The 7 Features of Habit for Highly Assured Systems Programming

Mark P. Jones, on behalf of the HASP project

May 2009

Portland State UNIVERSITY | galois |

About that title …

HASP: High Assurance Systems Programming

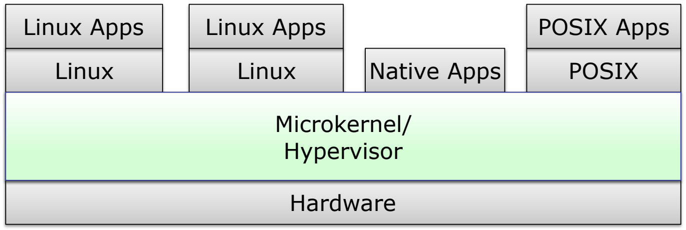
Tools and techniques to support the development of high assurance systems software:

- Operating system kernels
- Hypervisors
- VMMs
- Device drivers
- …

Vision

- A tool-chain for developing robust, reliable, and secure systems software that spans the full range of concerns:
  - From high-level analysis and verification
  - To low-level, performance-sensitive implementation

Example Application:



a working μ-kernel implementation with very high assurance of separation between domains

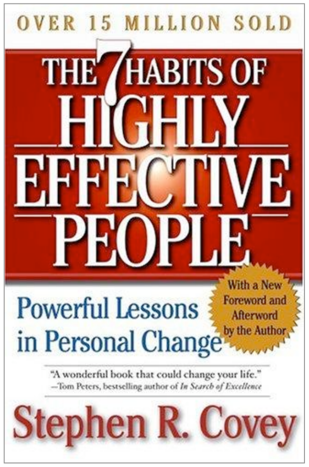
Habit (formerly "Systems Haskell")

- A dialect of Haskell that is designed to meet the needs of high assurance systems programming

Haskell + **bit**s
High **a**ssurance + **b**its

The Book

- A well-known "self-help" book by Stephen Covey
- "Powerful lessons in Personal Change"
- First published in 1989
- Nothing to do with HASP...



OVER 15 MILLION SOLD

THE 7 HABITS OF HIGHLY EFFECTIVE PEOPLE

Powerful Lessons in Personal Change

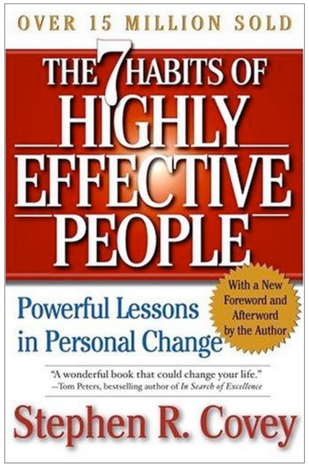
With a New Foreword and Afterword by the Author

"A wonderful book that could change your life."
—Tom Peters, bestselling author of *In Search of Excellence*

Stephen R. Covey

Original Talk Plan

- An introduction to the Habit language
- Showcase seven "cool" features of the design
- Only connection with the book: the number 7 and the word "Habit"



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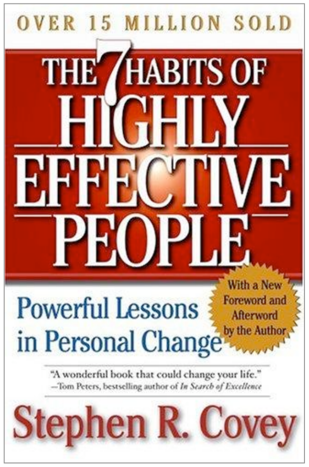
Maybe I should take a look …

- Personal Development
- Time Management
- Relationships
- Communication
- Leadership
- The Character Ethic
- The Abundance Mentality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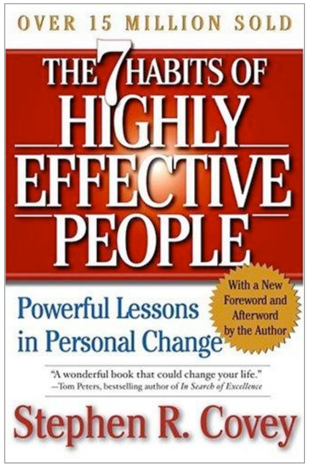
Principles & Values

"A holistic, integrated, **principle-centered** approach for solving personal and professional problems"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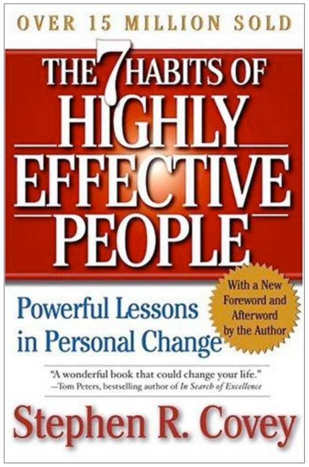
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The New Talk Plan

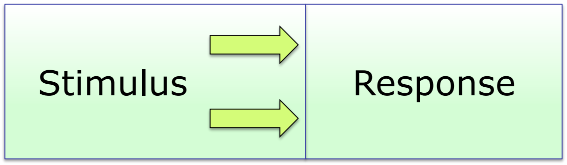
- An introduction to the Habit language
- Emphasis on underlying principles and values
- An occasional diversion into those "cool" technical features
- Use Dr Covey's names for the seven habits to structure the talk (sometimes with a very liberal reinterpretation)

Habit 1

Be Proactive

Principles of Personal Choice

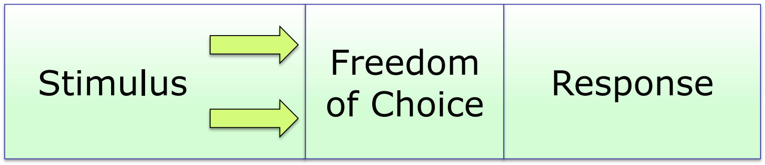
Between Stimulus & Response



Stimulus

Response

Between Stimulus & Response



Stimulus

Freedom of Choice

Response

- Response is a function of our decisions, not of our conditions
- We have the initiative and the responsibility to make things happen

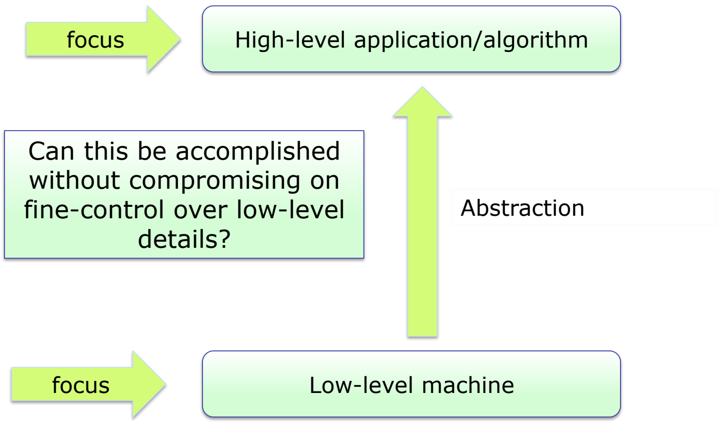
A Challenging Domain

Building high-assurance systems software is extremely challenging

1. Low-level operations, fine-grained control, performance sensitivity, …
2. Increasing functionality, increasing complexity, increasing need for assurance, …

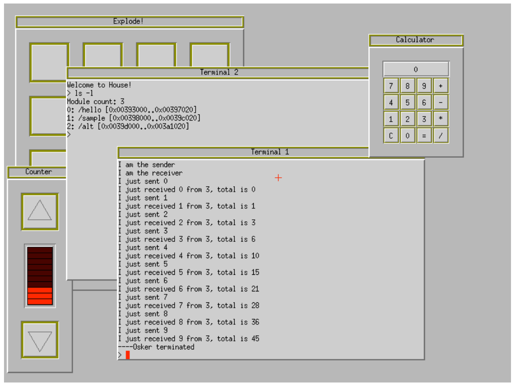
Current practice favors languages that are close to the metal, accommodating (1), neglecting (2)

Raising the Level of Abstraction


focus
High-level application/algorithm
Can this be accomplished without compromising on fine-control over low-level details?
Abstraction
focus
Low-level machine

The House Experience

- House is a proof-of-concept OS, written in Haskell:
  - Kernel + basic drivers (~5KLOC)
  - Network driver (~2KLOC)
  - GUI (~6KLOC)
  - Apps
  - User programs
- A starting point for the Galois HaLVM



```
Welcome to House!
> ls -l
Module count: 3
0: /hello [0x00393000..0x00397020]
1: /sample [0x00398000..0x0039c020]
2: /alt [0x0039d000..0x003a1020]
>
```

```
I am the sender
I am the receiver
I just sent 0
I just received 0 from 3, total is 0
I just sent 1
I just received 1 from 3, total is 1
I just sent 2
I just received 2 from 3, total is 3
I just sent 3
I just received 3 from 3, total is 6
I just sent 4
I just received 4 from 3, total is 10
I just sent 5
I just received 5 from 3, total is 15
I just sent 6
I just received 6 from 3, total is 21
I just sent 7
I just received 7 from 3, total is 28
I just sent 8
I just received 8 from 3, total is 36
I just sent 9
I just received 9 from 3, total is 45
----Osker terminated
>
```

Benefits of Using Haskell

Productivity: higher-level abstractions, genericity, reuse

Safety: built-in type and memory safety guarantees

Tractability: purity, referential transparency, encapsulation of effects, semantic foundations

The Price of Abstraction

- But for some systems programming applications, abstraction is a major barrier to adoption
- Examples:
  - Unknown data representation
  - Unpredictable execution behavior, performance, resource utilization, etc.
  - Runtime system: size and complexity
- Haskell has weaknesses in these areas

Habit 2

Begin with the End in Mind

Principles of Personal Vision

Habit

- A dialect of Haskell that is designed to meet the needs of high assurance systems programming

- Primary Commitments:
  - Systems Programming
  - High Assurance
  - Simplicity

Habit

- A dialect of Haskell that is designed to meet the needs of high assurance systems programming

- Systems Programming: Provide programmers with the ability to choose and make informed trade-offs between:
  - **Control** over data representation and performance
  - **Abstraction** and use of higher-level language mechanisms

Habit

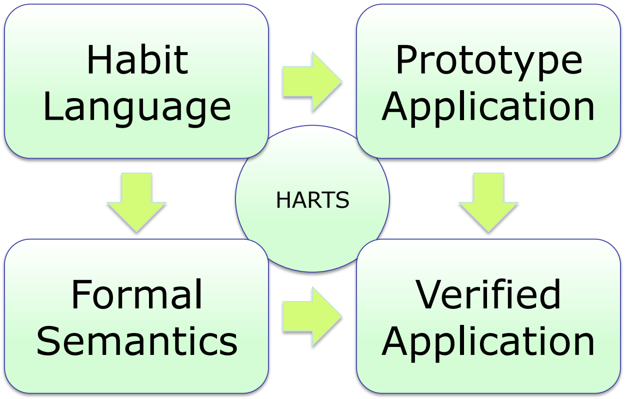
- A dialect of Haskell that is designed to meet the needs of high assurance systems programming

- High Assurance: a **full** and **formal** semantics that provides a basis for:
  - Mechanized reasoning
  - Meaningful assurance arguments
  - Verification of Habit programs (and, ultimately, Habit implementations)

Habit

- A dialect of Haskell that is designed to meet the needs of high assurance systems programming
- High Assurance Runtime System (**HARTS**):
  - Services for memory management, garbage collection, foreign function interface, …
  - Designed to be "as simple as possible", modular, formally verified

The Big Picture



Habit Language

Prototype Application

HARTS

Formal Semantics

Verified Application

Realizing the Big Picture

- Each of these areas provides opportunities for local innovations and advances
- But our sights are set on the combination
  - Feasibility: Functionality, assurance, performance, cost
  - Technology Transfer: A toolset and a real world case study

Habit 3

Put First Things First

Principles of Integrity & Execution

The Time Management Matrix

	Urgent	Not urgent
Important	I	II
Not important	III	IV

The Time Management Matrix

	Urgent	Not urgent
Important	• Crisis management • Patching	• Prevention • New opportunities
Not important	• Interruptions	• Busy work

Why Build on Haskell?

- Increasingly broad adoption/use of Haskell
- Growing interest, strong community
- Avoid reinventing the wheel:
  - Syntax: familiar notations and concepts
  - Semantics: powerful, expressive type system
- Leave time to focus on what is new

Semantic Foundations

- Exploring a formal semantic framework using denotational techniques that can be expressed in well-developed domain theory
- Automated (for example, in Isabelle; see upcoming publication in TPHOLs conference)
- Expect to develop a corresponding operational semantics for treatment of resource sensitivity

Properties for Assurance

- Properties about the language
  - Examples: type and memory safety
- Equivalences between program fragments
  - Examples: for use in reasoning, transformation, optimization, synthesis
- Properties of implementations
  - Example: preservation of semantics
- Properties of applications
  - Example: separation properties of a hypervisor

Habit 4

Think Win/Win

Principles of Mutual Benefit

Example: Type Safety

Developer Win:

Earlier detection of bugs during development

User Win:

More secure deployed systems

Example: Type Safety

Developer Win:

Earlier detection of bugs during development

User Win:

More secure deployed systems

Certifier Win:

Many safety properties enforced automatically via types

Example: Purity

- The output of a function of type `A -> B` depends only on the value of its input
- No hidden dependence on global variables or privileged state
- Explicit data flow; simplified reasoning
- The features that we omit can sometimes be as important as the features that we include

Example: Division

- Division has type: `t -> NonZero t -> t`
- Only two ways to construct a `NonZero t` value:
  - Runtime check (cost can be amortized):

    ```
    nonZero :: t -> Maybe (NonZero t)
    ```

  - Literal divisor checked at compile-time:

    ```
    instance (Lit n t, 0<n) => Lit n (NonZero t)
    ```

- Simple, safe, low-cost, generic

Example: Arrays

- The type `Ix n` contains only in-bound indices for an array of length `n`
- Array lookup can be fast (no bounds check) and safe: `(@) :: Ix n -> Ref (Array n t) -> Ref t`
- Amortized construction of safe indices with comparisons that are already required

```
(<=?) :: Unsigned -> Ix n -> Maybe (Ix n)
```

Example: Side Effects

- Presence of potential side-effects (e.g., state, exceptions, …) is made explicit in types via monads: `A -> M B`
- A single program can use multiple monads
- Some operations are generic in the monad, and others that are specific to a particular monad

- Particular relevance to systems domain where some sections of code are required to run in special “modes”

  Privileged? Blocking? Allocating?

  Preemptable? Exceptions? Transactional?

  Paging on? Protection on? Segmentation on?

- Correct usage traditionally depends on programmer discipline

- A monadic type system can document and enforce correct use of modes at compile-time

When Unsafe is the only Option

- Some low-level features are inherently unsafe
- In these cases, we strive:
  - To wrap them in safe interfaces (A key aspect in the design of House)
  - To ensure that they are easily located and identified for audit purposes

Habit 5

Seek First to Understand, Then to be Understood

Principles of Mutual Understanding

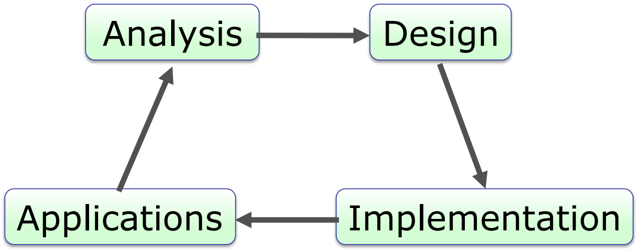
Understanding the Domain

- What are the driving needs of the systems programming domain?
- How can we best address those needs in our design?

Development Model

Prior work at PSU
and at Galois

Haskell, ML, …
Types, Monads



House, HaLVM, L4,
BAC, dombuilder, …

Hobbit, RML, …

Requirements

- Representation/Control
  - Code: optimization, implementation
  - Data: layout, initialization, conversion
  - Resource utilization
- Ease of use
  - Notation, type inference, user-defined control structures
- Verification
  - Semantic foundations
  - Type and memory safety

Initial Habit Design: Summary

- Simplified dialect of Haskell
  - Foundations: pure, higher-order, typed
  - Syntax: definitional style, lightweight notation
- Changes/additions
  - Strict evaluation; bitdata; memory areas; type-level numbers; unpointed types; monadic sugar

Controlling Representation

Bit-level data specifications

```
bitdata Bool  = False [ B0 ] | True [ B1 ]
bitdata Perms = Perms [ r, w, x :: Bool ]
bitdata Fpage
       = Fpage [ base :: Bit 22 | size :: Bit 6
               | reserved :: Bit 1 | perms :: Perms ]
```

Type-level numbers

Familiar box layout notation

… continued

```
class mempage_t {
public:
    union {
        struct {
            BITFIELD7(word_t,
                      execute           : 1,
                      write             : 1,
                      read              : 1,
                      reserved          : 1,
                      size              : 6,
                      base              : L4_FPAGE_BASE_BITS,
                      : BITS_WORD - L4_FPAGE_BASE_BITS - 10
                );
        } x __attribute__((packed));
        word_t raw;
    };
};
```

BITFIELD macro adjusts for variations between C compilers …

From L4Ka::Pistachio, a mature L4 implementation in C++ from the University of Karlsruhe, Germany

Permission values inlined

Macro-level numbers

gcc specific attribute: “a variable or structure field should have the smallest possible alignment”

Fine Control of Memory Layout:

In C:

```
struct Mapping {
  struct Space*    space;
  struct Mapping*  next;
  struct Mapping*  prev;
  unsigned         level;
  Fpage            vfp;
  unsigned         phys;
  struct Mapping*  left;
  struct Mapping*  right;
};
```

Exact layout is not guaranteed without compiler-specific annotations

In Habit:

```
type Mapping = struct
  [ space        :: Stored (Ptr Space)
  | next, prev   :: Stored (Ptr Mapping)
  | level        :: Stored (Bit 32)
  | vfp          :: Stored Fpage
  | phys         :: Stored (Bit 32)
  | left, right  :: Stored (Ptr Mapping) ]
```

Fine-control of memory layout, endianness, etc..

Area Alignment & Allocation:

Allocating an initial page directory:

- In C/C++ (from L4Ka::Pistachio):

```
static word_t init_pdir[1024]
          __attribute__((aligned(4096)))
          SECTION(".init.data");
```

- In assembly code (from pork):

```
            .align   (1<<PAGESIZE)
init_pdir:  .space   4096
```

- In Habit (based on Hobbit prototype):

```
area init_pdir :: ARef 4K (Array 1024 PDE)
```

Portable Assembly Language

- Habit shares with C the goal of being a portable assembly language:
  - High-level (e.g., expressions not registers)
  - Intuitive (albeit approximate) mapping to machine; predictable performance/costs
- Except that Habit will:
  - Provide a formal semantics from the outset
  - Allow more precise control over data layout
  - Support higher-level programming features
  - Eschew the use of unsafe primitives

Performance Annotations

- How are resource sensitivity and performance expectations captured in code?
- Open research problem
- Initial approach for Habit:
  - Performance annotations to guide code generation
  - Compiler feedback to guide programmer refactoring of code

```
[noalloc]
sum [1..10]

[noalloc]
let loop t n
 = if n>10 then t
   else loop (t+n) (n+1)
in loop 0 1


[noalloc]
natfold 0 (+) 10
```

Habit 6

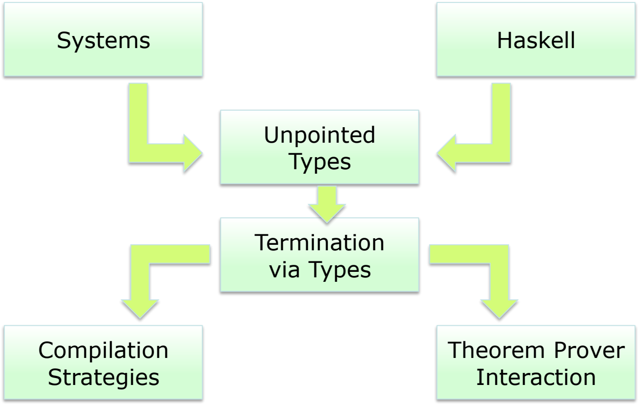
Synergize

Principles of Creative Cooperation

Synergy

- When 1 + 1 is more than 2
- Synergy via our collaboration with Galois
- Synergy via technical developments

Unpointed Types



Unpointed Types

- Every type in Haskell is **pointed**:
  - Includes a bottom element denoting failure to terminate
  - Enables general recursion, complicates reasoning
- But many types in systems programming (e.g., bit fields, references,…) are naturally viewed as **unpointed**:
  - No bottom element, stronger termination properties, primitive recursion still possible via "fold" operations
- Could be modeled by lifting to attach "false bottom"
  - Better to handle directly; more expressive types

Integrating Unpointed Types

- A strategy for integrating unpointed types in Haskell using type classes was proposed by Launchbury and Paterson
- We are scaling this to a full language design
- Example:

```
fpsize                      :: Bit 6 -> Bit 6
fpsize n | n==1              = 32
         | n<12              = 0
         | otherwise         = n
```

  Finite, pointed domain and range enables implementation as a lookup table, computed at compile-time

Habit 7

Sharpen the Saw

Principles of Balanced Self-Renewal

The Fable:

- Sawing down a tree will be easier if you pause from time to time to sharpen the saw
- Less time hacking
- Take some time to improve the tools

Paradigm Shifts

- According to Thomas Kuhn in “The Structure of Scientific Revolutions”:

- Almost every significant break through in the field of scientific endeavor is first a break with tradition, with the old ways of thinking

Time for a new Paradigm Shift?

- The systems programming community went through a major paradigm shift in the move from assembly to C**,** enabling:
  - New levels of functionality
  - New levels of portability

- Languages like Habit are positioning for a new paradigm shift that will enable:
  - New levels of assurance and security

Current Status

- On target to complete baseline design and implementation this summer:
  - Language design
  - Front-end implementation (parser, type checker, …)
  - Formal semantics
  - Small case studies

- In progress:
  - Prototype backend via Leroy’s Compcert framework for semantics preserving compilation
  - Integration with HARTS
  - Demonstration application

Conclusions

One Habit for Highly Effective High Assurance Systems Programming:

- Builds on critical successes in the design of Haskell

- Reflects requirements and feature set for the systems programming domain

- Provides foundations for formal verification

- Serves as a platform for future research and technology transfer activities