Implementing the STG

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Implementing the STG

- Last lecture: abstract machine for STG evaluation
- This lecture: implementing the STG on standard architectures
  - code generation
  - representation of the *heap* and *stacks*

1. Code generation
2. Heap representation
3. Implementation of stacks
4. Transitions of the abstract machine

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4. Transitions of the abstract machine

Code generation

Option: Generate C code rather than machine code.

Advantages

- facilitates suport for differente architectures
- re-uses optimizations in existing C compilers

Disadvantages

- generating machine code allows specializad otimizations
- standard C does not support everything necessary for a compiler backend (for example: cross function jump to a label)
- may require non-standard extensions (GCC)

Code generation (cont.)

Currently

- GHC suports native code generation for X86, AArch64, PPC and Wasm
- C code generation is no longer enabled by default
- Alternative: generate LLVM intermediate code

  `http://llvm.org/`

Code addresses

Used in three forms:

- to label code blocks;
- kept in data structures (stack, *closures*, . . .);
- as destination for control flow instruction (jump).

How can we represent this in C?

1st Version: use integers

```
#define JUMP(label) ((pc=label),break)

main () {
  int pc = 1;    /* program counter */
  while (TRUE) do
    switch(pc) {
       1:  /* code for label 1 */
           ....
           JUMP(...);
       2:  /* code for label 2 */
       ...
    }
}
```

Disadvantages

- One extra layer of interpretation
- Stresses the C compiler:
  a single function contains all compiled code
- Does not allow for separate compilation

2nd Version: function pointers

- Each basic block is a C function
- The return value is the address of the continuation
- A mini-interpreter executes the blocks in sequence

Return the continuation address

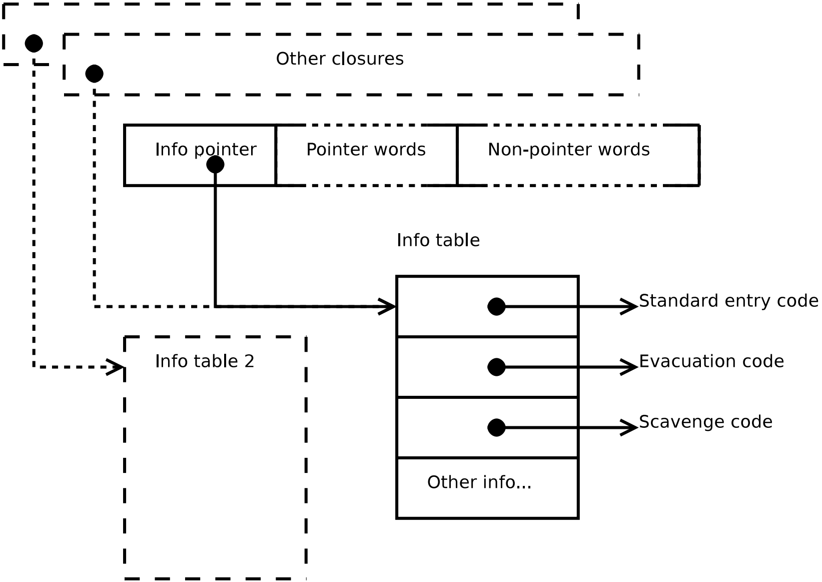
```
typedef void *(*codeptr)(void);
#define JUMP(label) return(label)

codeptr label1() {   /* code for label 1 */
    ....
    JUMP(label2);
}
codeprt label2() {   /* code for label 2 */
    ....
}

int main() {      /* mini-interpreter */
    codeprt pc = label1;
    for(;;) { pc=(*pc)() };
}
```

Advantages

- Code addresses correspond to machine code pointers
- Generates C functions for small code blocks
- Suports separate compilation using the standard *linker*
- Optimizations:
  - avoid creating the stack frame and *frame pointer*
  - generate *assembly* for direct jumps:

```
#ifdef __x86__
/* x86 specific (incomplete!) */
#define JUMP(label)  asm("jmp "#label)
#else
/* portable C */
#define JUMP(label)  return(label)
#endif
```

Representation for *closures*



Representation for *closures*

- An *info* pointer followed by a sequence of words
- The info pointer refers to static information about each kind of closure:
  1. *lambda-forms* declared in the program;
  2. construtors;
  3. indirections
- Pointers for running specific functions:

  standard entry: compiled code for each *lambda-form*;

  evacuation/scavenge: code for garbage collection
- Every closure with of same *lambda-form* shares the static table
- No need for tags or size information

Memory management

Two-space garbage collector:

- Heap divided in two areas: *fromspace* and *tospace*
- Allocations performed in *fromspace* (bumping a pointer)
- When the system runs out of available space:
  1. the colector copies every live closure to *tospace*
  2. the roles of the two areas are swapped

Closure rentention

Closures are live if:

- they are directly accessible from the execution stacks;
- they are accessible from other live closures;

i.e. they form the strongly connected component starting from the roots in the stack.

Requirements for the GC algorithm:

- reproduces the original heap graph;
- handles cycles and sharing;
- executes efficently (in time and space).

Copying GC algorithm

Cheney (1970)

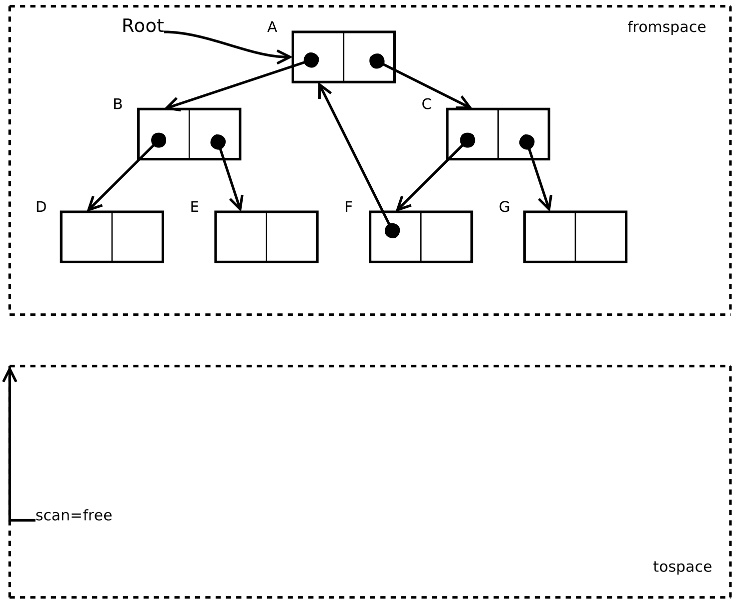
Evacuate: copy a closure *fromspace* $\rightarrow$ *tospace*:

1. places a *fowarding pointer* in the original address.
2. if it has been copied alread: returns immediatly.

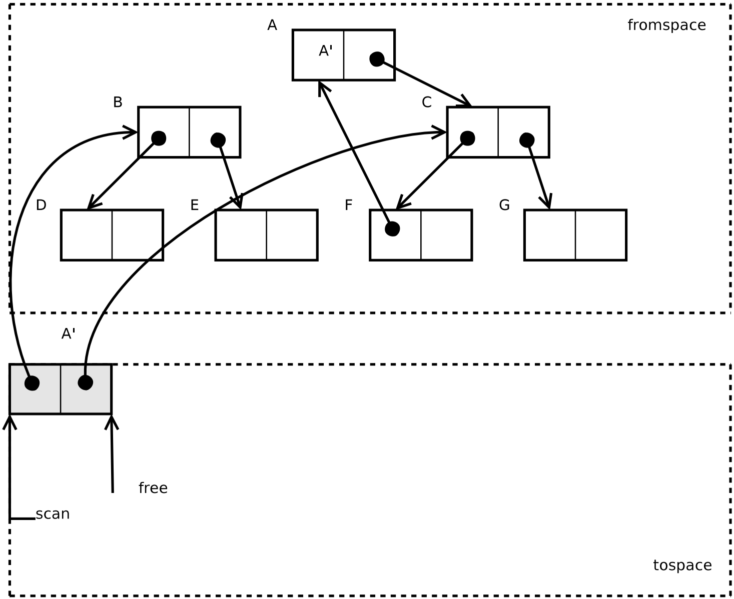
Scavenge: copies children of a closure in *tospace*

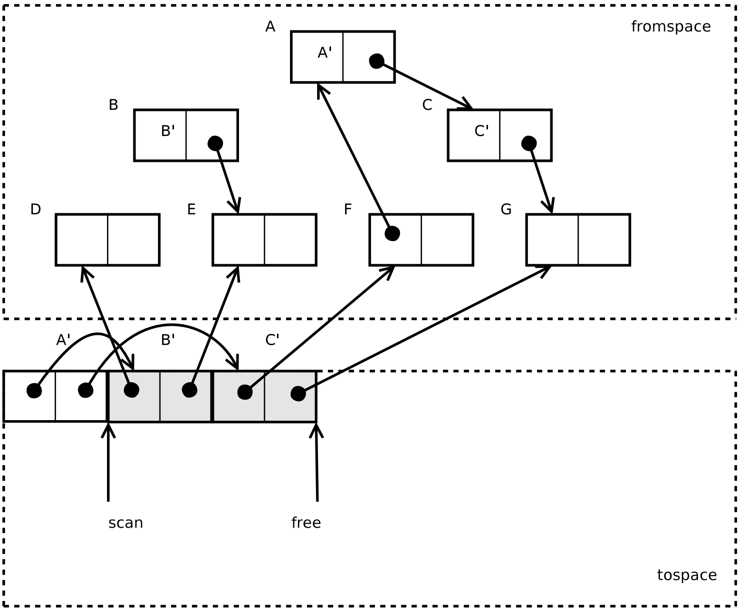
1. calls *evacuate* for each pointer in the copies closure;
2. replaces the pointer by the new address.

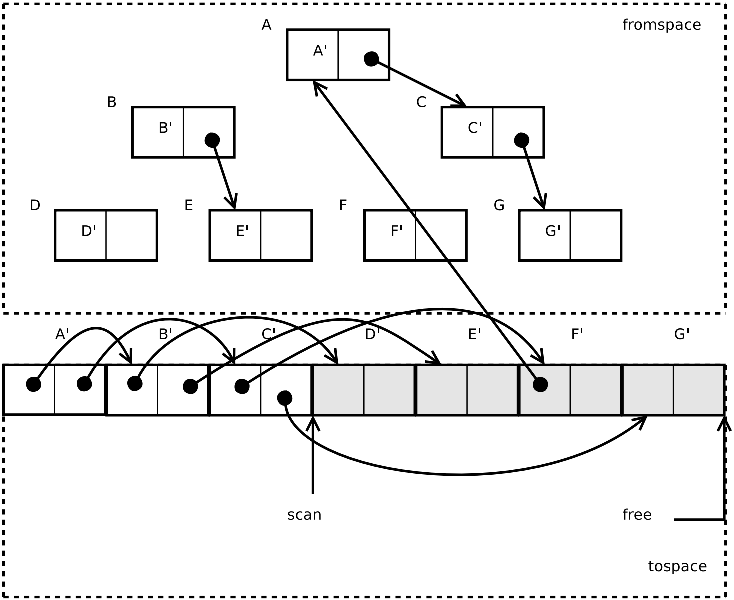
This algorithm is not recursive; instead it implements a queue using two pointers in *tospace*.



Root
A
fromspace
B
C
D
E
F
G
scan=free
tospace


fromspace
A
A'
B
C
D
E
F
G
A'
free
scan
tospace


fromspace
A
A'
B
B'
C
C'
D
E
F
G
A'
B'
C'
scan
free
tospace


fromspace
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
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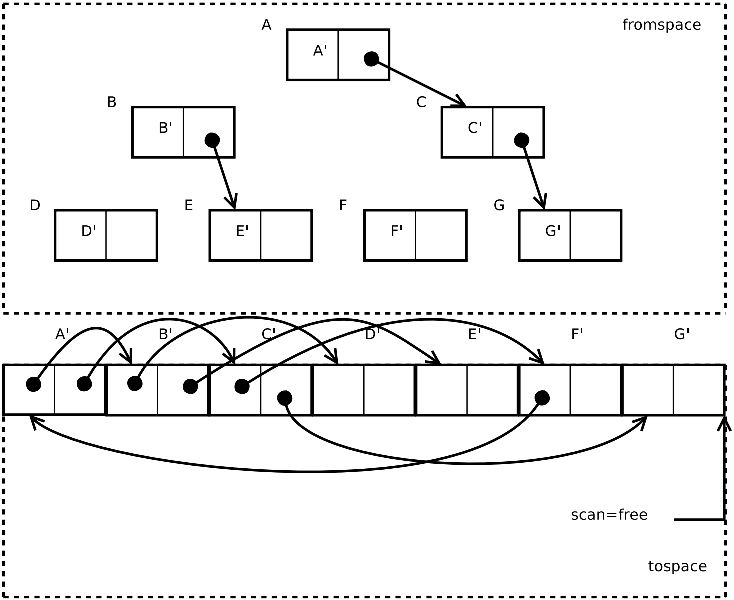
A'
B'
C'
D'
E'
F'
G'
scan
free
tospace


fromspace
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'
A'
B'
C'
D'
E'
F'
G'
scan=free
tospace

Two-space GC: advantages

- Preserves cycles and sharing of data structures
- Compacts the resulting semi-space
- Preserves *locality*: data that is used together is likely to be placed in the same page and cache line
- Facilitates memory allocation: simply bump a pointer in the resulting space
- Executes in constant space and time proportional to the size of live data
- Layout of the closures need to be known only in the *evacuate/scavenge* code
- No need for tags or size information
- Allows treating special cases (e.g. indirections)

Two-space GC: disadvantages

- Uses twice the live memory (2 spaces)
- Variant: *generational collectors*

Implementation of stacks

Three conceptually distinct stacks:

argument stack arguments to functions;

return stack continuations (case alternatives);

update stack update-frames.

How can we implement these?

A single stack?

- The three stacks works in sync
- It should be possible to combine into a single stack
- A contiguous block of words (e.g. *array* of `void *`)

Advantage: less space wasted

Disadvantage: mixing basic values (integers) and pointers in the stack makes GC harder

Two stacks

A-stack stack for pointers

B-stack stack for basic values

- The two stacks grow in oposing directions
- GC only goes throught stack A

Transitions of the abstract machine

- Each basic block is translated into a C function with no arguments sem parâmetros
- Function arguments passed on the stack
- Registers (e.g. stack pointers) kept in global variables

Function aplication

- Push arguments to the stack(s)
- Enter the closures associated to the function
- Global variable `Node` points to the active closure
- Access to free variables by indexes throught `Node`

Example

```
/* apply3 = {} \n {f,x} -> f {x,x,x}; */
/* SpA : top of stack A */

Node = SpA[0];    /* grab closure for f */
t = SpA[1];       /* grab x */
SpA[0] = t;       /* push extra args */
SpA[-1] = t;
SpA = SpA - 1;    /* adjust stack pointer;
  the A-stack grows to lower addresses */
ENTER(Node);       /* enter closure */
```

Enter a closure

- `Node` points to the *closure*
- Executes the code for the *standard entry*
- Always the 1st entry in the *info table*

```
#define ENTER(n)   JUMP((n)->info[0])
```

More information

Not covered:

- *let(rec)* and *case* expressions
- arithmetic operations
- *returns* and *updates*

See the bibliography: *Implementing lazy funcional languages on stock hardware: the Spineless Tagless G-machine*, Simon Peyton Jones, 1992.