L : $\{r_1 : \{r_2 : \text{int}\} \rightarrow \{\}, r_2 : \text{int}\} \rightarrow \{\}$

```
    jmp r1
```

Callee-Saves Registers

Common Strategy

- When calling a function...
- Save the contents of some registers on the stack...
- Allow the callee to save (and restore) other designated registers...
- If the callee does not use all registers, the cost of saving and restoring is not incurred...

Correctness Critereon

Callee must return the callee-saves registers to the caller with the same values as when the function was invoked.

Callee-Saves Example

callee: $\forall\alpha.\ \{r_1 : \text{int}, r_5 : \alpha, r_{31} : \{r_1 : \text{int}, r_5 : \alpha\} \rightarrow \{\}\} \rightarrow \{\}$

```
    mov r4,r5          % Save r5
    mov r5,7           % Use r5 for other work
    add r1,r1,r5
    mov r5,r4          % Restore r5
    jmp r31
```

caller : $\{\} \rightarrow \{\}$

```
    mov r5,255
    mov r1,5
    mov r31,L
    jmp callee[int]
```

$L : \{r_1 : \text{int}, r_5 : \text{int}\} \rightarrow \{\}$

```
    mul r3,r1,r5
        ...
```

Callee-Saves Bug

callee: $\forall\alpha.\ \{r_1 : \text{int}, r_5 : \alpha, r_{31} : \{r_1 : \text{int}, r_5 : \alpha\} \rightarrow \{\}\} \rightarrow \{\}$

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    mov r4,r5          % Save r5
    mov r5,7           % Use r5 for other work
    add r1,r1,r5
    mov r5,r4          % Restore r5
    jmp r31            % Error! r5:int
```

caller : $\{\} \rightarrow \{\}$

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    mov r5,255
    mov r1,5
    mov r31,L
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```

$L : \{r_1 : \text{int}, r_5 : \text{int}\} \rightarrow \{\}$

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Theorems for free!

Philip Wadler
University of Glasgow*

June 1989

Abstract

From the type of a polymorphic function we can derive a theorem that it satisfies. Every function of the same type satisfies the same theorem. This provides a free source of useful theorems, courtesy of Reynolds' abstraction theorem for the polymorphic lambda calculus.

1 Introduction

Write down the definition of a polymorphic function on a piece of paper. Tell me its type, but be careful not to let me see the function's definition. I will tell you a theorem that the function satisfies.

The purpose of this paper is to explain the trick. But first, let's look at an example.

Say that r is a function of type

$$r : \forall X.\ X^* \to X^*.$$

Here X is a type variable, and X^* is the type "list of X". From this, as we shall see, it is possible to conclude that r satisfies the following theorem: for all types A and A' and every total function $a : A \to A'$ we have

$$a^* \circ r_A = r_{A'} \circ a^*.$$

Here $\circ$ is function composition, and $a^* : A^* \to A'^*$ is the function "map a" that applies a elementwise to a list of A yielding a list of A', and $r_A : A^* \to A^*$ is the instance of r at type A.

The intuitive explanation of this result is that r must work on lists of X for *any* type X. Since r is provided with no operations on values of type X, all it can do is rearrange such lists, independent of the values contained in them. Thus applying a to each element of a list and then rearranging yields the same result as rearranging and then applying a to each element.

For instance, r may be the function $reverse : \forall X.\ X^* \to X^*$ that reverses a list, and a may be the function $code : Char \to Int$ that converts a character to its ASCII code. Then we have

$$\begin{array}{ll} & code^*\ (reverse_{Char}\ [\text{'a'}, \text{'b'}, \text{'c'}]) \\ = & [99, 98, 97] \\ = & reverse_{Int}\ (code^*\ [\text{'a'}, \text{'b'}, \text{'c'}]) \end{array}$$

which satisfies the theorem. Or r may be the function $tail : \forall X.\ X^* \to X^*$ that returns all but the first element of a list, and a may be the function $inc : Int \to Int$ that adds one to an integer. Then we have

$$\begin{array}{ll} & inc^*\ (tail_{Int}\ [1, 2, 3]) \\ = & [3, 4] \\ = & tail_{Int}\ (inc^*\ [1, 2, 3]) \end{array}$$

which also satisfies the theorem.

On the other hand, say r is the function $odds : Int^* \to Int^*$ that removes all odd elements from a list of integers, and say a is inc as before. Now we have

$$\begin{array}{ll} & inc^*\ (odds_{Int}\ [1, 2, 3]) \\ = & [2, 4] \\ \neq & [4] \\ = & odds_{Int}(inc^*\ [1, 2, 3]) \end{array}$$

and the theorem is *not* satisfied. But this is not a counterexample, because $odds$ has the wrong type: it is too specific, $Int^* \to Int^*$ rather than $\forall X.\ X^* \to X^*$.

This theorem about functions of type $\forall X.\ X^* \to X^*$ is pleasant but not earth-shaking. What is more exciting is that a similar theorem can be derived for *every* type.

1

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Paper: P. Wadler. "Theorems for Free!" In *FPCA*, pp. 347–359. September 1989.

Operational Semantics

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  $(H, R, \text{jmp } v[\tau_1, \ldots, \tau_k]) \mapsto (H, R, B[\tau_1/\alpha_1, \ldots, \tau_k/\alpha_k])$
  where $R(v) = L$ and $H(L) = \forall \alpha_1, \ldots, \alpha_k. \Gamma \to \{\}. B$

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  $(H, R, \text{beq } r, v[\tau_1, \ldots, \tau_k]; B) \mapsto (H, R, B'[\tau_1/\alpha_1, \ldots, \tau_k/\alpha_k])$
  where $R(r) = 0$, $R(v) = L$, and $H(L) = \forall \alpha_1, \ldots, \alpha_k.\, \Gamma \to \{\}.\, B'$

Typing Polymormphism

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Type application

$$\frac{\Psi; \Delta; \Gamma \vdash v : \forall \alpha_1, \ldots, \alpha_k.\, \Gamma' \to \{\} \qquad \Delta \vdash \tau}{\Psi; \Delta; \Gamma \vdash v\,[\tau] : (\forall \alpha_2, \ldots, \alpha_k.\, \Gamma' \to \{\})[\tau/\alpha]}$$

TAL-2: Stack Types

Run-Time Stack

Almost every compiler uses a *run-time stack*

- What is a stack?
- A consecutive sequence of memory addresses with one end designated as the *top* of the stack
- Values are stored on the top of the stack and retrieved later
- The compiler may grow or shrink the stack as needed

Stack uses

- Local variables
- Spilled registers
- Return addresses

Stack Syntax

- Machine states:

  $M ::= (H, R, S, B)$

- Stacks:

  $S ::= [] \mid v :: S$

- Instructions:

  $i ::= \cdots \mid \text{salloc } n \mid \text{sfree } n \mid \text{sld } r_d, n \mid \text{sst } v, n$

- Errors:
  - Free too many values
  - Read too deep in the stack
  - Write too deep in the stack

Stack Instructions

The new stack instructions can be easily encoded:

- A designated register *sp* points to the top of the stack
- salloc *n* subtracts *n* from *sp* (i.e., sub *sp*, *sp*, *n*)
- sfree *n* adds *n* to *sp* (i.e., add *sp*, *sp*, *n*)
- sld r_d, *n* reads a value at offset *n* relative to *sp* (i.e., ld r_d, *sp*(*n*))
- sst *v*, *n* writes a value at offset *n* relative to *sp* (i.e., st *sp*(*n*), *v*)

CISC-like stack instructions can also be encoded:

- push *v* is salloc 1; sst *v*, 1
- pop r_d is sld r_d, 1; sfree 1

Example: Factorial

$$
\begin{aligned}
&\mathit{fact}(n) = \\
&\quad \text{if } n \leq 0 \text{ then } 1 \\
&\quad \text{else } n \times \mathit{fact}(n-1)
\end{aligned}
$$

Example: Factorial

```
fact:   bgt r1,L1        % if n > 0, goto L1
        mov r1,1
        jmp r31          % if n ≤ 0, return
L1 :    salloc 2         % allocate space for frame
        sst r31,1        % save return address
        sst r1,2         % save n
        sub r1,r1,1      % n := n − 1
        mov r31,L        % set return address
        jmp fact         % recursive call
L :     sld r2,2         % restore n
        sld r31,1        % restore return address
        sfree 2          % free space for frame
        mul r1,r1,r2     % result := n × fact(n − 1)
        jmp r31          % return
```

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$$\frac{S = v_1 :: \cdots :: v_n :: S'}{(H, R, S, \text{sld } r_d, n; B) \mapsto (H, R[r_d := v_n], S, B)}$$

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$$\frac{S = v_1 :: \cdots :: v_n :: S'}{(H, R, S, \text{sst } v, n; B) \mapsto (H, R, v_1 :: \cdots :: R(r_s) :: S', B)}$$

Type System

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- Register file types contain a special variable *sp*

$$\{sp : \text{int} :: \text{int} :: [], r_1 : \text{int}, \ldots\}$$

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- Code label types can be polymorphic over stack types

  $$\forall \rho.\ \{sp : \text{int} :: \rho, r_1 : \text{int}\} \rightarrow \{\}$$

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  $$\forall \rho.\ \{sp : \text{int} :: \rho, r_1 : \text{int}\} \rightarrow \{\}$$

- Junk values "?" have junk types "?"

Typing Stacks

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Stack allocation

$$\frac{\Gamma(sp) = \sigma}{\Psi; \Delta \vdash \mathsf{salloc}\, n : \Gamma \to \Gamma[sp := ? :: \cdots :: ? :: \sigma]}$$

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Stack free

$$\frac{\Gamma(sp) = \tau_1 :: \cdots :: \tau_n :: \sigma}{\Psi; \Delta \vdash \text{sfree}\ n : \Gamma \to \Gamma[sp := \sigma]}$$

Typing Stacks

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Stack load

$$\frac{\Gamma(sp) = \tau_1 :: \cdots :: \tau_n :: \sigma}{\Psi; \Delta \vdash \mathsf{sld}\, r_d, n : \Gamma \to \Gamma[r_d := \tau_n]}$$

Typing Stacks

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Stack store

$$\frac{\Psi; \Delta; \Gamma \vdash v : \tau \qquad \Gamma(sp) = \tau_1 :: \cdots :: \tau_n :: \sigma}{\Psi; \Delta \vdash \mathsf{sst}\, v, n : \Gamma \to \Gamma[sp := \tau_1 :: \cdots :: \tau :: \sigma]}$$

Example: Factorial Bug

$fact$: $\forall\rho.\ \{sp : \rho, r_1 : \text{int}, r_{31} : \{r_1 : \text{int}, sp : \rho\} \to \{\}\} \to \{\}$

```
    bgt r1,L1[ρ]
    mov r1,1
    jmp r31
```

$L1$: $\forall\rho.\ \{sp : \rho, r_1 : \text{int}, r_{31} : \{r_1 : \text{int}, sp : \rho\} \to \{\}\} \to \{\}$

```
    salloc 2
    sst r31,1
    sst r1,2
    sub r1,r1,1
    mov r31,L[ρ]
    jmp fact
```

L : $\forall\rho.\ \{sp : \{r_1 : \text{int}, sp : \rho\} \to \{\} :: \text{int} :: \rho, r_1 : \text{int}\} \to \{\}$

```
    sld r2,2
    sld r31,1
    sfree 2
    mul r1,r1,r2
    jmp r31          % Error! sp : {r1 : int, sp : ρ} → {} :: int :: ρ
```

Example: Callee Bug

$caller$: $\forall\rho.\ \{sp : \tau_{code} :: \rho\} \rightarrow \{\}$

```
    salloc 1
    mov r1,17
    sst r1,1
    mov r31,L[ρ]
    jmp callee[τcode :: ρ]
```

$callee : \forall\rho.\ \{sp : \text{int} :: \rho, r_{31} : \{sp : \rho, r_1 : \text{int}\} \rightarrow \{\}\} \rightarrow \{\}$

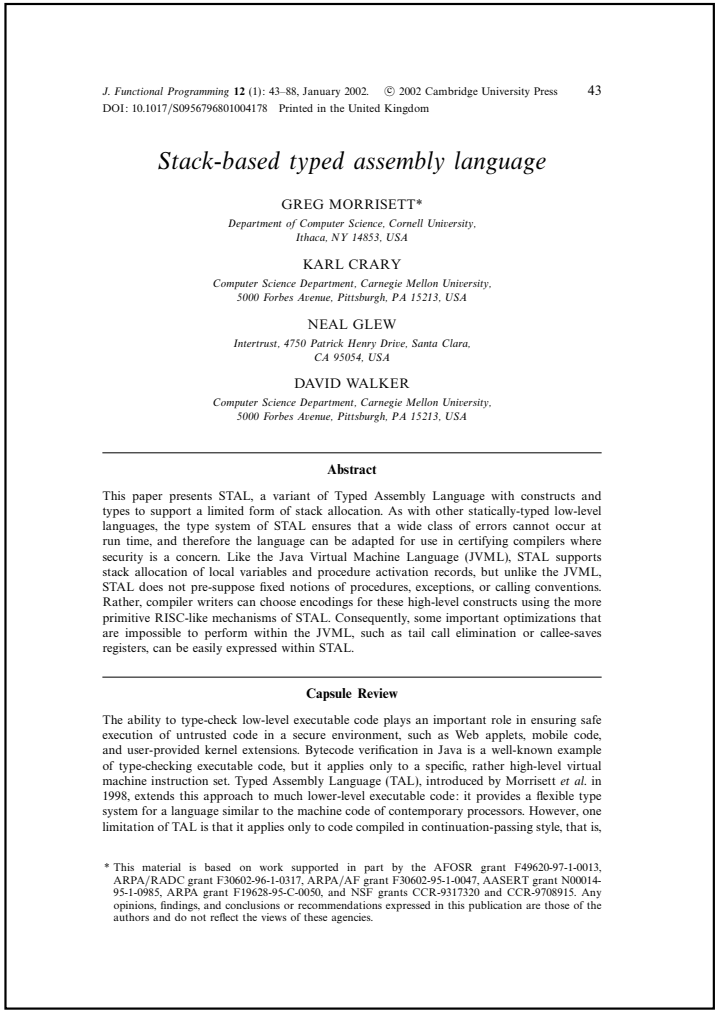
```
    sld r1,1
    add r1,r1,r1
    sst r1,2                    % Error!
    sfree 1
    jmp r31
```

$L : \forall\rho.\ \{sp : \tau_{code} :: \rho, r_1 : \text{int}\} \rightarrow \{\}$

```
    ...
```

Type Safety

- Type safety ensures we don't get stuck
- With a few additional features, can handle exceptions
- Paper: G. Morrisett, K. Crary, N. Glew, and D. Walker. "Stack-based Typed Assembly Language." In *JFP*. 12(1):43–88. January 2002.



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Stack-based typed assembly language

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Abstract

This paper presents STAL, a variant of Typed Assembly Language with constructs and types to support a limited form of stack allocation. As with other statically-typed low-level languages, the type system of STAL ensures that a wide class of errors cannot occur at run time, and therefore the language can be adapted for use in certifying compilers where security is a concern. Like the Java Virtual Machine Language (JVML), STAL supports stack allocation of local variables and procedure activation records, but unlike the JVML, STAL does not pre-suppose fixed notions of procedures, exceptions, or calling conventions. Rather, compiler writers can choose encodings for these high-level constructs using the more primitive RISC-like mechanisms of STAL. Consequently, some important optimizations that are impossible to perform within the JVML, such as tail call elimination or callee-saves registers, can be easily expressed within STAL.

Capsule Review

The ability to type-check low-level executable code plays an important role in ensuring safe execution of untrusted code in a secure environment, such as Web applets, mobile code, and user-provided kernel extensions. Bytecode verification in Java is a well-known example of type-checking executable code, but it applies only to a specific, rather high-level virtual machine instruction set. Typed Assembly Language (TAL), introduced by Morrisett *et al.* in 1998, extends this approach to much lower-level executable code: it provides a flexible type system for a language similar to the machine code of contemporary processors. However, one limitation of TAL is that it applies only to code compiled in continuation-passing style, that is,

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  - Arguments on stack or in registers?
  - Results on stack or in registers?
  - Return address: caller pops? callee pops?
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Moral: orthogonal combination of type system constructs makes it easy to scale language features