Return to C

- A potpourri of stuff:
  - Idiomatic C
  - Scope
  - Preprocessor, conditional compilation
- Separate modules in C (i.e., ADTs)
- Dynamic memory (malloc, realloc, calloc)
- Arrays that grow in C
- Linked lists in C
- Trees in C

C string programming idioms

- "programming idiom"
  - "means of expressing a recurring construct in one or more programming languages"
  - use of idioms indicates language fluency
  - also assumes some comfort with the language
- idioms also imply terseness
  - expressions using idioms tend to be the "ideal" size
  - "terseness" can even have an impact as machine-code level
- non-string example: infinite loop

A C-language idiom: Infinite loop

```
/*
 * Not the ideal technique
 */

while (1) {
    some_function();
    if (someflag == 0) {
        break;
    }
    some_other_function();
}
```

Loop must always perform a check at the start of the loop.

```
/*
 * Recommended approach ("idiomatic").
 */

for (;;) {
    some_function();
    if (someflag == 0) {
        break;
    }
    some_other_function();
}
```

There is no check at the start of the loop -- no extra instructions!

Example: Computing string length

- Note!
  - Normally we use built-in library functions wherever possible.
  - There is a built-in string-length function ("strlen").
  - These libraries functions are very efficient and very fast (and bug free)
- Algorithm:
  - Function accepts pointer to a character array as a parameter
  - Some loop examines characters in the array
  - Loop terminates when the null character is encountered
  - Number of character examined becomes the string length

First example

```
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define MAX_STRING_LEN 100

int stringlength_1(char a_string[])
{
        int len = 0;

        while (a_string[len] != '\0') {
                len = len + 1;
        }
        return len;
}

int main(int argc, char *argv[])
{
        char buffer[MAX_STRING_LEN];

        if (argc == 1) { exit(0); }
        strncpy(buffer, argv[1], MAX_STRING_LEN);
        printf("%d\n", stringlength_1(buffer));

         exit(0);
}
```

C knows nothing about the bounds of arrays!

"char a_string[]" is the same as "char *a_string"

Each character is explicity compared against the null character. Note the single quotes!

Name of character array is passed as the parameter to stringlength_1.

"buffer" is the same as "&buffer[0]"

First example: not idiomatic

- C strings are usually manipulated via indexed loops
  - "for" statements
- "For" statements are suitable to use with loops:
  - where termination depends the size of some array
  - where termination depends upon the size of some linear structure
  - where loop tests are at loop-top and loop-variable update operations occur at the loop-end
- "While" statements are most suitable with loops:
  - where termination depends on the change of some state
  - where termination depends on some property of a complex data structure
  - where actual loop operations can possibly lengthen or shorten number of loop iterations (e.g., "worklist" algorithms)

Second example

```
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define MAX_STRING_LEN 100

int stringlength_2(char a_string[])
{
        int len;

        for (len = 0; a_string[len] != '\0'; len = len + 1) { }

        return len;
}

int main(int argc, char *argv[])
{
        char buffer[MAX_STRING_LEN];

        if (argc == 1) { exit(0); }
        strncpy(buffer, argv[1], MAX_STRING_LEN);
        printf("%d\n", stringlength_2(buffer));

         exit(0);
}
```

Each character is explicity compared against the null character, but this is done within the "for" header.

"For" loop itself is empty.

Second example: not idiomatic

- C strings are most often accessed via char pointers
- Accessing individual characters by array index is rare
  - Principle is that strings are usually processed in one direction or another
  - That direction proceeds char by char
- More idiomatic usage also depends upon pointer arithmetic

Third example

```
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define MAX_STRING_LEN 100

int stringlength_3(char a_string[])
{
        char *c;
        int len = 0;

        for (c = a_string; *c != '\0'; c = c + 1) {
                len = len + 1;
        }
        return len;
}

int main(int argc, char *argv[])
{
        char buffer[MAX_STRING_LEN];

        if (argc == 1) { exit(0); }
        strncpy(buffer, argv[1], MAX_STRING_LEN);
        printf("%d\n", stringlength_3(buffer));

         exit(0);
}
```

Note that a character pointer is used (i.e., dereferenced in the control expression, and incremented in the post-loop expression).

The body of the "for" loop is not empty here as variable "len" is increment in it.

(Note: We could add "len" to our "for"-loop header and keep the body empty. What would that look like?

Fourth example

```
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define MAX_STRING_LEN 100

int stringlength_4(char a_string[])
{
        char *c;
        int len;

        for (len = 0, c = a_string; *c; c++, len++) { }

        return len;
}

int main(int argc, char *argv[])
{
        char buffer[MAX_STRING_LEN];

        if (argc == 1) { exit(0); }
        strncpy(buffer, argv[1], MAX_STRING_LEN);
        printf("%d\n", stringlength_4(buffer));

         exit(0);
}
```

Note the "for"-loop termination condition!

We depend here on the meaning of "true" and "false" in C.

Note use of commas in the "for"-loop header.

Last examples: more idiomatic

- Char pointers were dereferenced
  - Value of dereference directly used to control loop.
- Char pointers were incremented
  - The most idiomatic code (not shown) combines dereferencing with incrementing
  - Example: `*c++`
  - Only works because "*" has a higher precedence than "++"
  - Meaning of example: "read the value stored in variable 'c', read the memory address corresponding to that value, return the value in that address as the expression value, and then increment the address stored in variable 'c'."

And tighter still…

```
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define MAX_STRING_LEN 100

int stringlength_5(char a_string[])
{
        char *c;

        for (c = a_string; *c; c++);

        return c - a_string;
}

int main(int argc, char *argv[])
{
        char buffer[MAX_STRING_LEN];

        if (argc == 1) { exit(0); }
        strncpy(buffer, argv[1], MAX_STRING_LEN);
        printf("%d\n", stringlength_5(buffer));

         exit(0);
}
```

Scope of Names

- The scope of a variable determines the region over which you can access the variable by its name.

- C provides four types of scope:
  - **Program** scope
  - **File** scope
  - **Function** scope
  - **Block** scope

Program Scope

- The variable exists for the program's lifetime and can be accessed from any file comprising the program.
  - To define a global variable, omit the extern keyword, and include an initializer (needed if you want a value other than 0).
  - To link to a global variable, include the extern keyword but omit an initializer
- Example:
  - Variable with program scope is declared and referenced file 1.
  - Variable with program scope is referenced in file 2.

```
/*
 * file 1
 */

int ticks = 1

void tick_tock() {
    ticks += 1;
}
```

```
/*
 * file 2
 */

extern int ticks;

int read_clock() {
    return ticks * TICKS_PER_SECOND;
}
```

File Scope

- The variable is visible from its point of declaration to the end of the source file.
- To give a variable file scope, define it outside a function with the **static** keyword

```
/*
 * file 3
 */

static long long int boot_time = 0;

void at_boot(void) {
    boot_time = get_clock();
}

...

int main(void) {
    printf("%i\n", boot_time);
}
```

```
/*
 * file 4
 */

/* THE LINE BELOW WILL FAIL
 * when the executable is constructed.
*/

extern long long int boot_time = 0;
```

Function Scope

- The name is visible from the beginning to the end of a function.
- According to the ANSI standard, the scope of function arguments is the same as the scope of variables defined at the outmost scope of a function. Shadowing of function arguments is not allowed.
- (Shadowing of global variables is permitted, however.)

```
/*
 * file 5
 */

void function_f(int x)
{
    ... = x + ...;
}
```

```
/*
 * file 6
 */

/* The variable declaration within the
 * function below will cause a compiler
 * error.
 */
void function_g (int x)
{
   int x;  /* Not possible. */
}
```

```
/*
 * file 7
 */
int sum = 0;

void function_h(int x)
{
    int sum = init_sum(); /* different! */
}
```

Block Scope

- The variable is visible from its point of declaration to the end of the block. A block is any series of statements enclosed by braces.

```
/*
 * file 7
 */

int sum;

void function_y (int X[], int n) {
    int j;

    {
        /* Start of a nested scope */

        int j;
        for (j = 0, sum = 0; j < n; j += 1)
{
            sum += X[j];
        }

        /* End of a nested scope */
    }
}
```

Abstract Data Types

- So far, we have described basic data types, all the standard C statements, operators and expressions, functions, and function prototypes.
- We want to introduce the concept of modularization
- Before there were object-oriented languages like Java and C++, users of imperative languages used **abstract data types** (ADT):
  - an abstract data type is a set of operations which access a collection of stored data
  - in Java and C++ this idea is called **encapsulation**

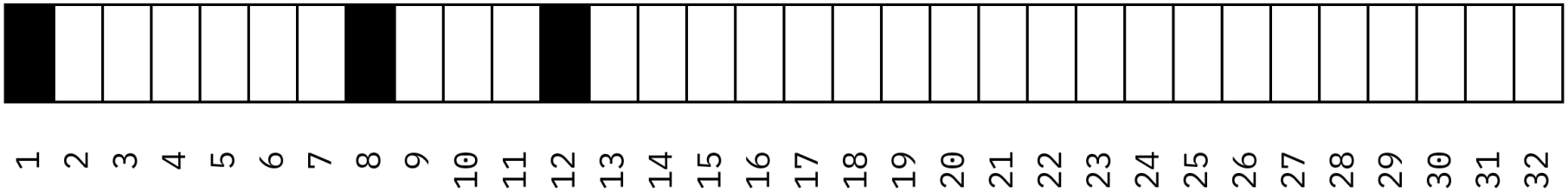
Abstract Data Types

- Since ANSI compilers support separate compilation of source modules, we can use abstract data types and function prototypes to **simulate modules**:
  - this is simply for convenience
  - a C compiler does not force us to use separate files
  - allows us to implement the “one declaration – one definition” rule

Abstract Data Types (2)

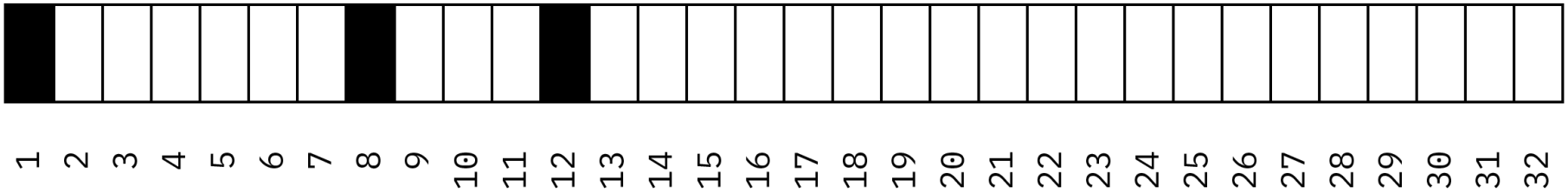
- For module "mod" there are two file
- **Interface module**: named "mod.h" contains function prototypes, public type definitions, constants, and when necessary declarations for global variables. Interface modules are also called header files.
  - Interface modules are accessed using the `#include` C preprocessor directive
- **Implementation module**: named "mod.c" contains the implementation of functions declared in the interface module.

Idea: bit storage



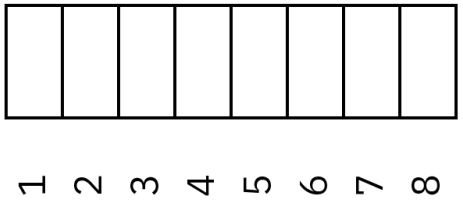

```
set_bit(set, 1)
set_bit(set, 8)
set_bit(set, 12)
```

Idea: bit storage (up to 32)

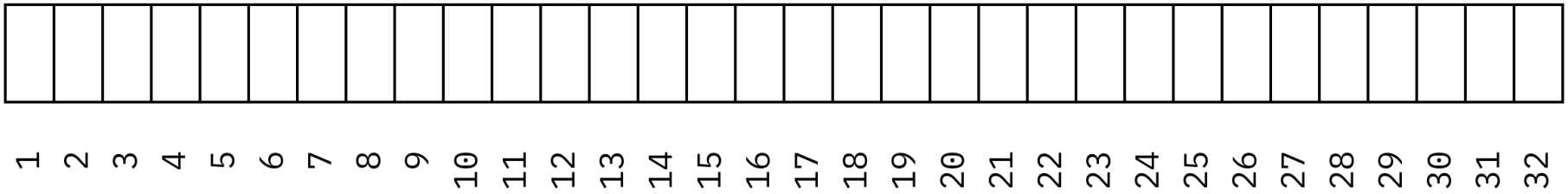



```
set_bit(set, 1)
set_bit(set, 8)
set_bit(set, 12)
```

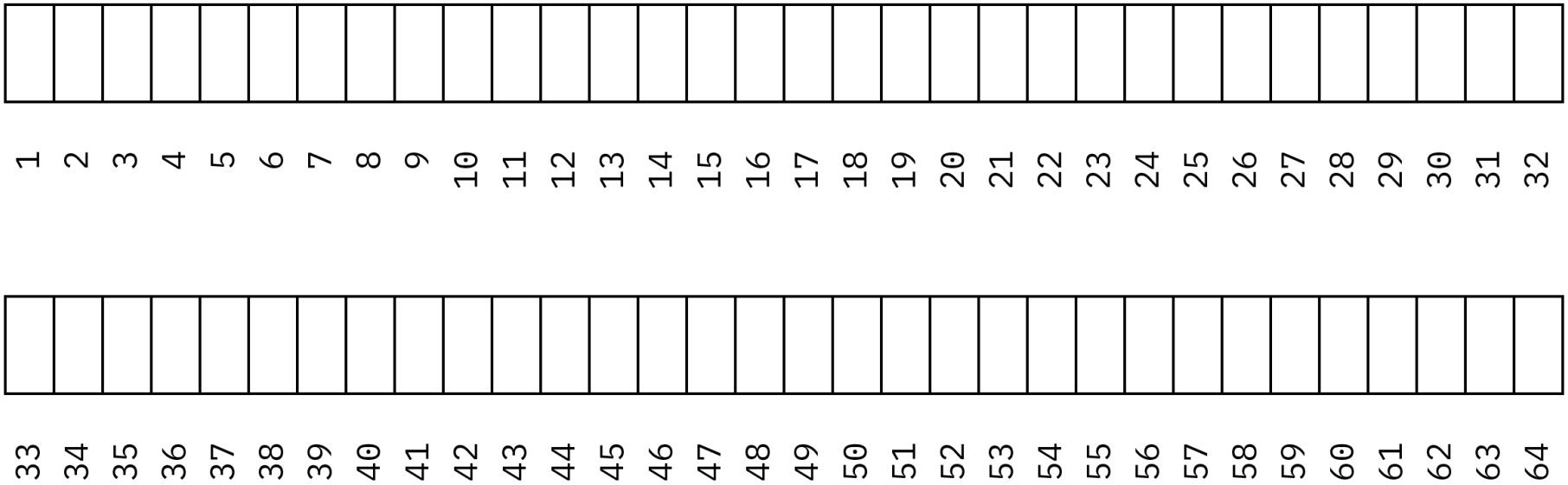
Smallest size: a byte



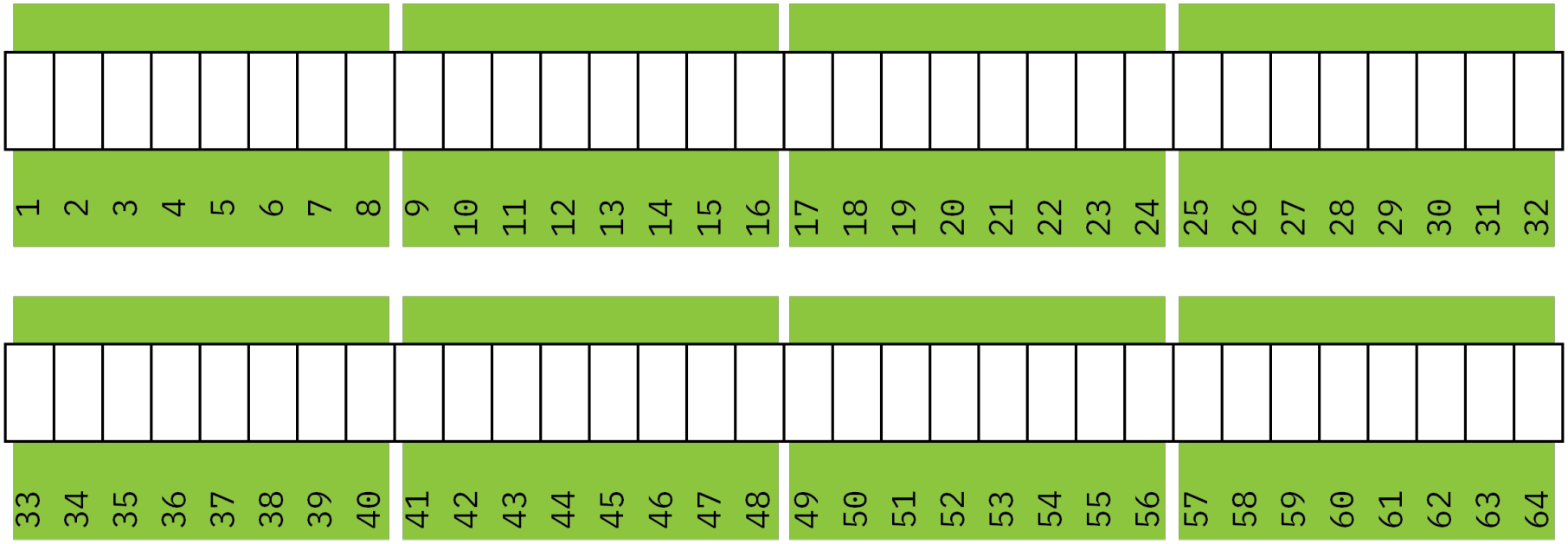
Another size: four bytes



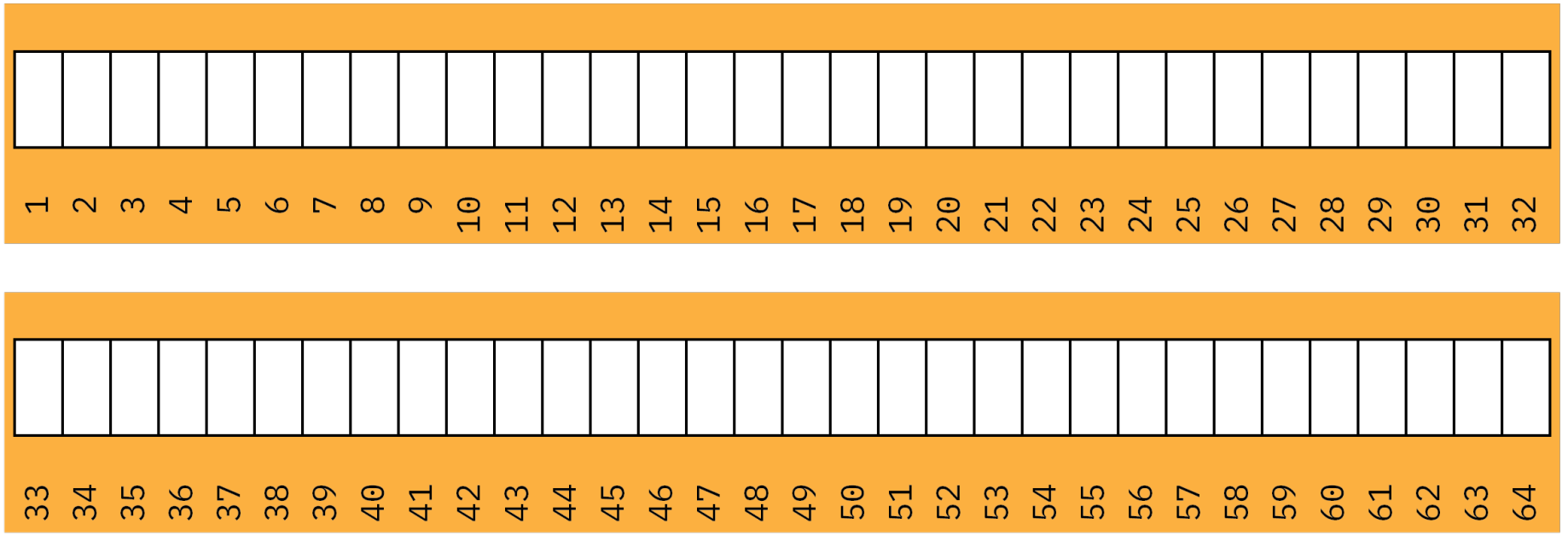
Another size: eight bytes



Byte boundaries



Four-byte integer boundaries



Example: module bitstring

- **Module** `bitstring`
  - Interface module: `bitstring.h` contains the declarations for data structures and operations required to support bitstring manipulation. Contains items (i.e., types, functions) which **must** be visible to the user of the module.
  - Implementation module: `bitstring.c` contains implementation of bitstring operations

Interface Module: bitstring.h

```
#ifndef BITSTRING_H
#define BITSTRING_H

typedef unsigned int Uint;
typedef enum _bool { false = 0, true = 1 } bool;

#define BITSPERBYTE     8
#define ALLOCSIZE       (sizeof(Uint)* BITSPERBYTE)
#define BYTESPERAUNIT   (sizeof(Uint))

/* -- Bit Operations */

extern void clear_bits( Uint[], Uint );
extern void set_bit( Uint[], Uint );
extern void reset_bit( Uint[], Uint );
extern bool test_bit( Uint[], Uint );

#endif
```

Implementation Module: bitstring.c

```
#include "bitstring.h"

/* Clear a bit string */
void clear_bits( Uint bstr[], Uint naunits ) {
    Uint i;

    for ( i = 0; i < naunits; i++ )
        bstr[i] = 0;
}

/* Set a bit in a bit string */
void set_bit( Uint bstr[], Uint bit ) {
    Uint b_index = ( bit - 1 ) / ALLOCSIZE;
    Uint b_offset = ( bit - 1 ) % ALLOCSIZE;

    bstr[b_index] |= ( 1 << b_offset );
}
```

Implementation Module (2)

```
/* Reset a bit in a bit string */

void reset_bit( Uint bstr[], Uint bit ) {
    Uint b_index = ( bit - 1 ) / ALLOCSIZE;
    Uint b_offset = ( bit - 1 ) % ALLOCSIZE;

    bstr[b_index] &= (~( 1 << b_offset));
}


/* Determine the state of a bit in a bitstring */

bool test_bit( Uint bstr[], Uint bit ) {
    Uint b_index = ( bit - 1 ) / ALLOCSIZE;
    Uint b_offset = ( bit - 1 ) % ALLOCSIZE;

    return( (bstr[b_index] & (1 << b_offset)) ? true : false );
}
```

Using the Bitstring Module

```
#include "bitstring.h"

#define NUNITS 4

int main( int argc, char *argv[] ) {
    Uint set[NUNITS];

    clear_bits(set, NUNITS);
    set_bit(set, 8);
    set_bit(set, 12);

    if (test_bit(set, 12) == true)
        reset_bit(set, 12);

    return 0;
 }
```

```
$ gcc module_user.c bitstring.c -o module_user
```

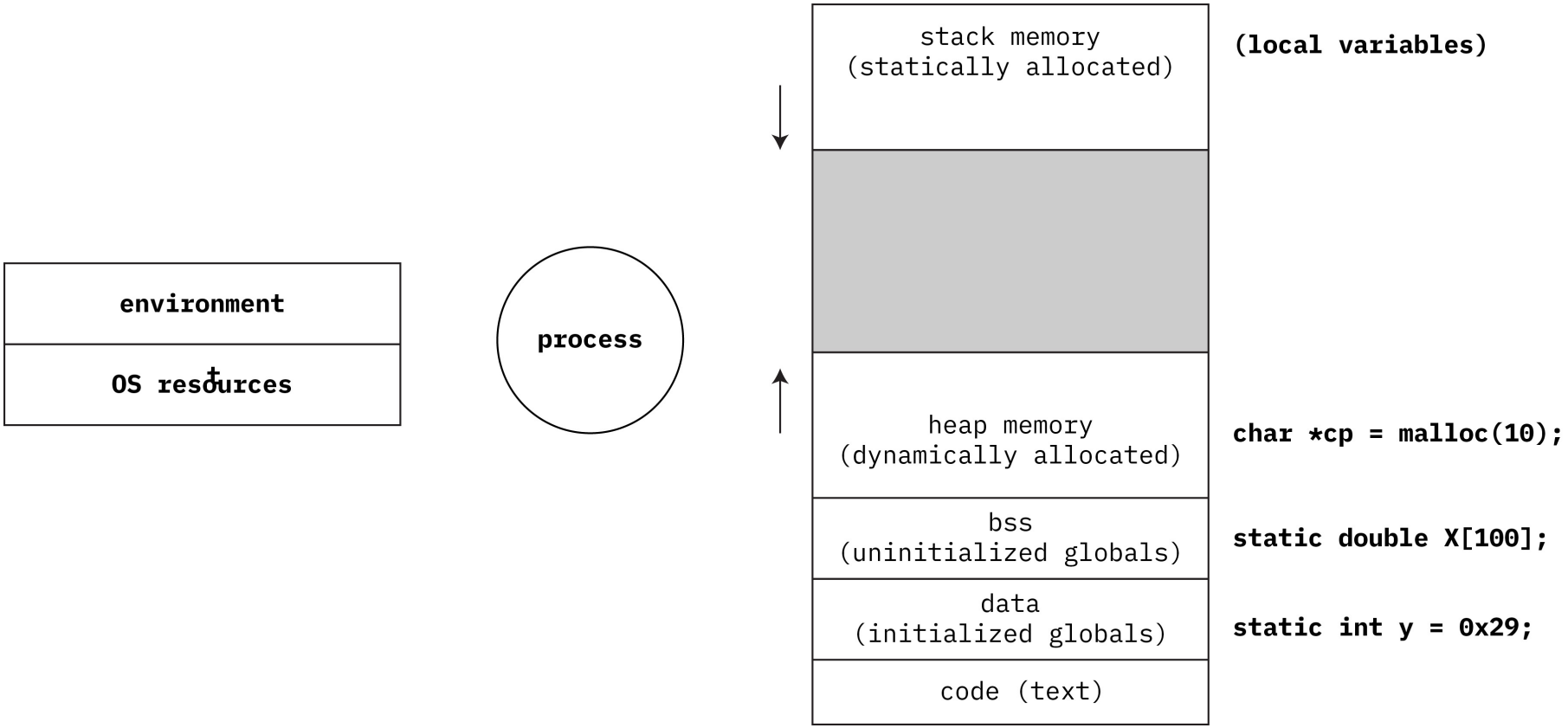
Dynamic memory in C

- The C memory model
- Managing the heap: `malloc()` and `free()`
- The void pointer and casting
- Memory leaks
- Applying the concepts:
  - **arrays that grow**
  - **linked lists**
  - **binary trees**
  - **hash maps**

C memory model

- Memory is divided into five segments: **uninitialized data**, **initialized data**, **heap**, **stack**, and **code**
- **Stack** is used to store **automatics** and activation records (stack frames) for functions
- Stack is located at the "top" of writable memory (high addresses)
- **Heap** stores explicitly requested memory which must be **dynamically allocated**
- Limits of heap and stack can bump into each other
- Initialized and uninitialized data located at at "top" of writable memory (high addresses)

C memory model



C memory model

- As the program executes, and function call-depth increases, the stack **grows downward**
- Similarly, as memory is explicitly requested for allocation, the heap **grows upward**
- Every time a function call is made, a new **stack frame** is created and memory allocated for variables to be used by the function
- Eventually, if stack and heap continue to grow, all memory available to the process will be exhausted and an **out of memory** condition will occur

Motivation for dynamic memory

- Memory must be allocated for storage before variables can be used, yet the amount might not be known at compile time
- Examples:
  - Reading records from a file in order to sort them, where file size is not known at time program is written
  - Constructing a list of "keywords" based on the content of some text file (whose size is unknown at compile time)
  - Representing a set as a linked list

Motivation for dynamic memory

- One solution: Write the program by hard-coding in the largest amount of memory that could possible be needed
- Problem with this approach: Possibly occupies a large, unused area of memory if program-input sizes for most executions are almost always small
  - Note: virtual-memory systems mitigate the effects of this somewhat

Where to store what…

- Use **heap memory** for dynamic allocation when size is not known until run-time
- Use **stack memory** for parts where size is known at compile time
- Working with the stack is easy -- all variables are defined at compile time (no extra work for you)
- Working with the heap is a bit harder
  - In Java and Python, heap memory is automatically allocated to objects through use of the "new" keyword
  - Also in Java & Python, heap memory no longer used by a variable may be reclaimed for the system (**garbage collection**)

Heap memory in C

- Memory addresses in the heap are sometimes called **anonymous variables**
  - These variables do not have names like automatics and static variables
- `malloc()`: allocate dynamic memory
  - Takes a single parameter representing the **number of bytes of heap memory to be allocated**
  - **Returns a memory address** to the beginning of newly allocated block of memory
  - **If allocation fails**, `malloc()` returns NULL
- `#include <stdlib.h>` : contains function prototypes for malloc and related functions.

sizeof

- `sizeof()` is a macro that computes the number of bytes allocated for a specified type or variable (basic types, aggregate types)
- Use `sizeof()` to determine block size required by `malloc()`
- You must **always** check the value returned by `malloc()`!

```
int *a = malloc (sizeof(int));
if (a == NULL) { /* error */ }

struct datetype *dt = malloc (sizeof(struct datetype));
if (dt == NULL) { /* error */ }

char *buffer = malloc (sizeof(char) * 100);
if (buffer == NULL) { /* error */ }
```

malloc() + casting

- Function prototype for malloc() :
  - `extern void *malloc( size_t n );`
  - `typedef unsigned int size_t;`
- The pointer returned is a generic pointer
- To use the allocated memory, we must **typecast** the returned pointer
  - Denoted by (`<sometype> *`)
  - Casting is a hint to the compiler (applies different typechecking to the block of memory after the typecast)

```
double *f = (double *) malloc (sizeof(double));

char *buf = (char *) malloc(100);
```

Casting

- What if we do not typecast?

```
double *f = malloc(sizeof(double));
...
<from some compilers>
 warning: assignment makes pointer from
          double without a cast
```

- Always a good idea to cast
- Once heap memory is allocated:
  - It stays allocated for the duration of the program's execution…
  - … unless it is **explicitly deallocated**
  - … and this is true regardless of what functions calls malloc()
  - All memory used in heap is automatically returned to system when process/program terminates.

A family of functions

- There is more than just `malloc`:
  - `calloc`
  - `realloc`
  - `valloc`
- These serve slightly different purposes
  - One function both allocates and initializes the block of heap memory
  - One function adjusts heap structures to change size of a previously allocated block/chunk
  - One is now pretty much obsolete (i.e., meant to force allocation on some page boundary – which will make more sense in CSC 360)
- As we need these extra functions we'll trot them out

free()

- We use `free()` to return heap memory no longer needed back to the heap pool

```
extern void free( void * );
```

- `free()` takes a pointer to the allocated block of memory

```
void very_polite_function( int n )
{
    int *array = (int *) malloc (sizeof(int) * n);

    /* Code using the array */

    free (array);
}
```

Issues with dynamic memory

- A **memory leak** occurs when heap memory is **constantly allocated** but is **not freed** when no longer needed
- Memory leaks are almost always unintentional
  - Allocation and deallocation code locations are often widely separated.
  - Can be hard to find the memory-leak bug as it often depends upon the program running for a long time.
- Systems with automatic garbage collection (almost) never have memory leaks
  - Redundant memory is returned to heap for re-use
  - Downside: garbage collection is not always under control of the programmer
  - Also: some garbage collectors cannot reclaim some kinds of redundant instances of data types.

Arrays that grow

- All of our C programs using arrays up to now have been static in size
  - Assignment specifications state the largest input size.
  - Memory is allocated for these arrays from the C compiler and run time
  - We never need to manage this memory.
- Arrays are very handy structure
  - Easy to index and access (O(1) operations)
  - Contiguous block of memory can be exploited by other functions (qsort, memcpy).
- Therefore we would like to keep the convenience of arrays but also obtain the benefits of dynamic memory
  - … and do so without having to write more complex structures like lists, heaps, etc.

Nameval array

- Suppose we wish to maintain an array of <name, value> pairs
  - Name is a string
  - Value is an integer
- We want to add new items to our array as the arrive
- If there is not enough room in the array, we want to grow it.
- To support this we'll keep the array's size and items-to-date associated with the array via a struct.
  - Note use of "typedef"

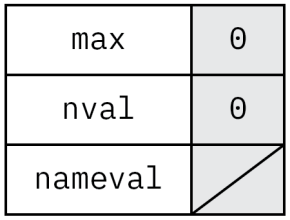
```
typedef struct Nameval Nameval;
struct Nameval {
    char   *name;
    int     value;
};
```

```
struct Nvtab {
    int   nval;
    int   max;
    Nameval *nameval;
} nvtab;

enum { NVINIT = 1, NVGROW = 2 };
```

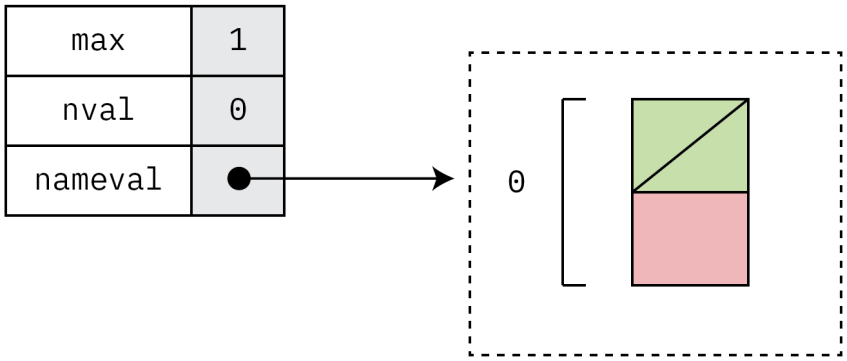
Creating a new nameval

```
Nameval *new_nameval(char *name, int value)
{
    Nameval *temp;

    temp = (Nameval *)malloc(sizeof(Nameval));
    if (temp == NULL) {
        fprintf(stderr, "Error mallocing a Nameval");
        exit(1);
    }

    /* temp->name === (*temp).name */
    temp->name = (char *)malloc((strlen(name)+1) * sizeof(char));
    if (temp->name == NULL) {
        fprintf(stderr, "Error mallocing a memory for string");
        exit(1);
    }
    strncpy(temp->name, name, strlen(name)+1);

    temp->value = value;

    return temp;
}
```

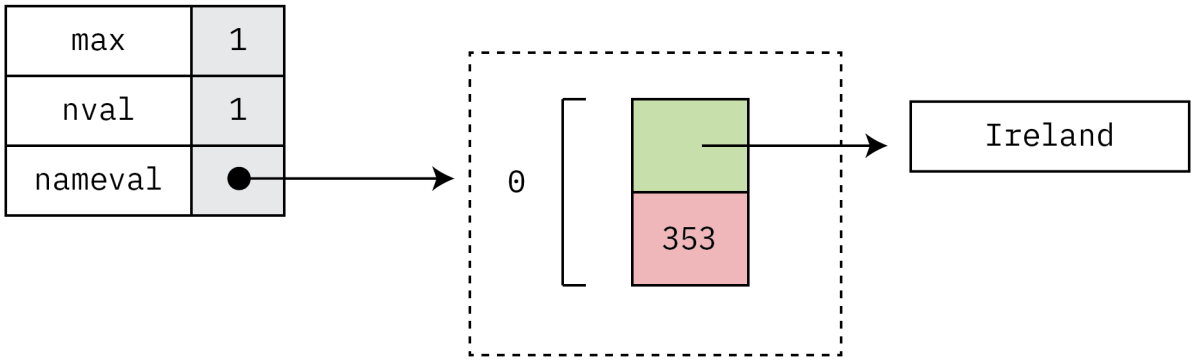
Initial value of **nvtab** variable



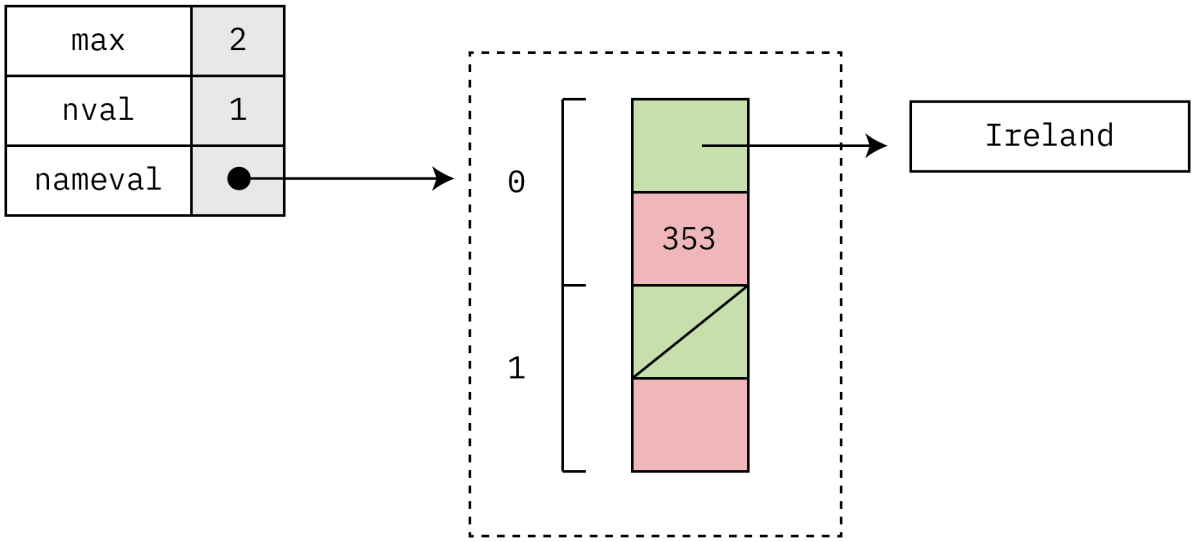
Adding ("Ireland", 353): after array in heap is allocated, but before assigning actual value



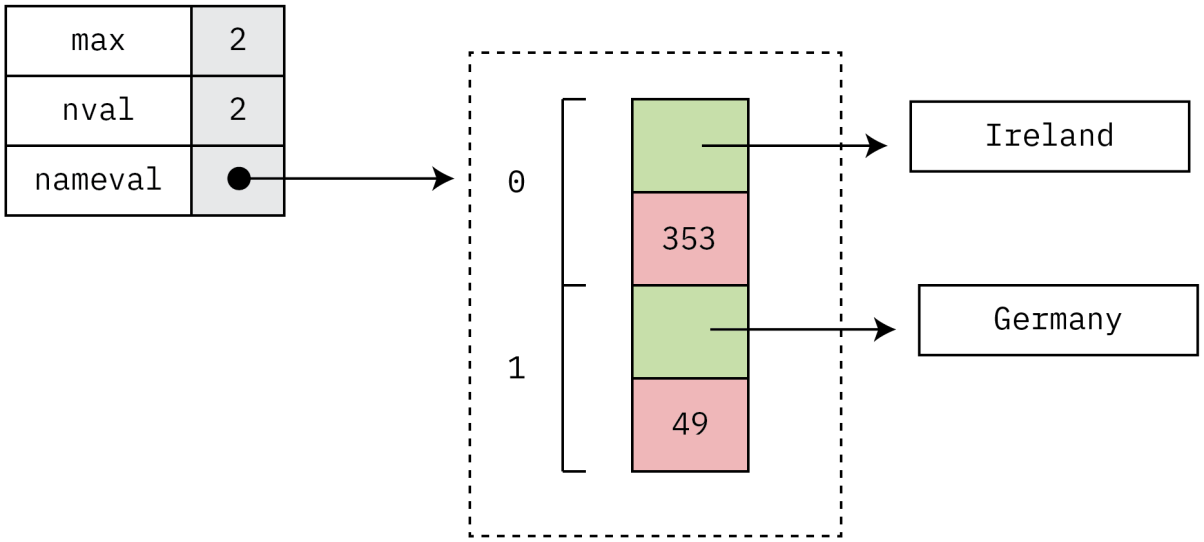
Adding ("Ireland", 353): after array in heap is allocated, and after assigning the actual value



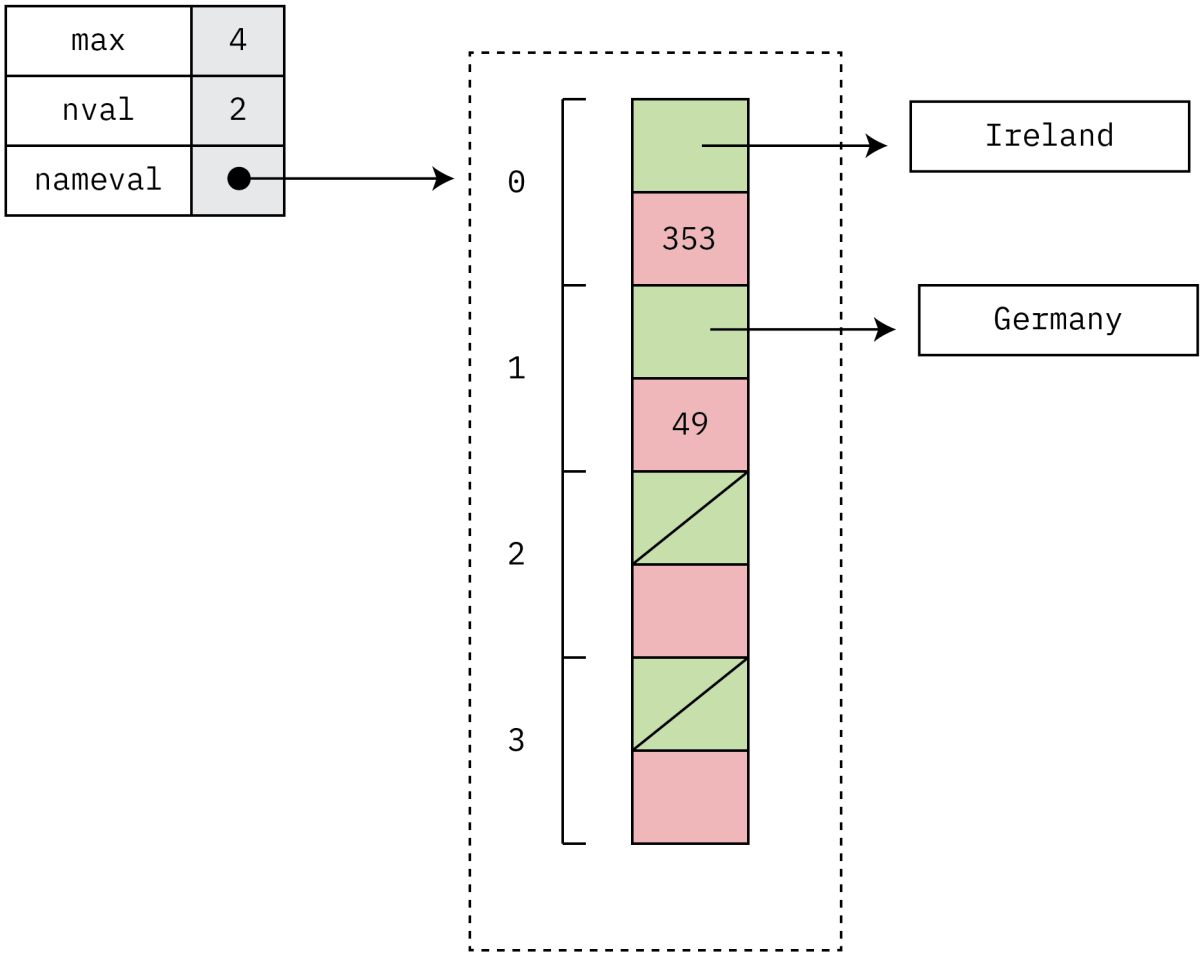
Adding ("Germany", 49): after array grows, but before assigning the actual value



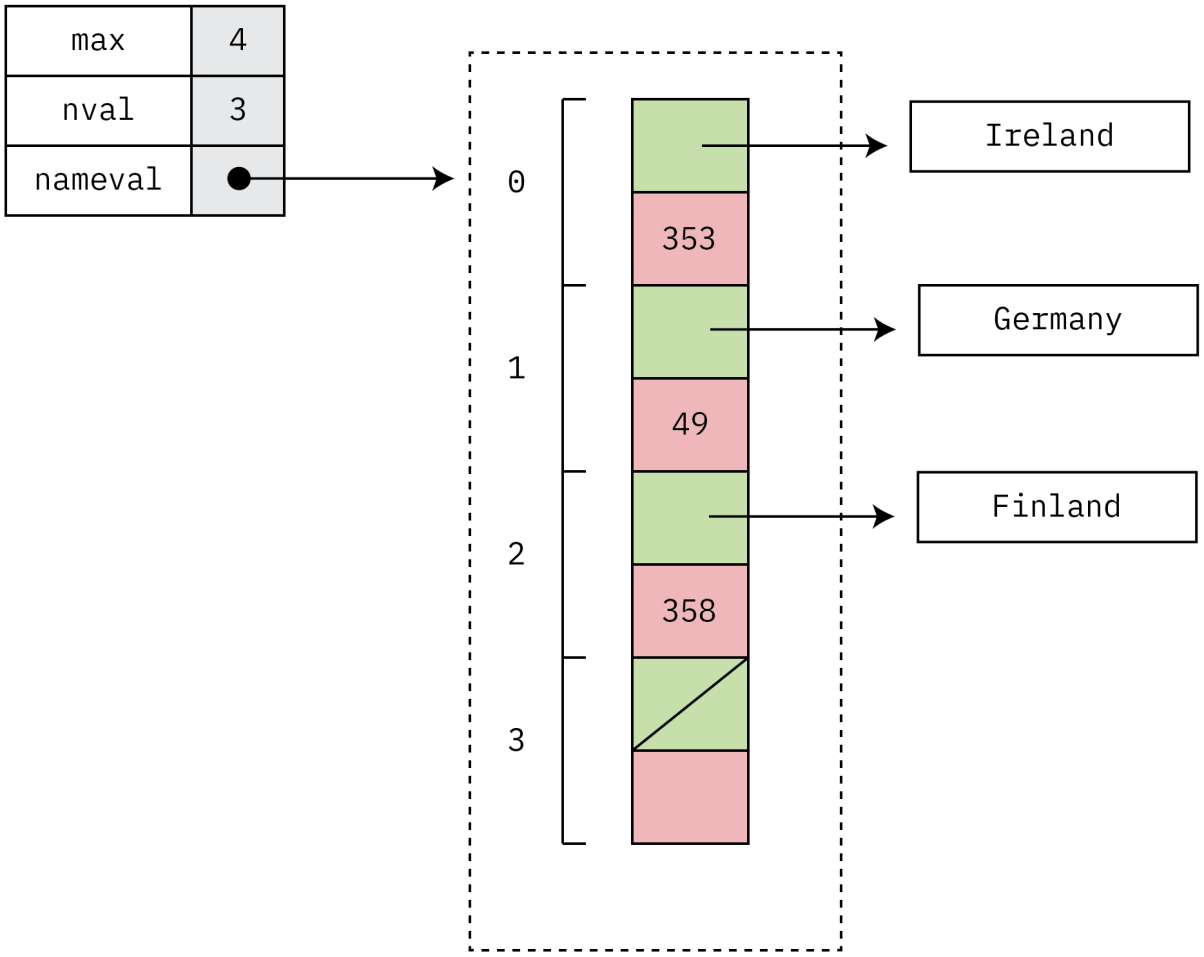
Adding ("Germany", 49): after array grows, and after assigning the actual value



Adding ("Finland", 358): after array grows, but before assigning the actual value



Adding ("Finland", 358): after array grows, and after assigning the actual value



... and notice that the next call to additem() will not result in the array needing to grow before assignment

addname

```
int addname(Nameval newname)
{
    Nameval *nvp;

    if (nvtab.nameval == NULL) { /* first use of array */
        nvtab.nameval =
            (Nameval *) malloc(NVINIT * sizeof(Nameval));
        if (nvtab.nameval == NULL) { return -1; }
        nvtab.max = NVINIT;
        nvtab.nval = 0;
    } else if (nvtab.nval >= nvtab.max) {
        nvp = (Nameval *) realloc(nvtab.nameval,
            (NVGROW * nvtab.max) * sizeof(Nameval));
        if (nvp == NULL) { return -1; }
        nvtab.max = NVGROW * nvtab.max;
        nvtab.nameval = nvp;
    }
    nvtab.nameval[nvtab.nval] = newname;
    return nvtab.nval++;
}
```

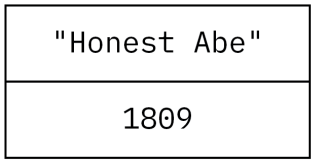
addname

```
int addname(Nameval newname)
{
    Nameval *nvp;

    if (nvtab.nameval == NULL) { /* first use of array */
        nvtab.nameval =
            (Nameval *) malloc(NVINIT * sizeof(Nameval));
        if (nvtab.nameval == NULL) { return -1; }
        nvtab.max = NVINIT;
        nvtab.nval = 0;
    } else if (nvtab.nval >= nvtab.max) {
        nvp = (Nameval *) realloc(nvtab.nameval,
            (NVGROW * nvtab.max) * sizeof(Nameval));
        if (nvp == NULL) { return = -1; }
        nvtab.max = NVGROW * nvtab.max;
        nvtab.nameval = nvp;
    }
    nvtab.nameval[nvtab.nval] = newname;
    return nvtab.nval++;
}
```

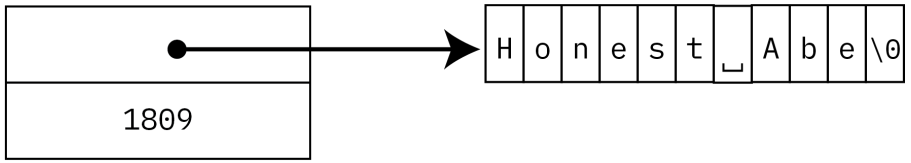
Deleting a name

- Arrays are contiguous…
  - Yet we may sometimes want to remove elements that are within the array
  - That is, neither at the start or end
- This can be tricky:
  - We need to decide what to do with the resulting gap in the array.
  - If element order doesn't matter: just swap last item in array with gap
  - If element order does matter (i.e., must be preserved), the we must move all the elements beyond the gap by one position

Reminder: This...

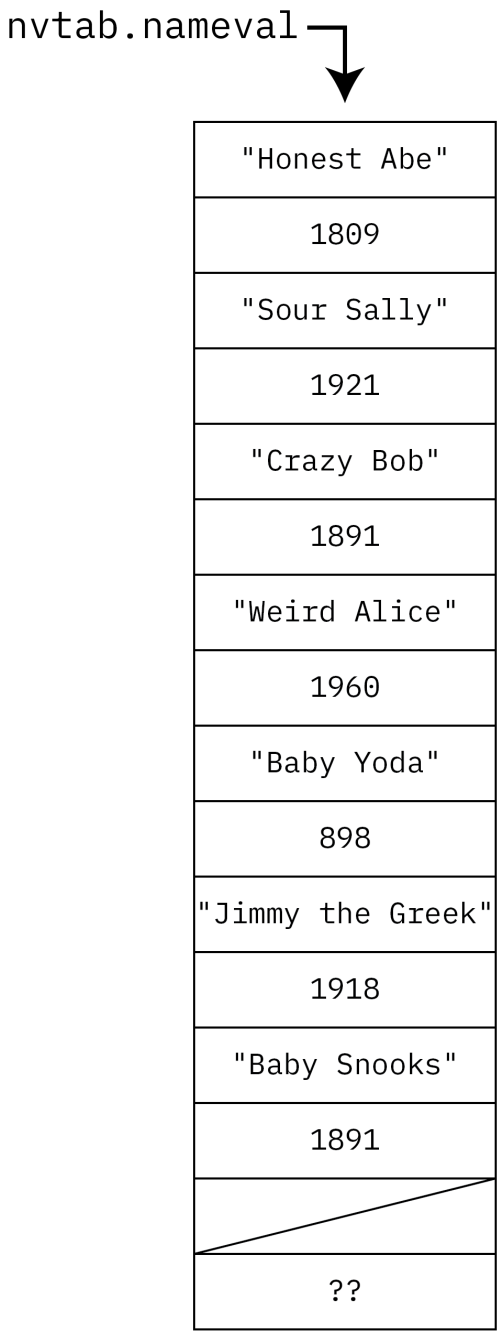


... is a shorthand way of representing this:



delname

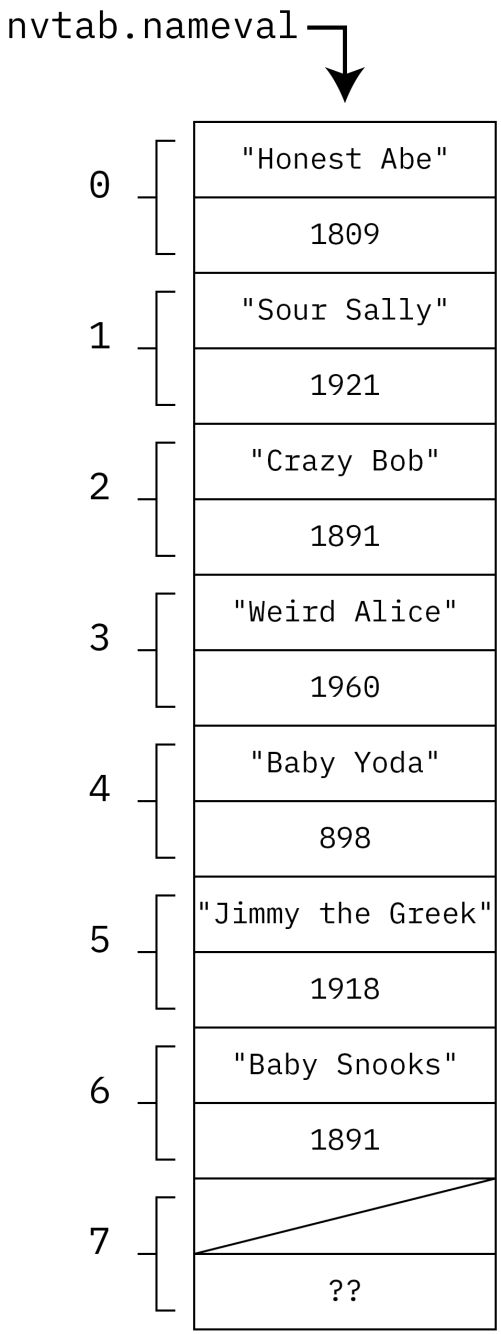
```
int delname (char *name)
{
    int i;

    for (i = 0; i < nvtab.nval; i++) {
        if (strcmp(nvtab.nameval[i].name, name) == 0) {
            memmove(nvtab.nameval + i, nvtab.nameval + i + 1,
                (nvtab.nval-(i+1)) * sizeof(Nameval));
            nvtab.nval--;
            return 1;
        }
    }
    return 0;

    /* Note that no realloc is performed to resize the array.
     * Do you think this action is needed???
     */
}
```




```
nvtab.max  == 8
nvtab.nval == 7
```

delname("Crazy Bob")

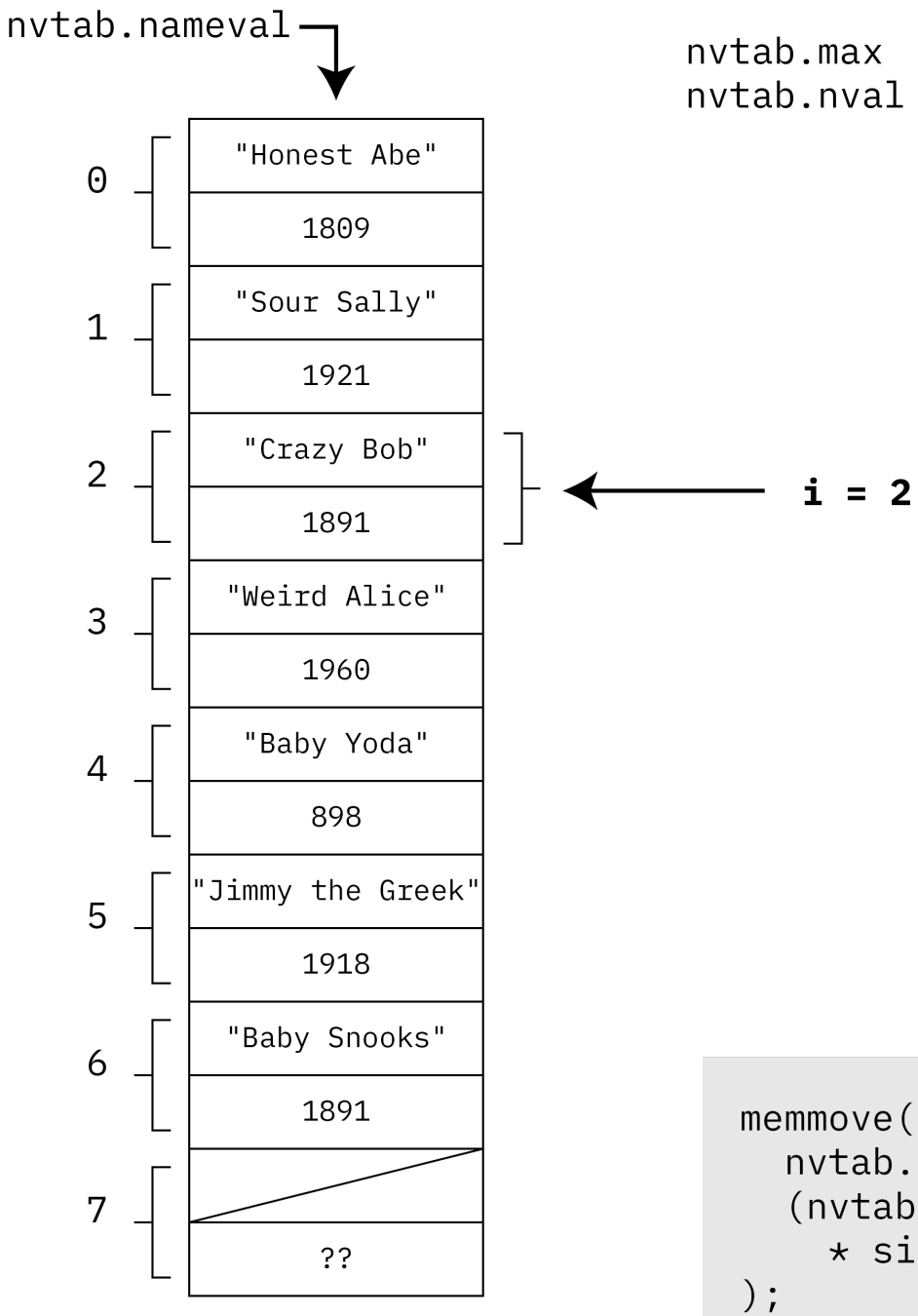
```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```



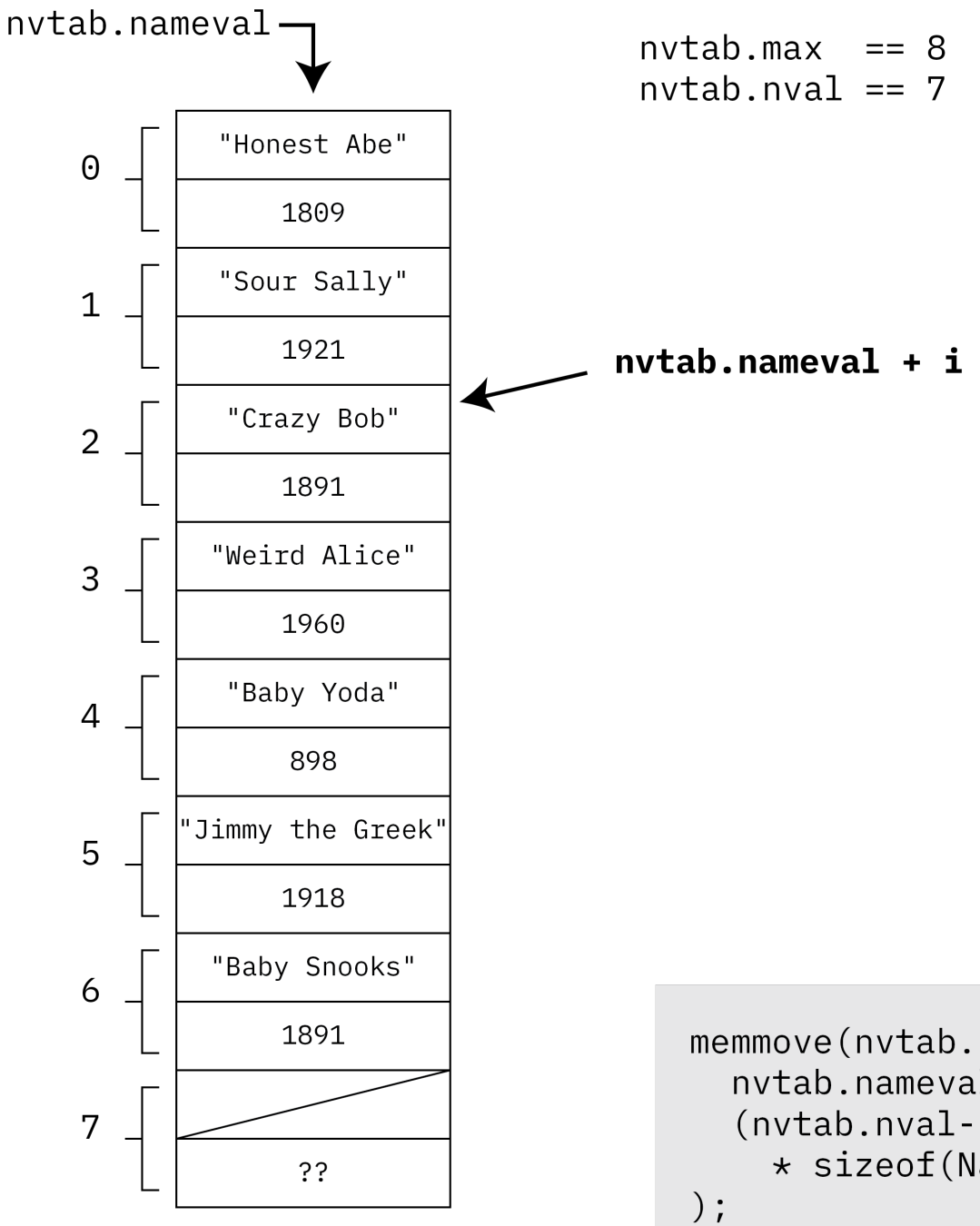

```
nvtab.max  == 8
nvtab.nval == 7
```

delname("Crazy Bob")

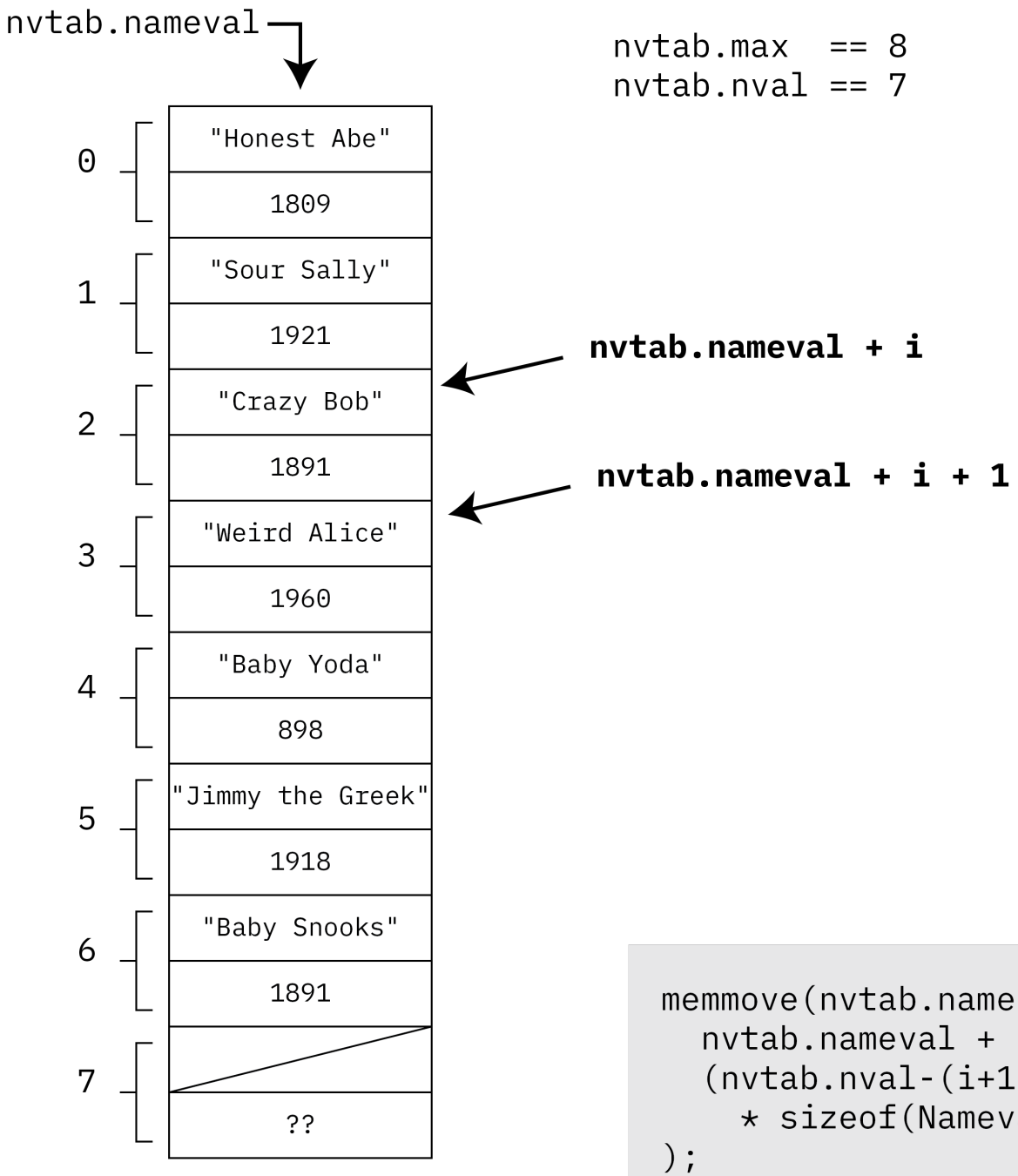
```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```



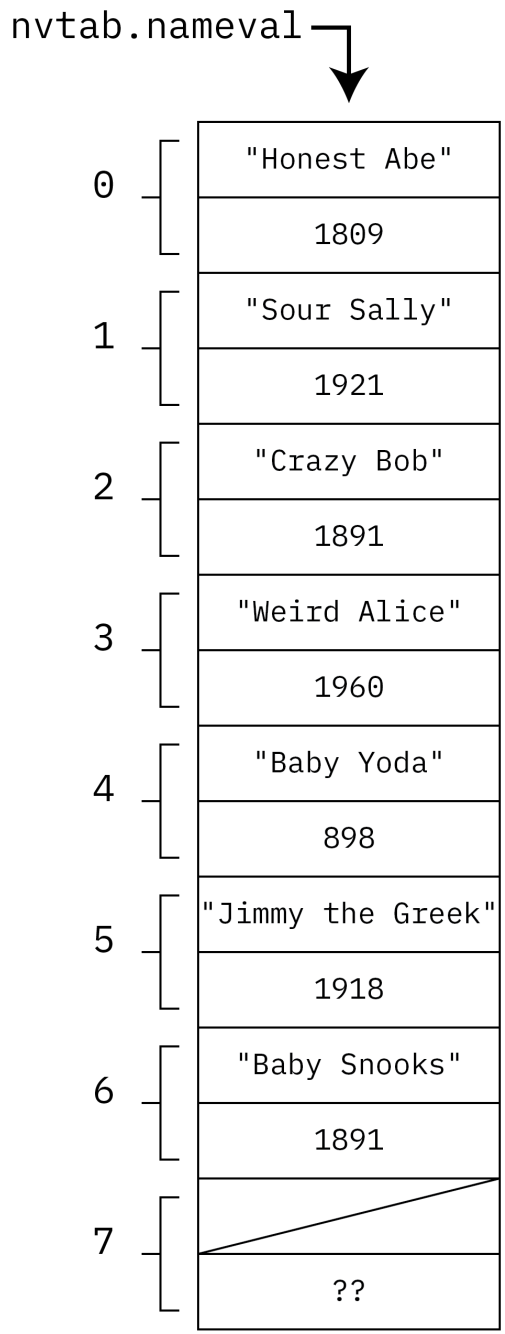

```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```




```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```




```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```



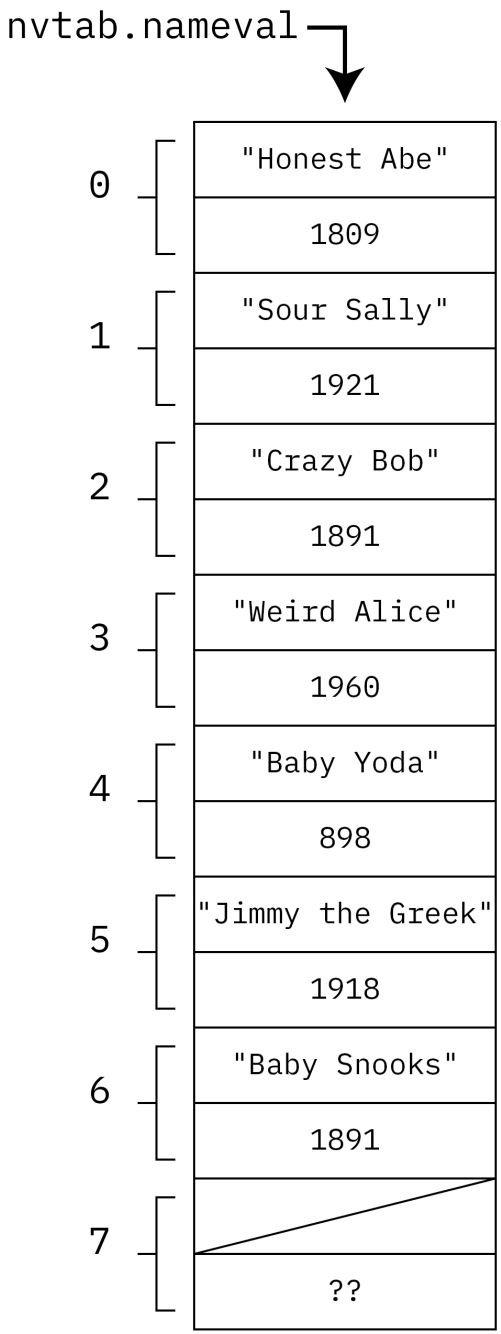

```
nvtab.max  == 8
nvtab.nval == 7
```

nvtab.nameval + i

nvtab.nameval + i + 1

nvtab.nval - (i + 1)
** * sizeof(Nameval)**

```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```



nvtab.max == 8
nvtab.nval == 7

nvtab.nameval + i

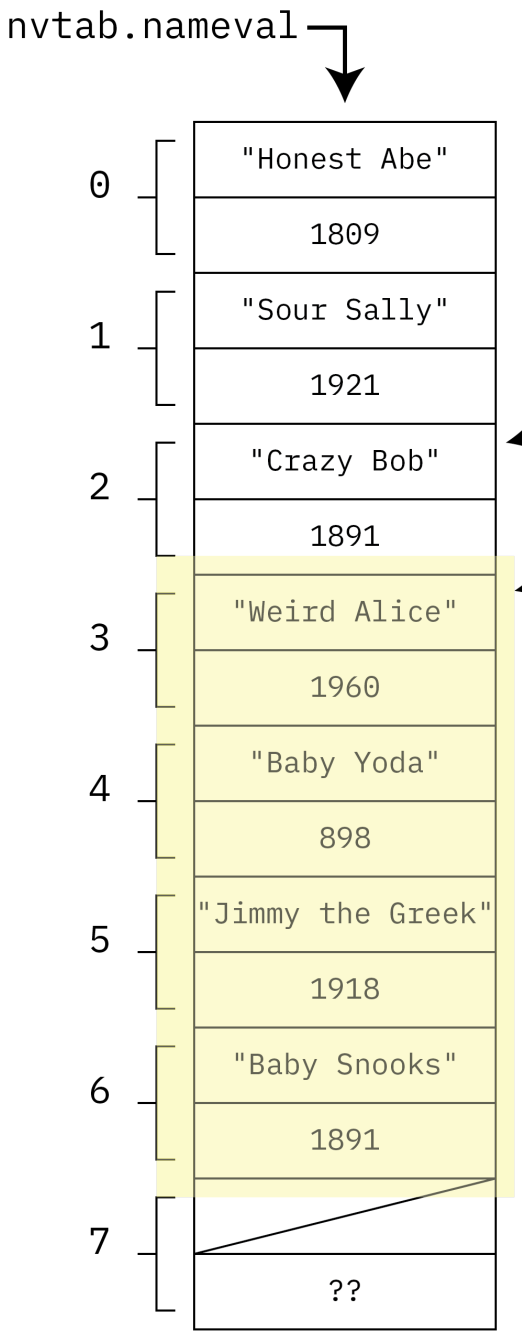
nvtab.nameval + i + 1

nvtab.nval - (i + 1)
*** sizeof(Nameval)**

= 7 - (2 + 1)
*** sizeof(Nameval)**

= 4 * sizeof(Nameval)

```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```



nvtab.max == 8
nvtab.nval == 7

nvtab.nameval + i

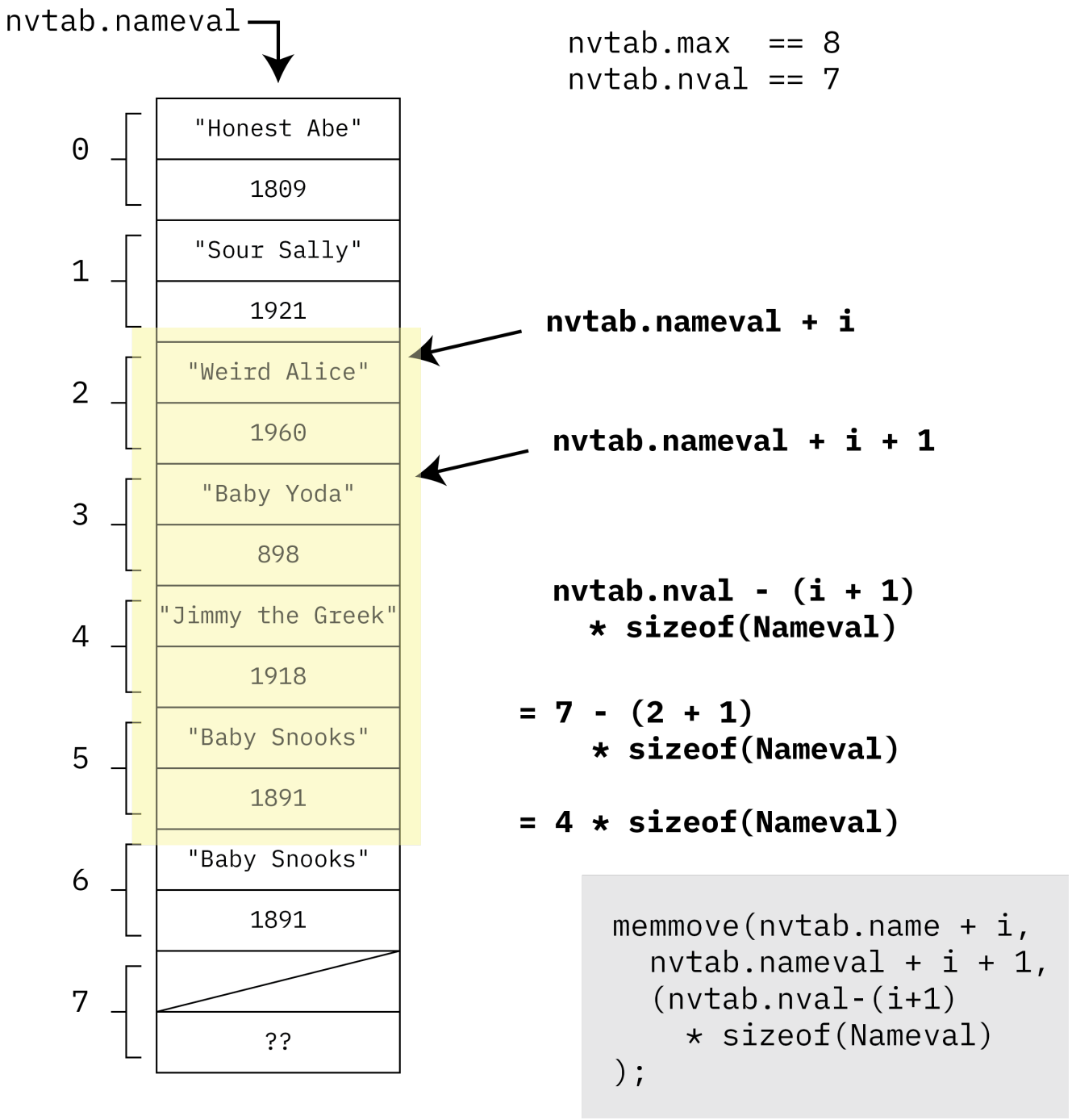
nvtab.nameval + i + 1

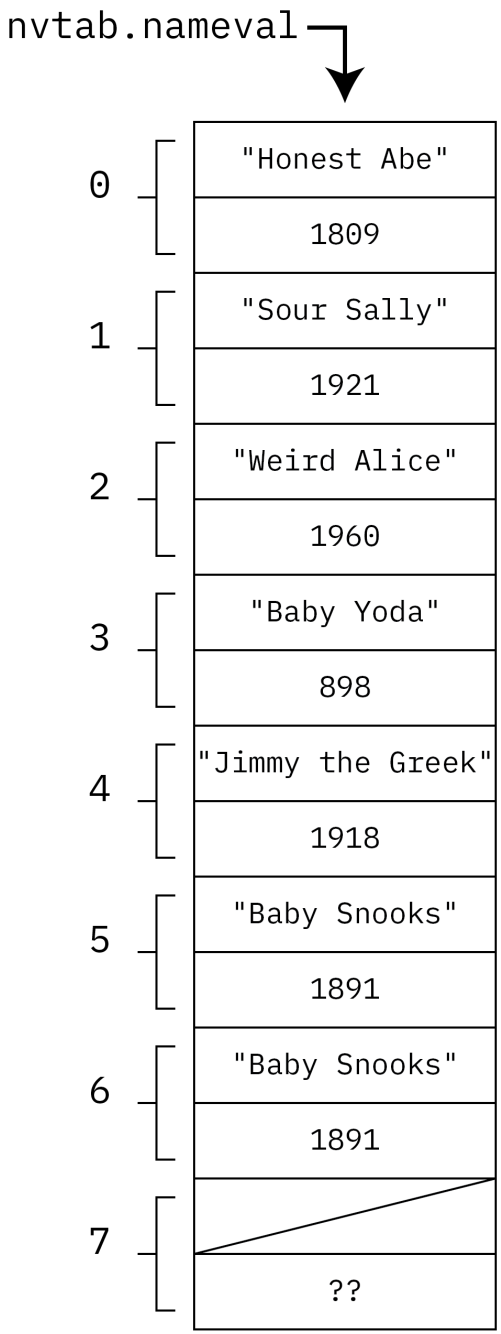
nvtab.nval - (i + 1)
*** sizeof(Nameval)**

= 7 - (2 + 1)
*** sizeof(Nameval)**

= 4 * sizeof(Nameval)

```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```


nvtab.nameval
nvtab.max == 8
nvtab.nval == 7
0
"Honest Abe"
1809
1
"Sour Sally"
1921
2
"Weird Alice"
1960
3
"Baby Yoda"
898
4
"Jimmy the Greek"
1918
5
"Baby Snooks"
1891
6
"Baby Snooks"
1891
7
??
nvtab.nameval + i
nvtab.nameval + i + 1
nvtab.nval - (i + 1)
* sizeof(Nameval)
= 7 - (2 + 1)
* sizeof(Nameval)
= 4 * sizeof(Nameval)
memmove(nvtab.name + i,
nvtab.nameval + i + 1,
(nvtab.nval-(i+1)
* sizeof(Nameval)
);




```
nvtab.max  == 8
nvtab.nval == 6
```

nvtab.nameval + i

nvtab.nameval + i + 1

nvtab.nval - (i + 1)
** * sizeof(Nameval)**

= 7 - (2 + 1)
** * sizeof(Nameval)**

= 4 * sizeof(Nameval)

```
memmove(nvtab.name + i,
  nvtab.nameval + i + 1,
  (nvtab.nval-(i+1)
    * sizeof(Nameval)
);
```

Chicken-and-egg...

- Consider this statement:
  - We must write our code **to be flexible for as many situations as possible**...
  - ... although this means we **cannot make some assumptions about input sizes**.
- Example:
  - For a file that processes text files, cannot make assumptions about the length of an input line
- Practical result:
  - Must (somehow) use malloc, realloc and possibly free appropriately
  - Safe alternative: `getline()`

getline() solution

```
#include <stdio.h>
#include <stdlib.h>

int main(void)
{
    FILE *fp;
    char *line = NULL;
    size_t len = 0;   /* size_t is really just an unsigned int */
    ssize_t read;     /* ssize_t is where a function may return a size or a
                       * negative number. The first "s" means "signed".*/

    fp = fopen("/etc/motd", "r");
    if (fp == NULL) {
        exit(1);
    }

    while ((read = getline(&line, &len, fp)) != -1) {
        printf("Retrieved line of length %zu :\n", read);
        printf("%s", line);
    }

    if (line) {
        free(line);
    }
    exit(0);
}
```

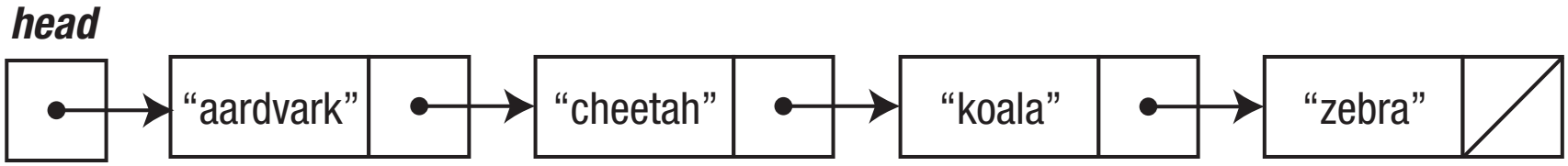
Lists

- While arrays are a convenient structure, they are not always the most suitable choice.
  - Arrays have a fixed size (albeit it may be resized with effort), yet a linked-list is exactly the size it needs to be to hold its contents.
  - Lists can be rearranged by changing a few pointers (which is cheaper than a block move like that performed by **memmove** in our dynamic-array implementation of **delname**)
  - When items are inserted or deleted from a list, the other items are not moved in memory.
  - If we store addresses to the **list elements** in some other data structure, the **list elements themselves** won't be necessarily be invalidated by changes to the **list**.

Lists

- So:
  - If the set of items we want to maintain changes frequently…
  - … especially if the number of items is unpredictable…
  - then **a list is one good way to store them.**
- Typical usage of list for problem will dictate the kind of linked-list:
  - singly
  - singly, with head & tail pointers
  - doubly
  - circular
  - skip-list

Singly-linked list (no tail pointer)



- Set of four items
  - Each item has data (in this case a string) along with a pointer to the next item.
  - Head of the list is a pointer to the first item
  - End of the list is denoted by a NULL pointer.
  - Handful of operations (add new item to front; find a specific item; add new item before or after a specific item; perhaps delete item)

Other languages

- Some languages have lists built into their core
  - Python does this
  - As does Lisp, Scheme, F#, etc.
- Other languages implement lists via a library
  - C++
  - Java
  - C#
- Most of these languages have a List type
  - However, the approach (or idiom) in C is to start with the element type and then work outwards to the node.
  - That is, we are able to construct lists not via a list type but rather via a **node type**.

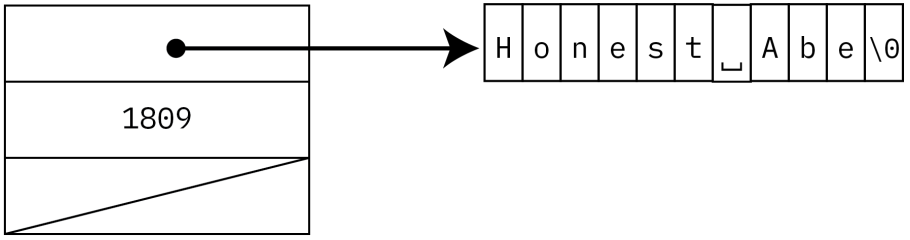
List node

- We'll revisit the same problem as described earlier (that of storing <name, value> pairs)
- The one addition to the Nameval struct is a "next" field
  - This field's type is a pointer to the node type Nameval
  - This is the usual style in C of declaring types for self-referencing structures.
  - We'll see more recursive structures later…

```
typedef struct Nameval Nameval;
struct Nameval {
    char    *name;
    int      value;
    Nameval *next; /* in list */
};
```

This...

... is a shorthand way of representing this:



Slight detour

- One of the tedious aspects of working with malloc is checking for success or failure
- We can accomplish this while still keeping our code clean by writing a small support function.
  - `emalloc`: a **wrapper function** that calls malloc; if allocation fails, it reports an error and exits the program.
  - Therefore we can use it as a memory allocator that never returns failure (but does terminate the program if there was an error).

```
void *emalloc(size_t n)
{
    void *p;

    p = malloc(n);
    if (p == NULL) {
        fprintf(stderr, "malloc of %u bytes failed", n);
        exit(1);
    }
    return p;
}
```

Constructing an item

- Before "creating a list", let us write a function that constructs an item.
  - It will allocate memory from the heap…
  - … and then assign appropriate values to fields.
  - We will make heavy us of "->" syntax
  - We assume here that some other function has allocated memory for the name

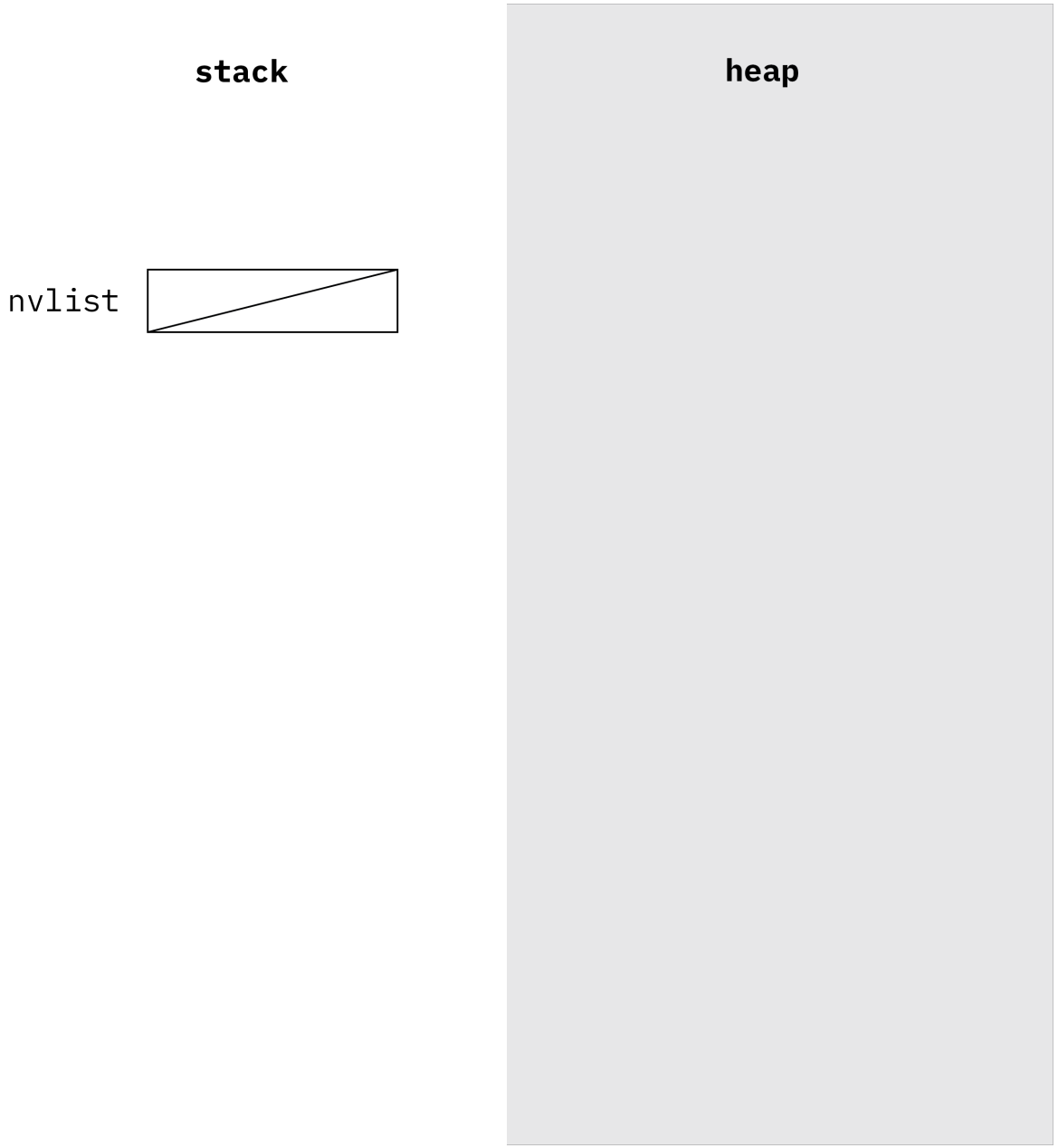
```
Nameval *newitem (char *name, int value)
{
    Nameval *newp;

    newp = (Nameval *) emalloc(sizeof(Nameval));
    newp->name  = name;  /* Is this exactly what we want??? */
    newp->value = value;
    newp->next  = NULL;
    return newp;
}
```

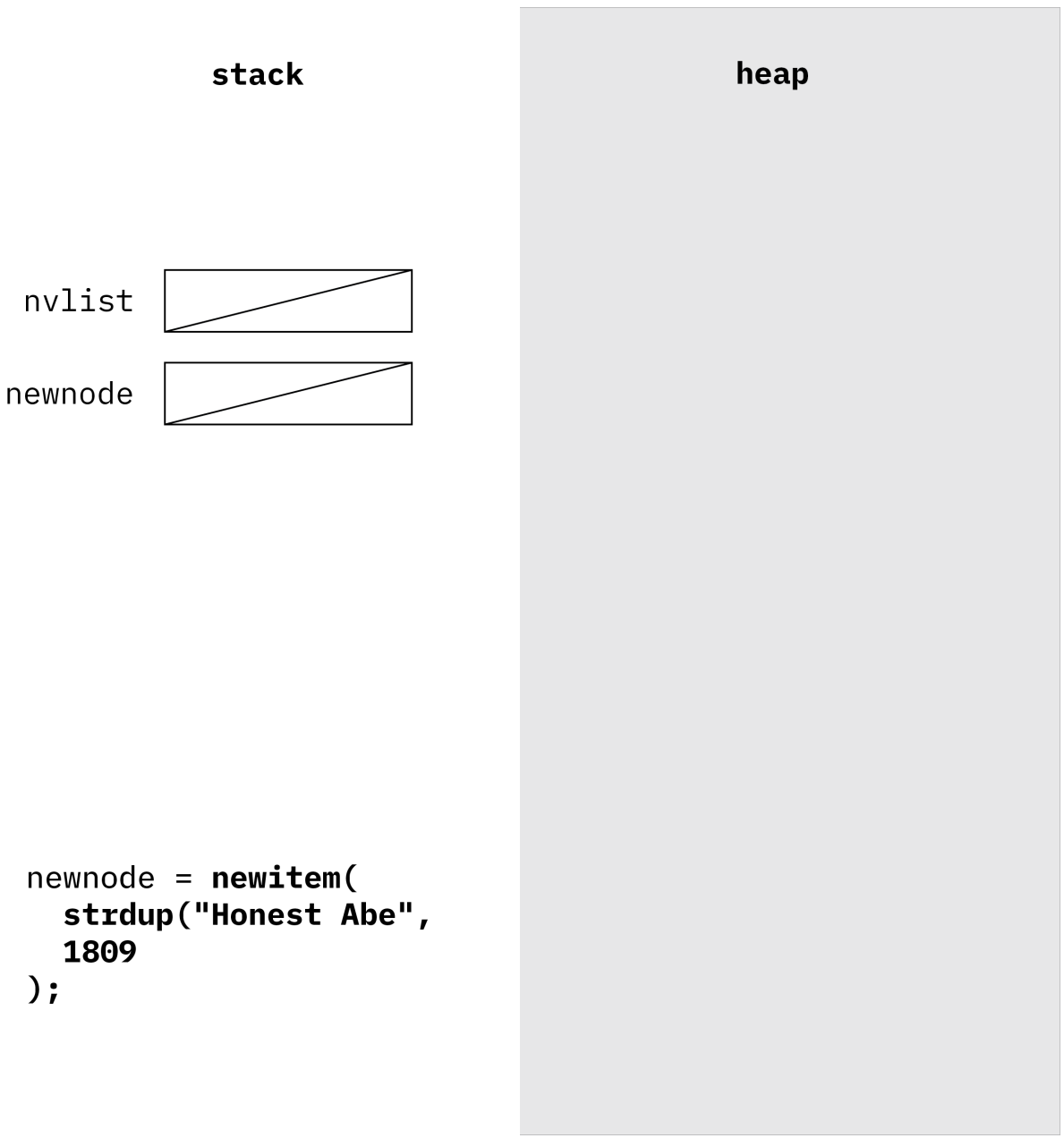
Adding an item to the front

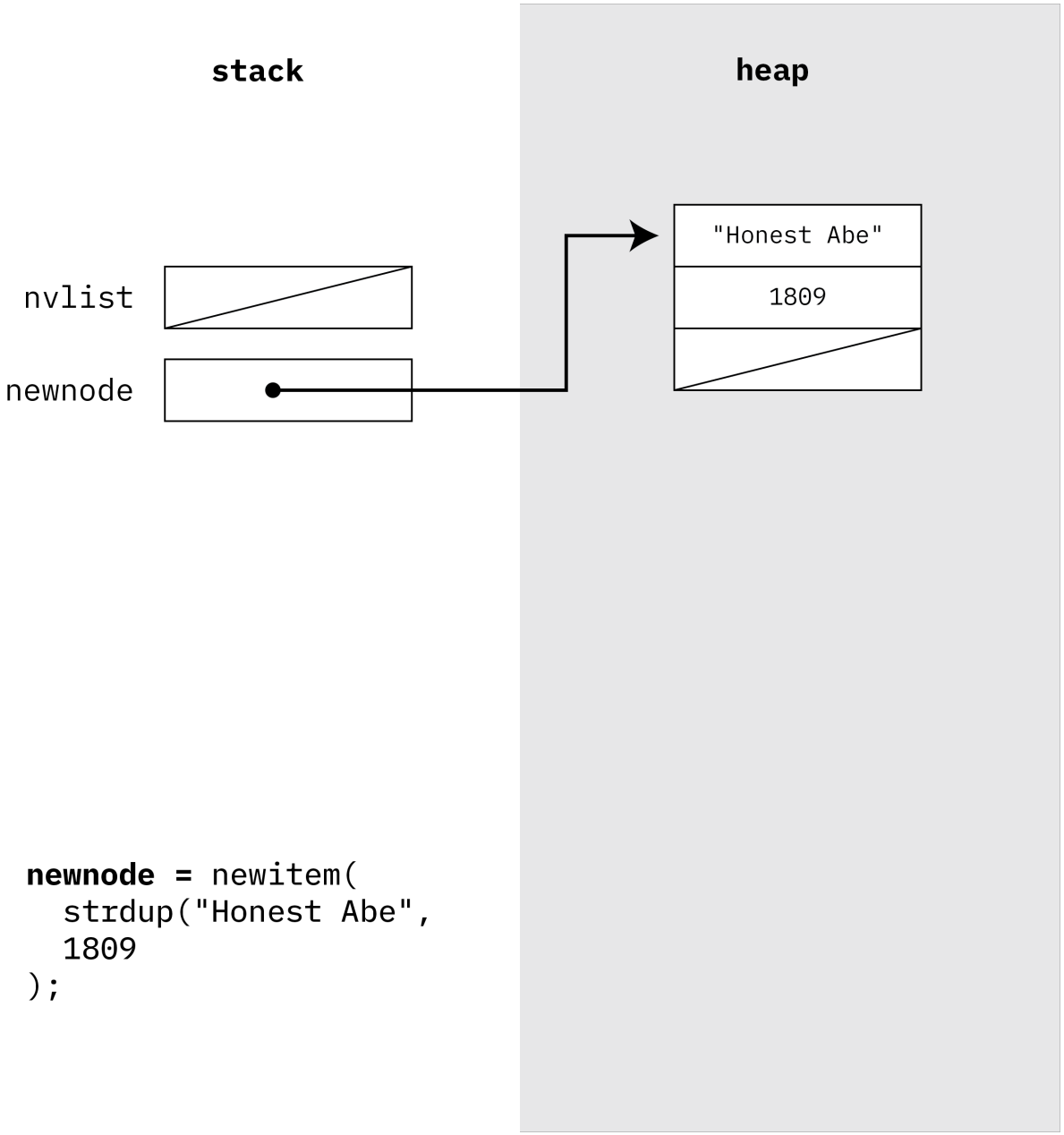
- This is the simplest way to assemble a list
  - Also the fastest.
- This function (and others we'll write) all return a pointer to the first element as their function value
  - Note that this even works if the list is empty (e.g., pointing to NULL)

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```

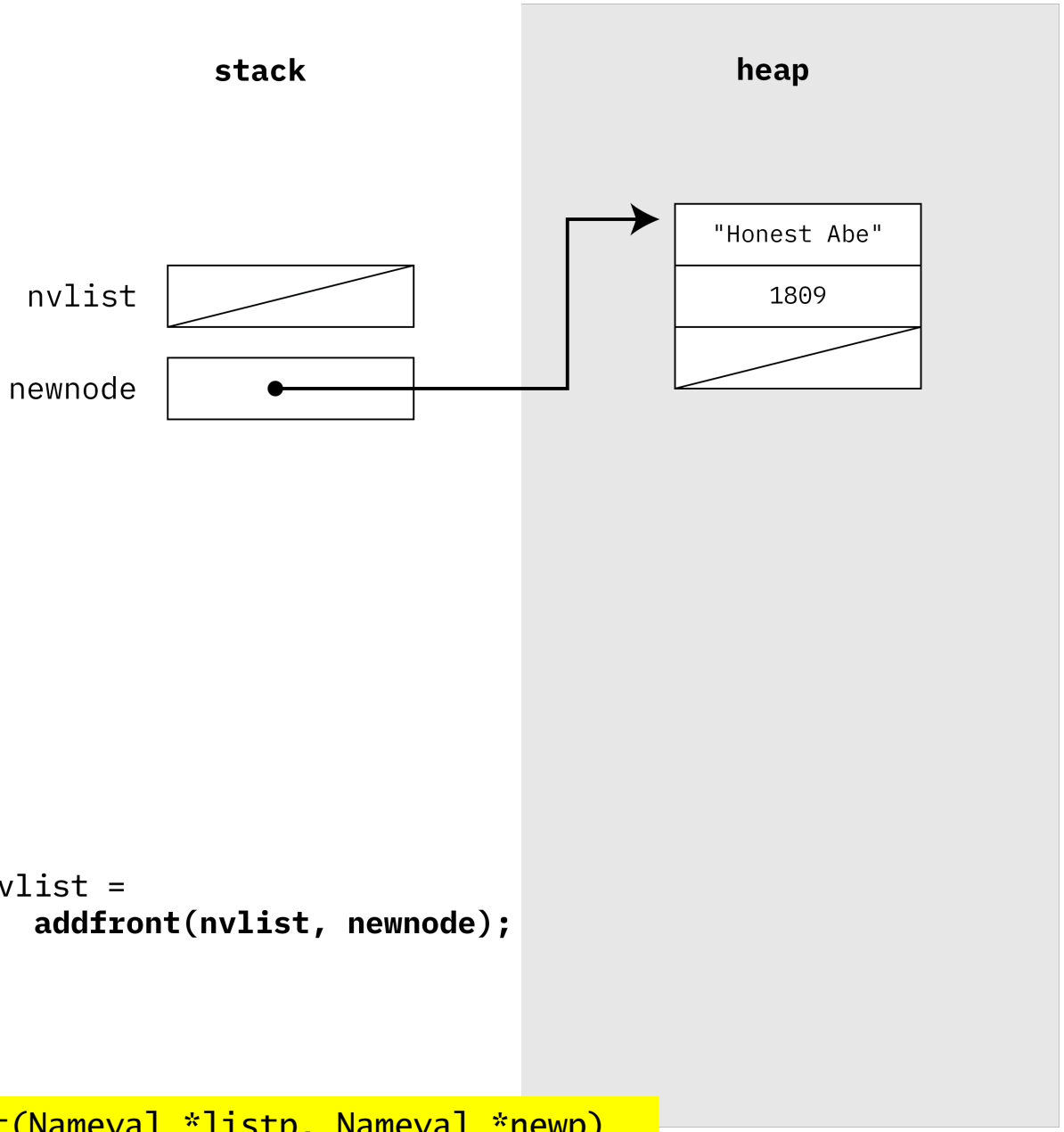
```
/* typical usage */
Nameval *nvlist = NULL;
...
Nameval *newnode = newitem(strdup("Honest Abe"), 1809);
nvlist = addfront(nvlist, newnode);
```


stack
heap
nvlist


stack
heap
nvlist
newnode
newnode = newitem(
strdup("Honest Abe",
1809
);

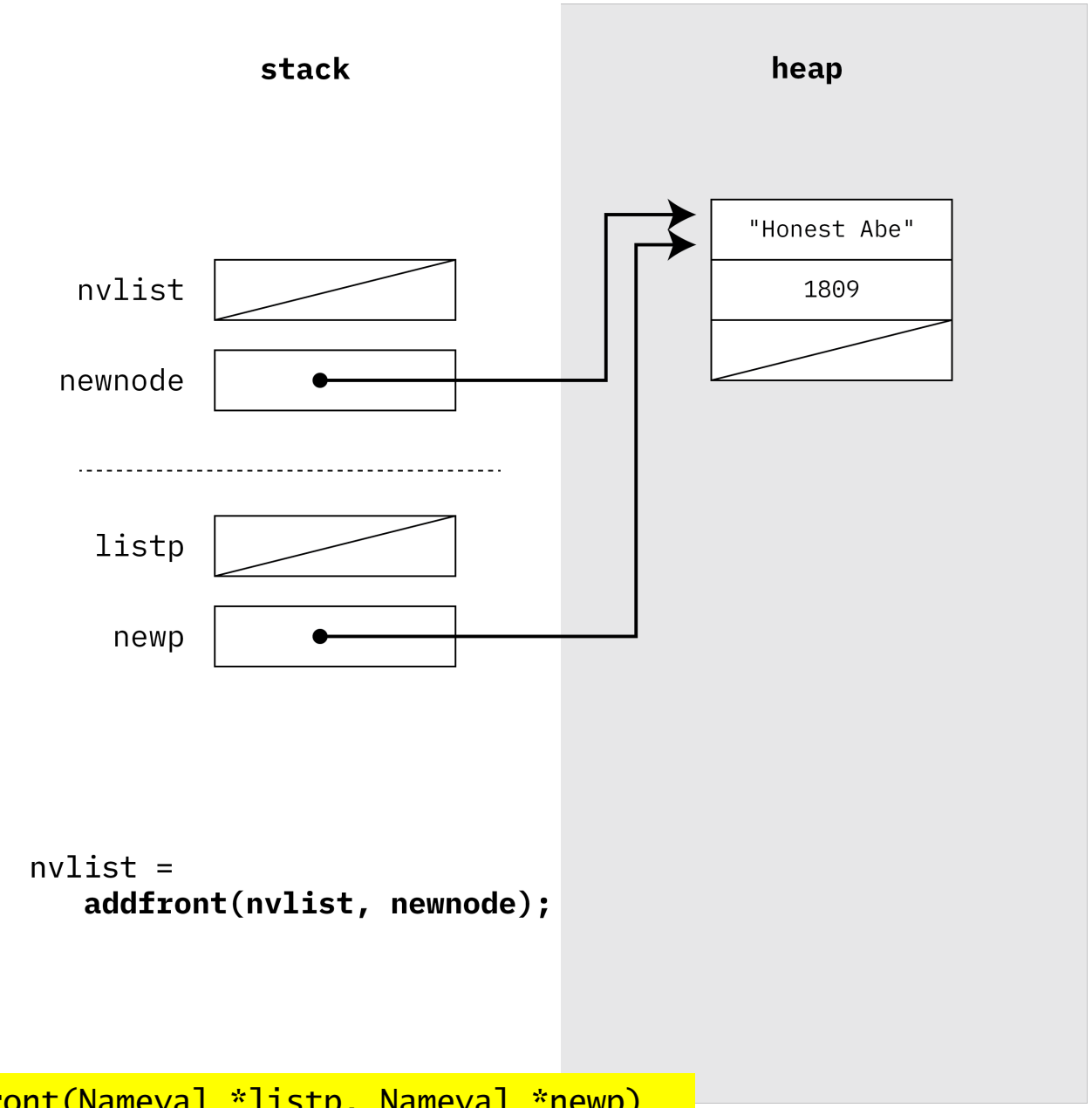



```
newnode = newitem(
  strdup("Honest Abe",
  1809
);
```



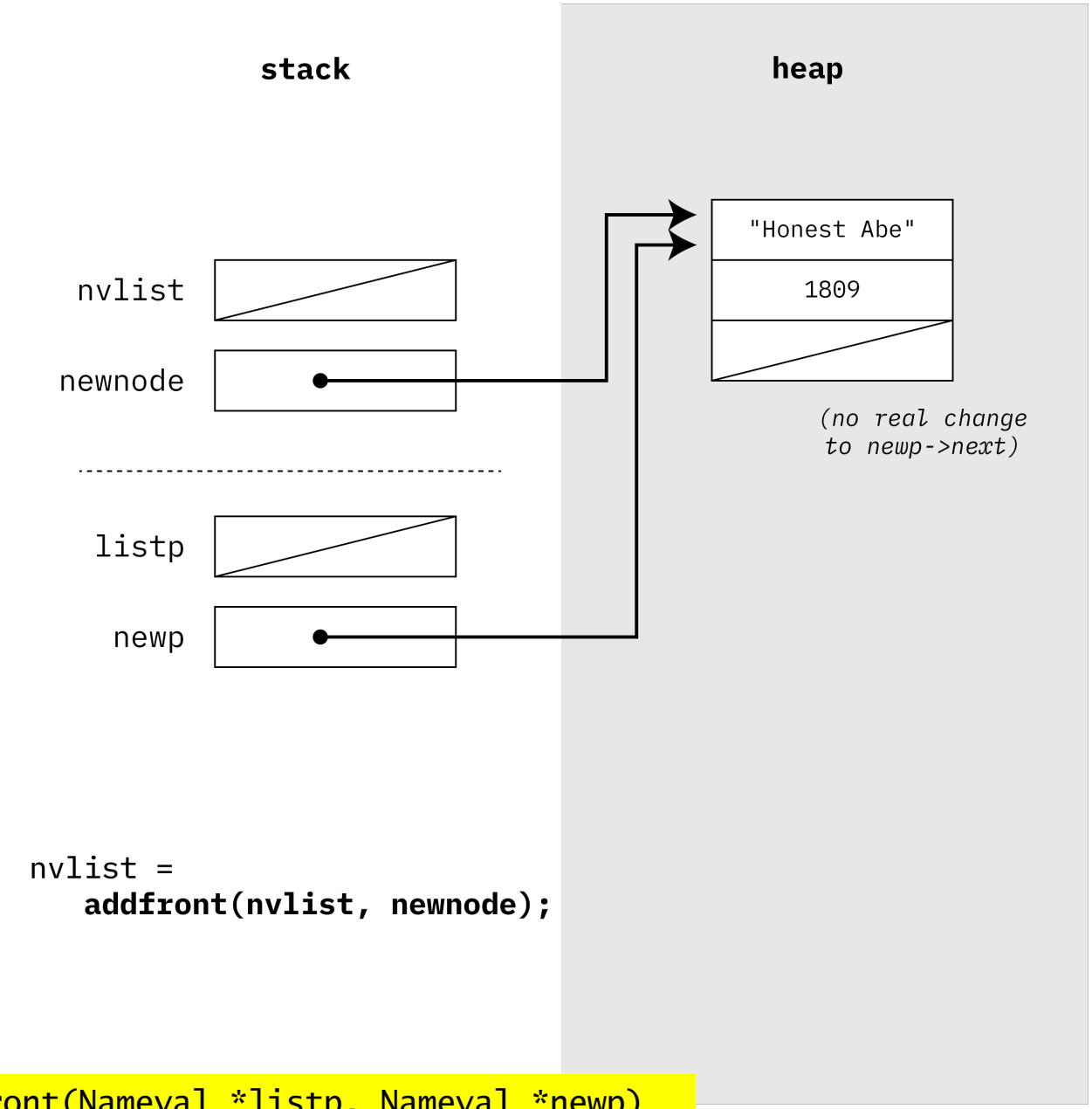

```
nvlist =
   addfront(nvlist, newnode);
```

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```



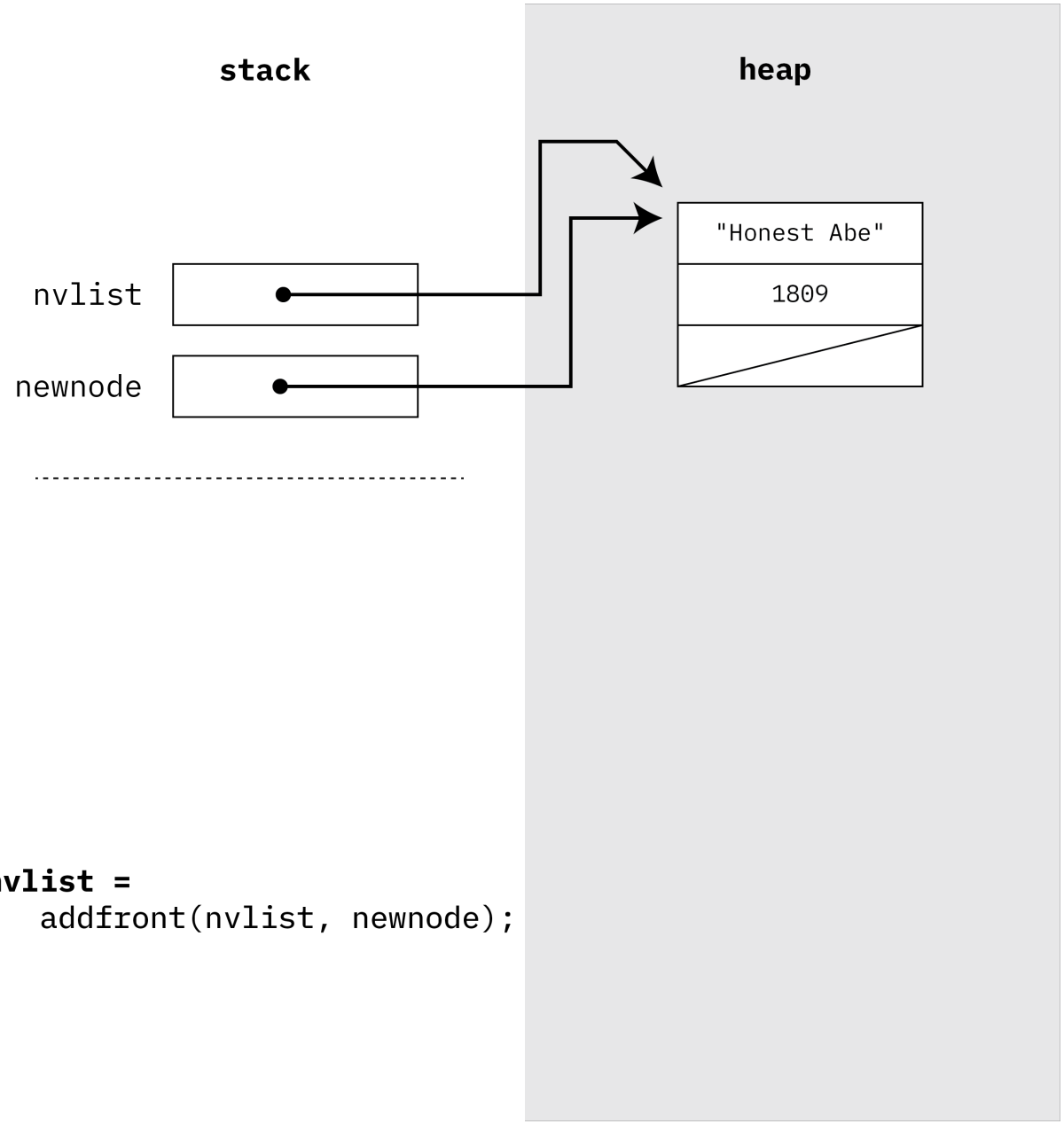

```
nvlist =
   addfront(nvlist, newnode);
```

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```

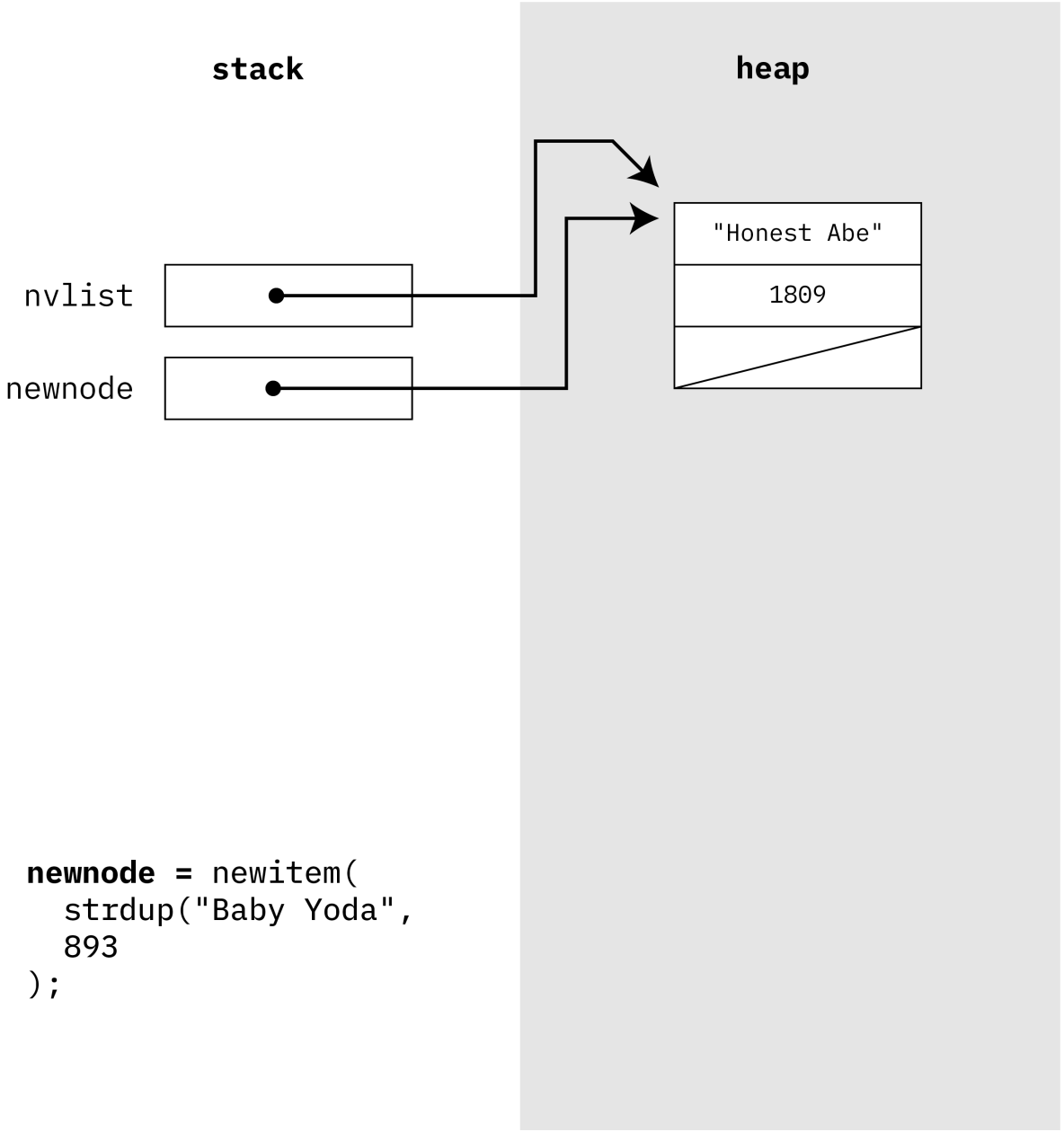



```
nvlist =
   addfront(nvlist, newnode);
```

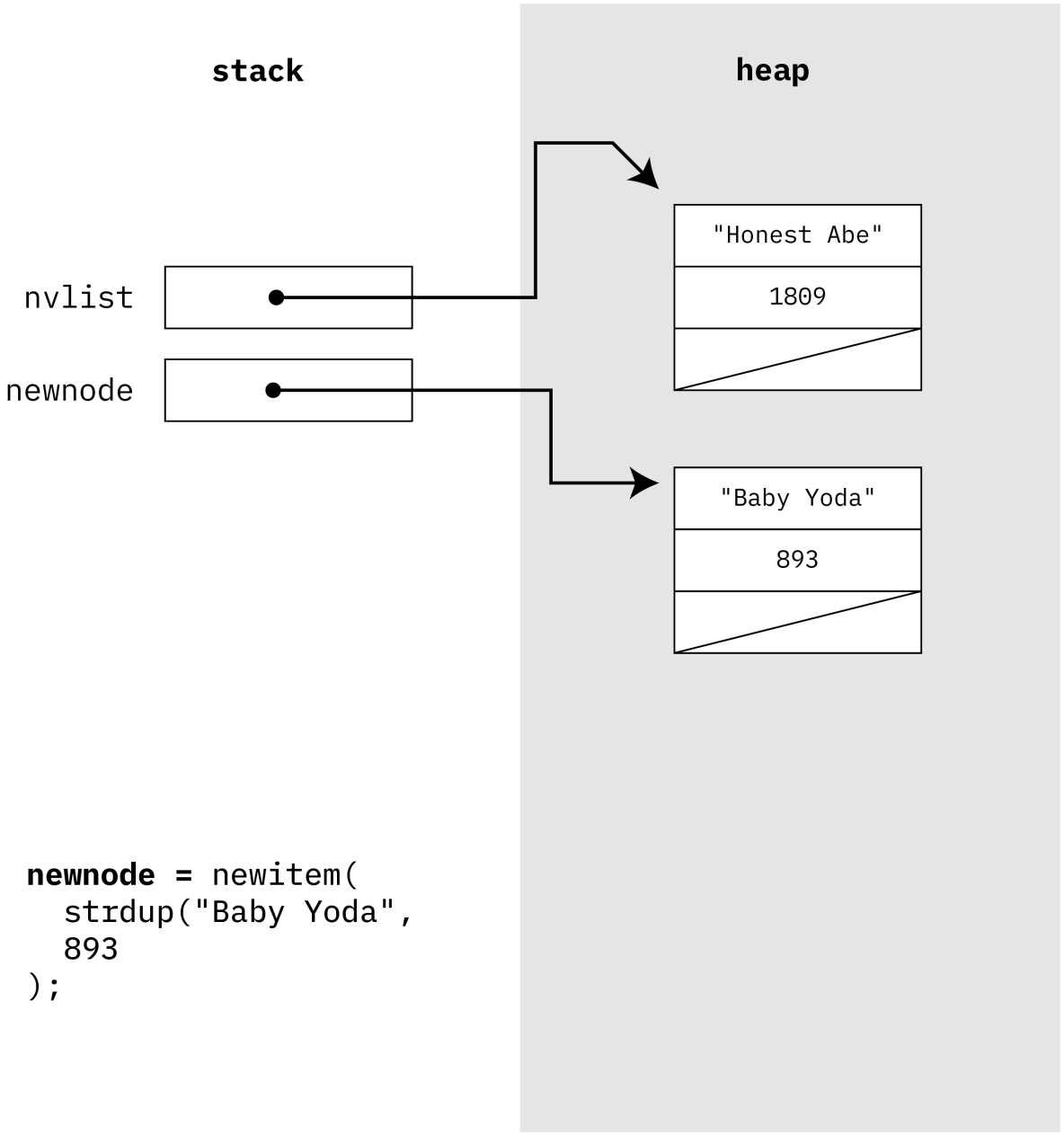
```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```



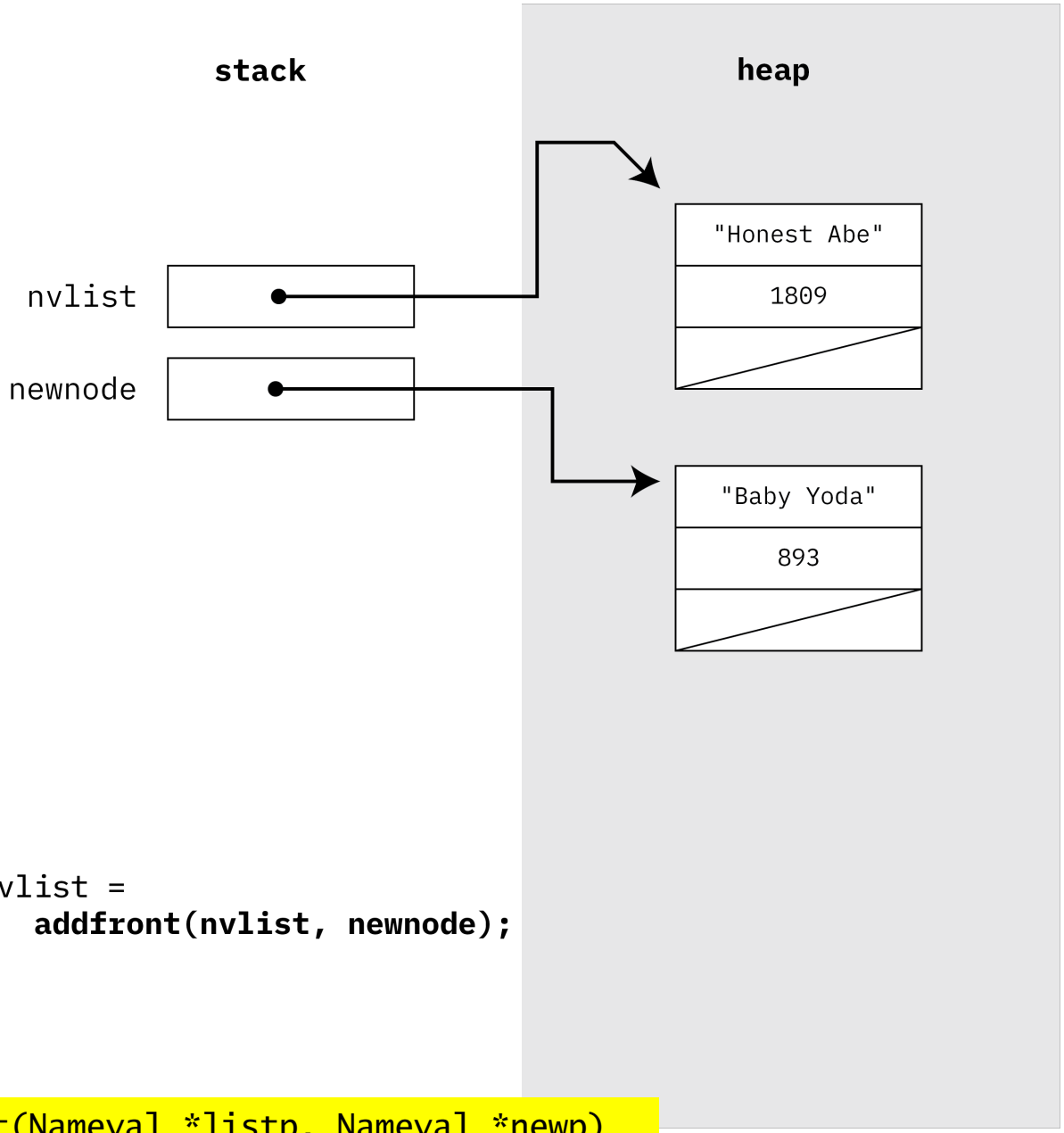

```
nvlist =
   addfront(nvlist, newnode);
```




```
newnode = newitem(
  strdup("Baby Yoda",
  893
);
```

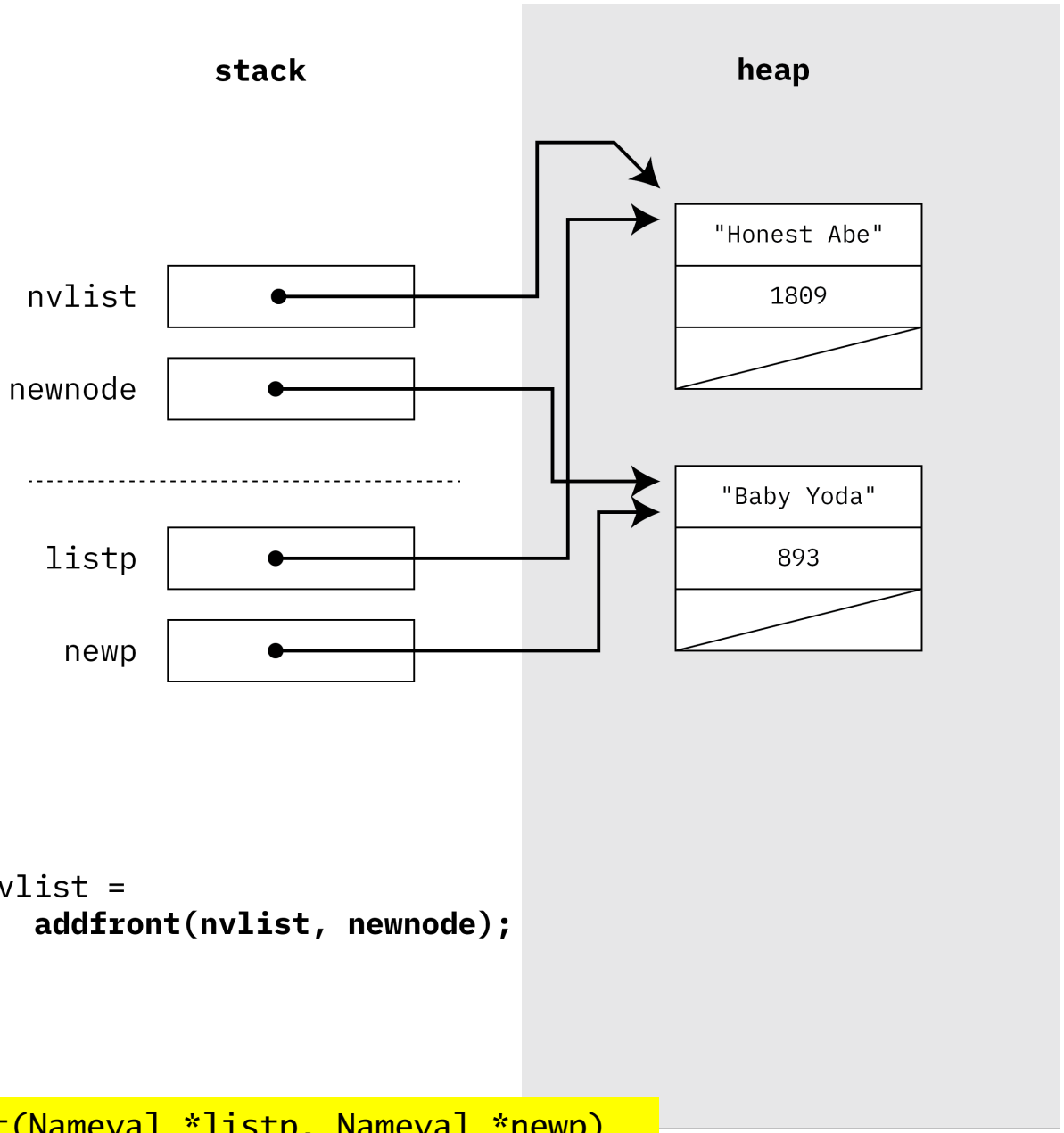



```
newnode = newitem(
  strdup("Baby Yoda",
  893
);
```



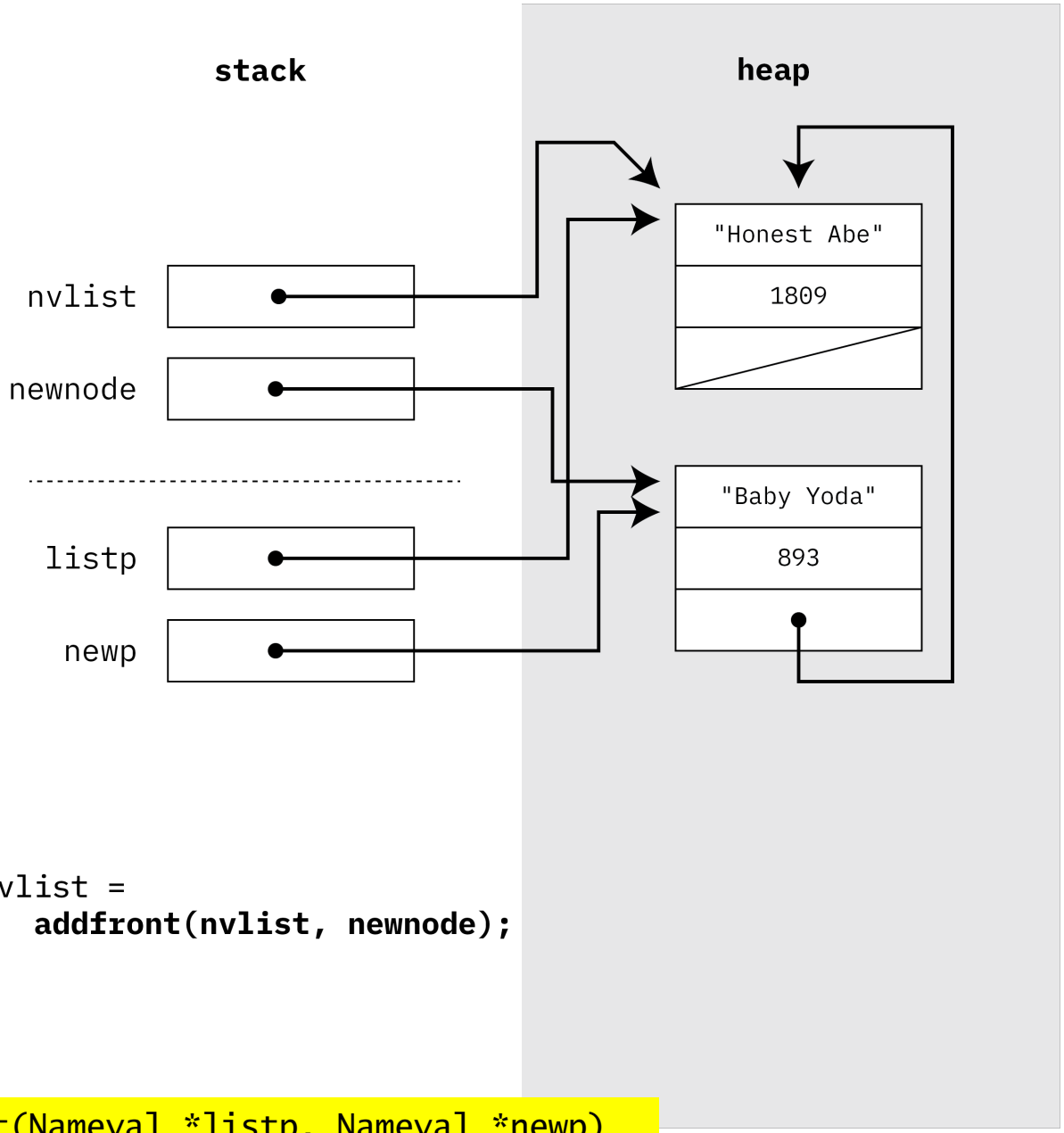

```
nvlist =
   addfront(nvlist, newnode);
```

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```



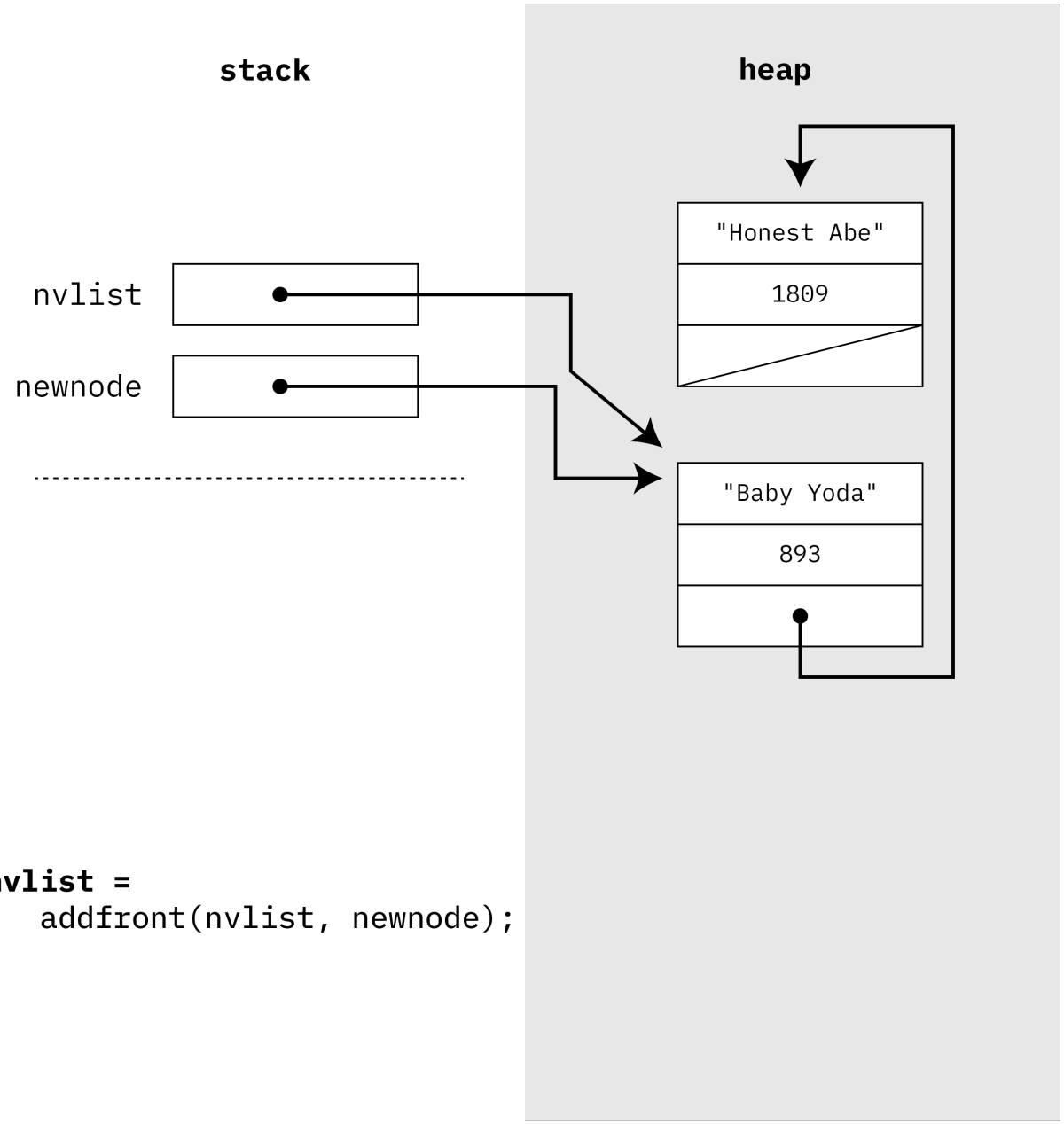

```
nvlist =
   addfront(nvlist, newnode);
```

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```

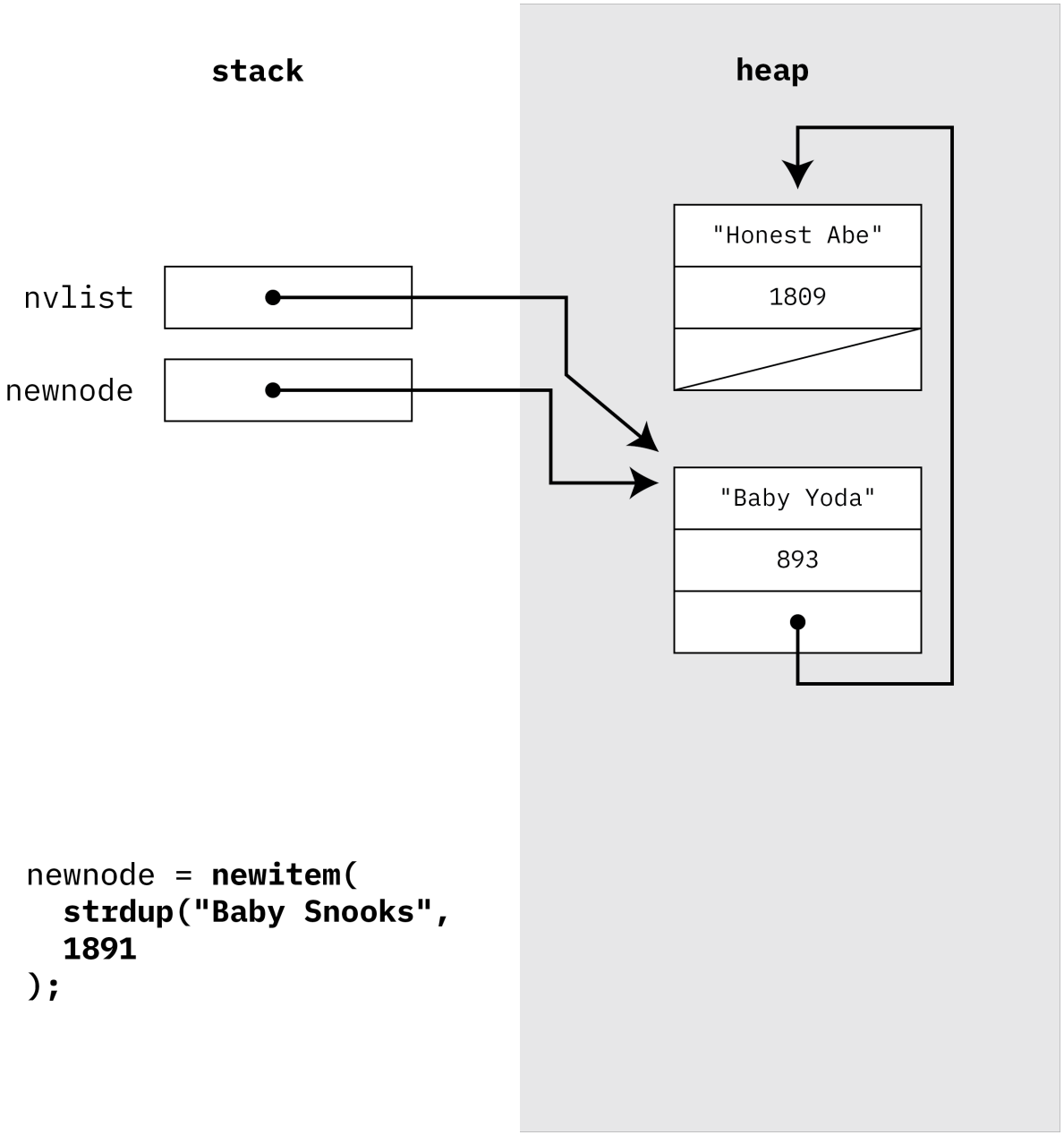



```
nvlist =
   addfront(nvlist, newnode);
```

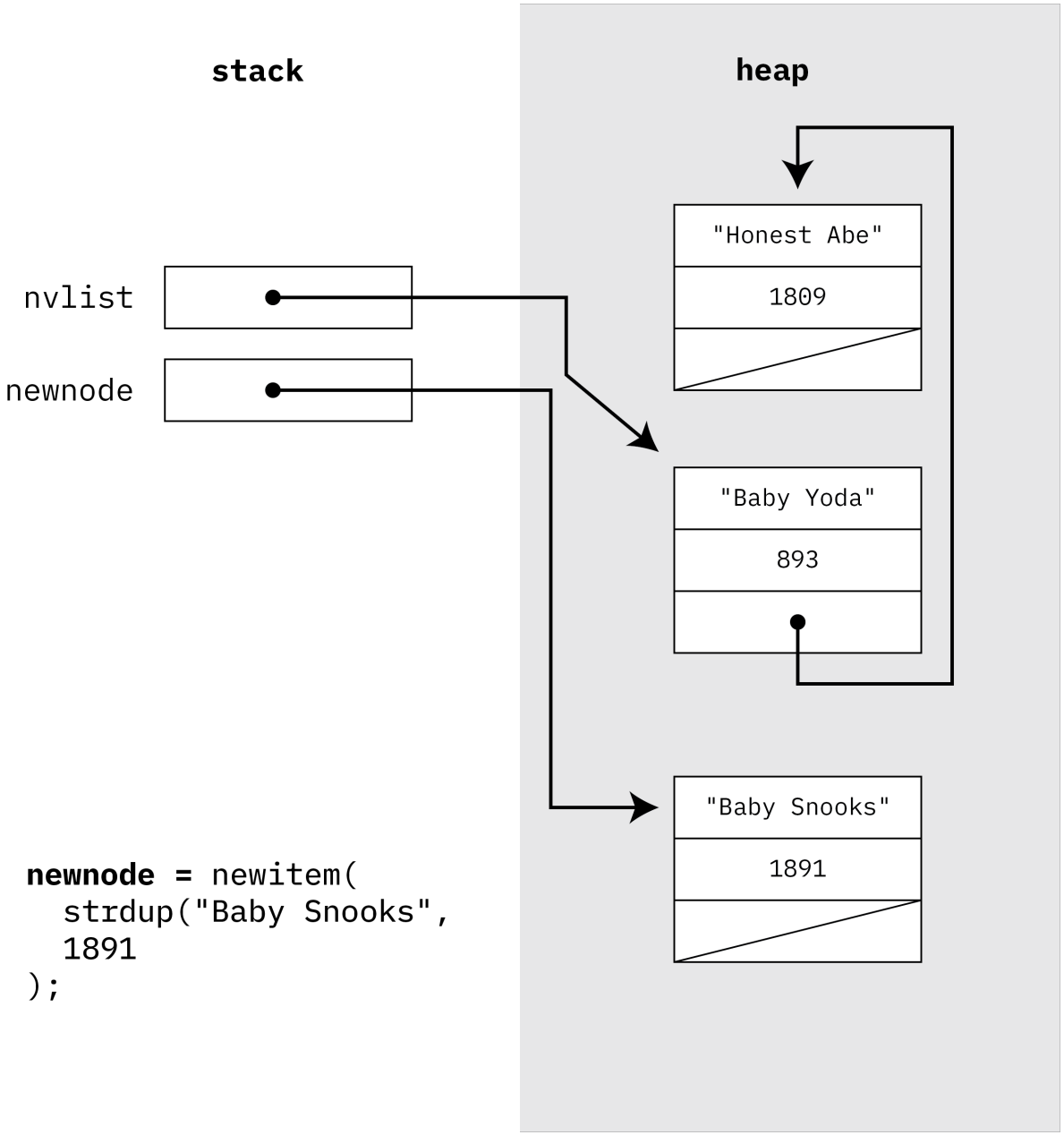
```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```



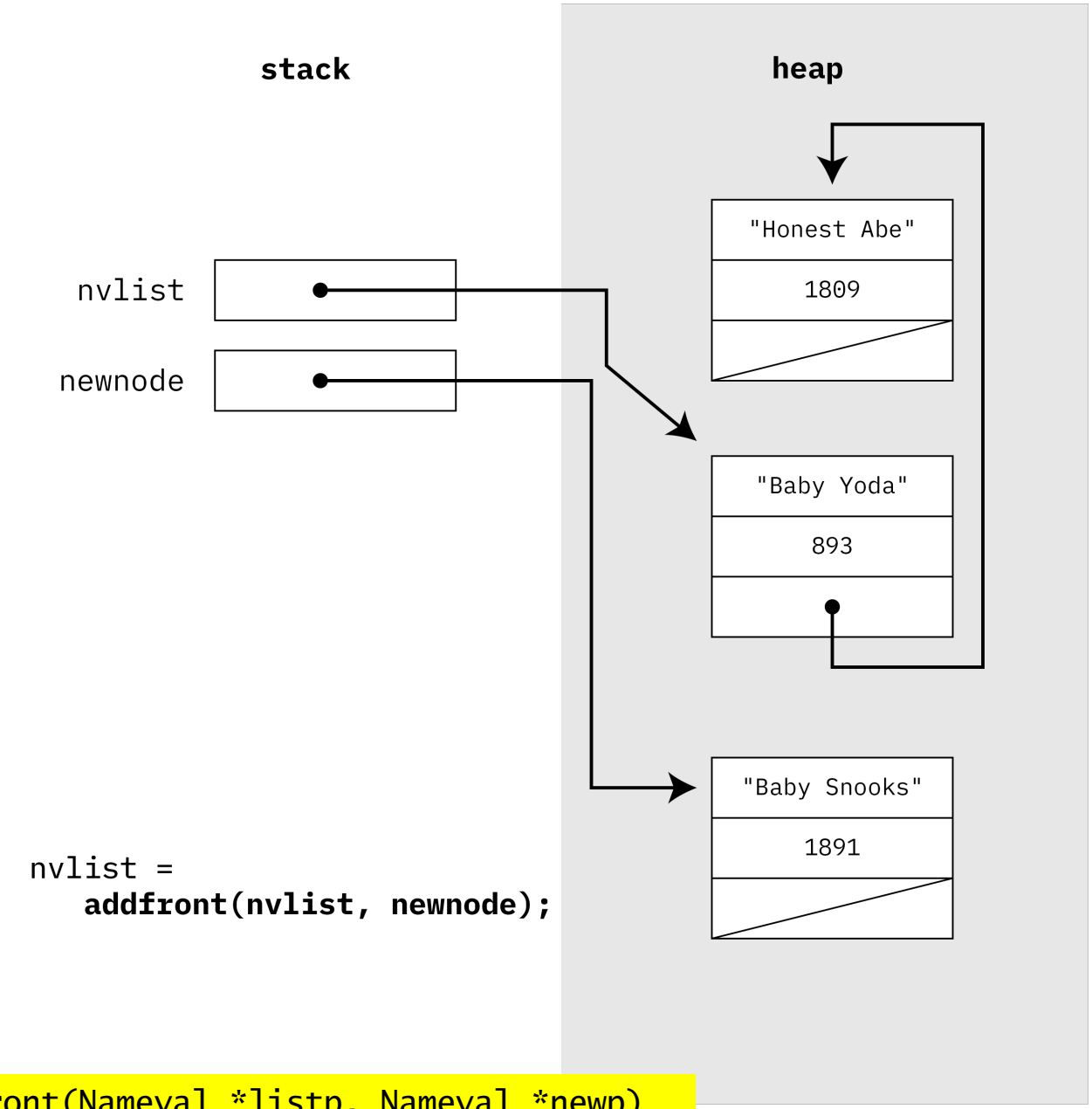

```
nvlist =
   addfront(nvlist, newnode);
```



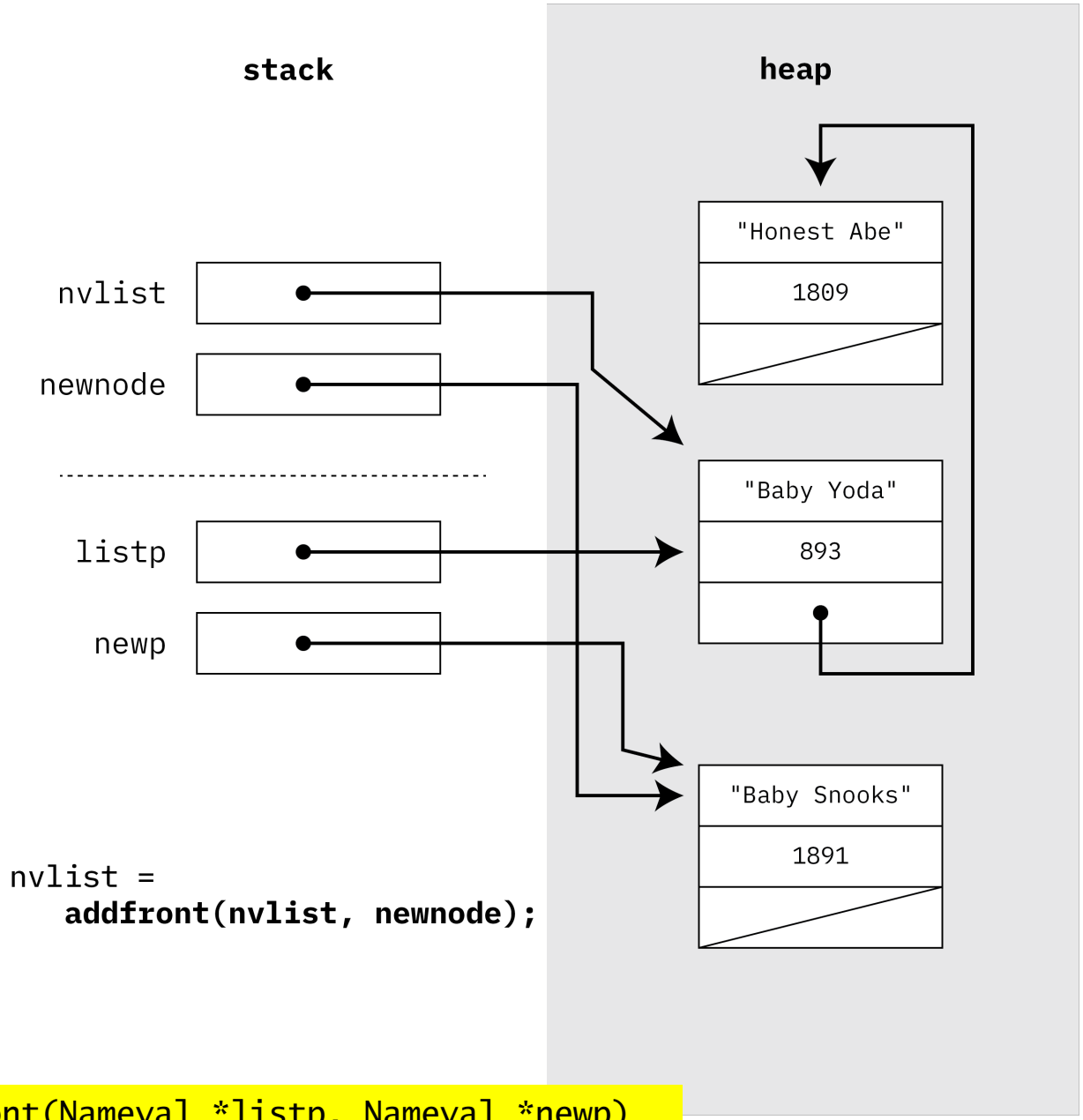

```
newnode = newitem(
  strdup("Baby Snooks",
  1891
);
```



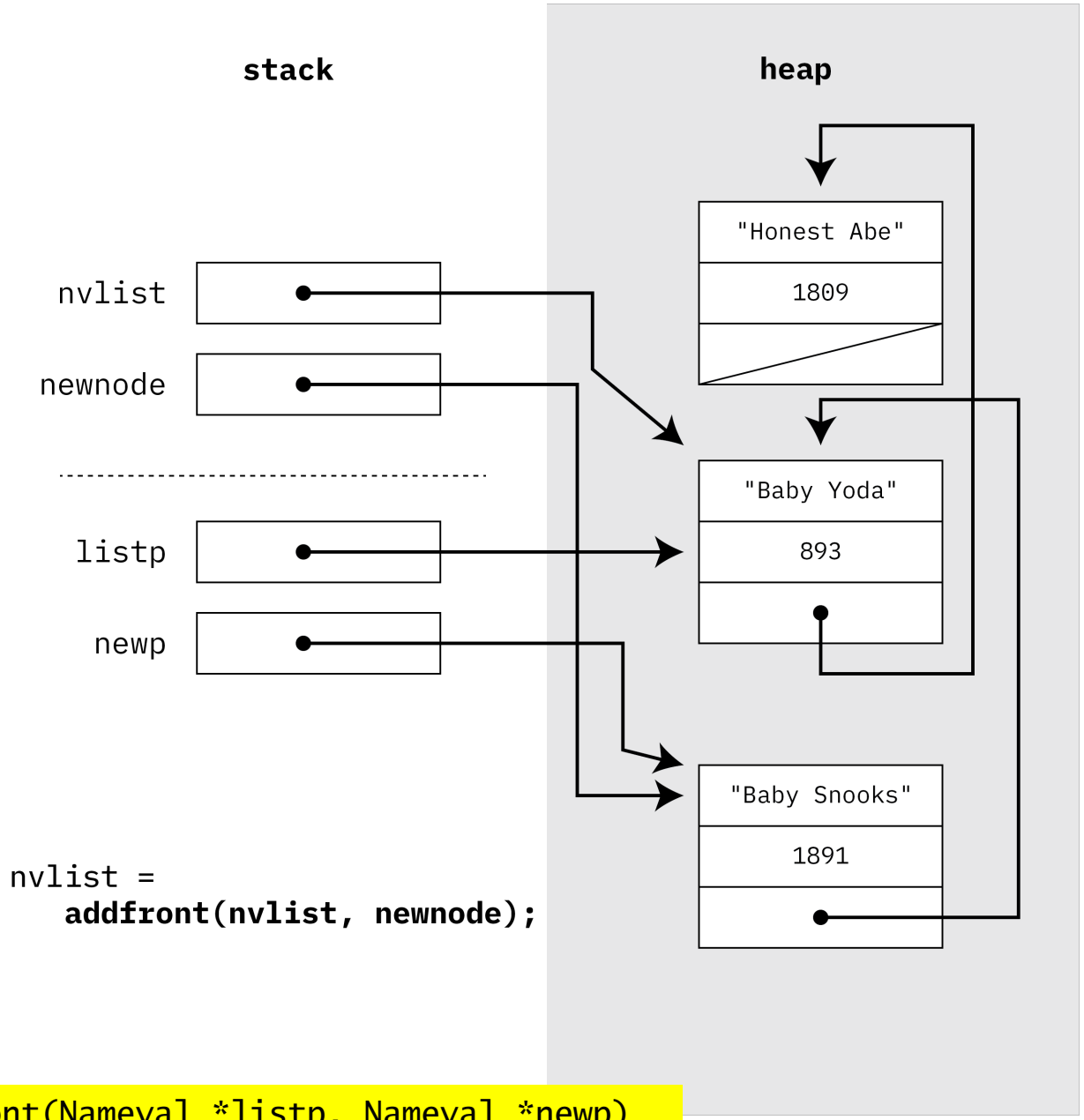

```
newnode = newitem(
  strdup("Baby Snooks",
  1891
);
```



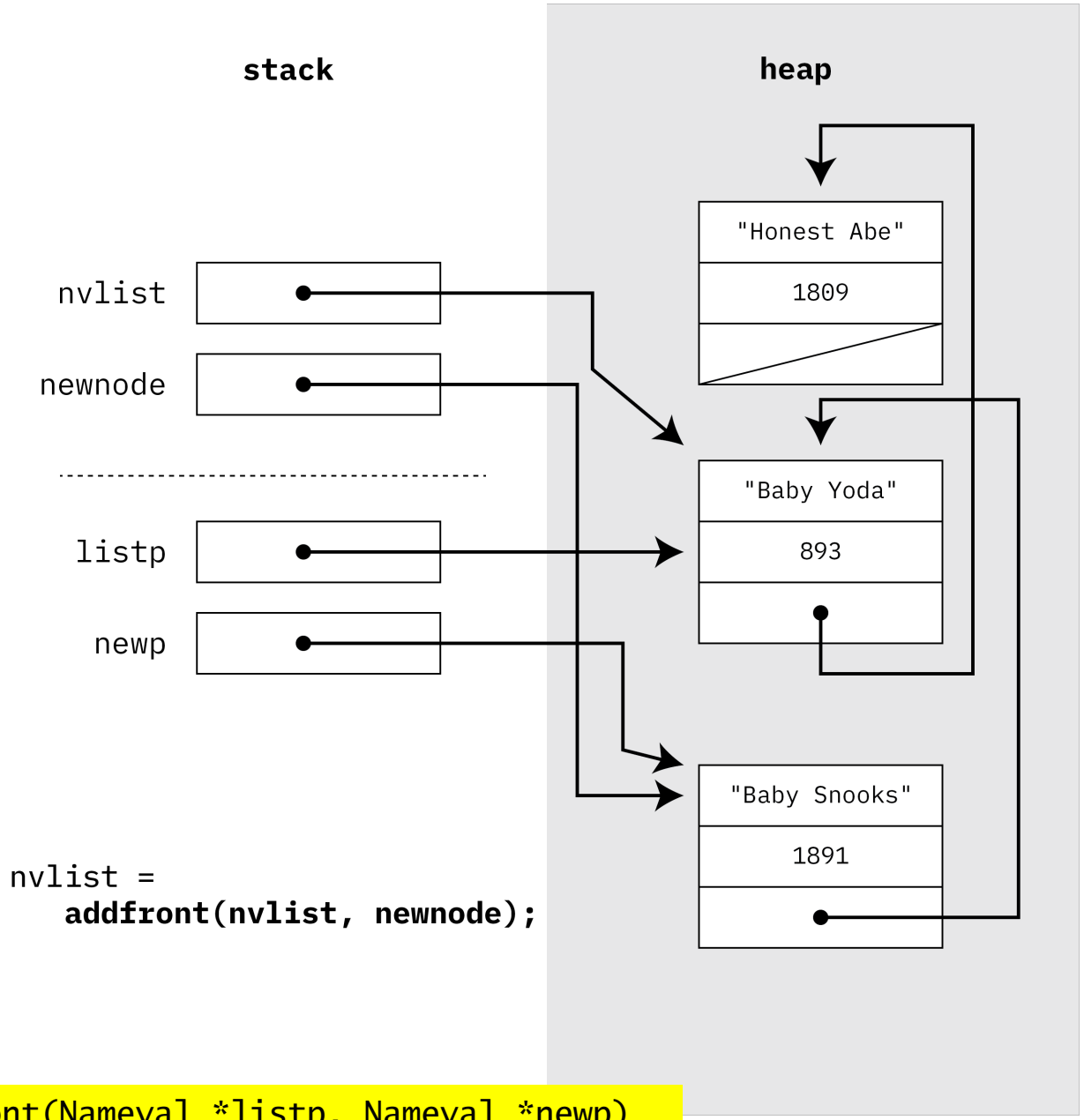

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```



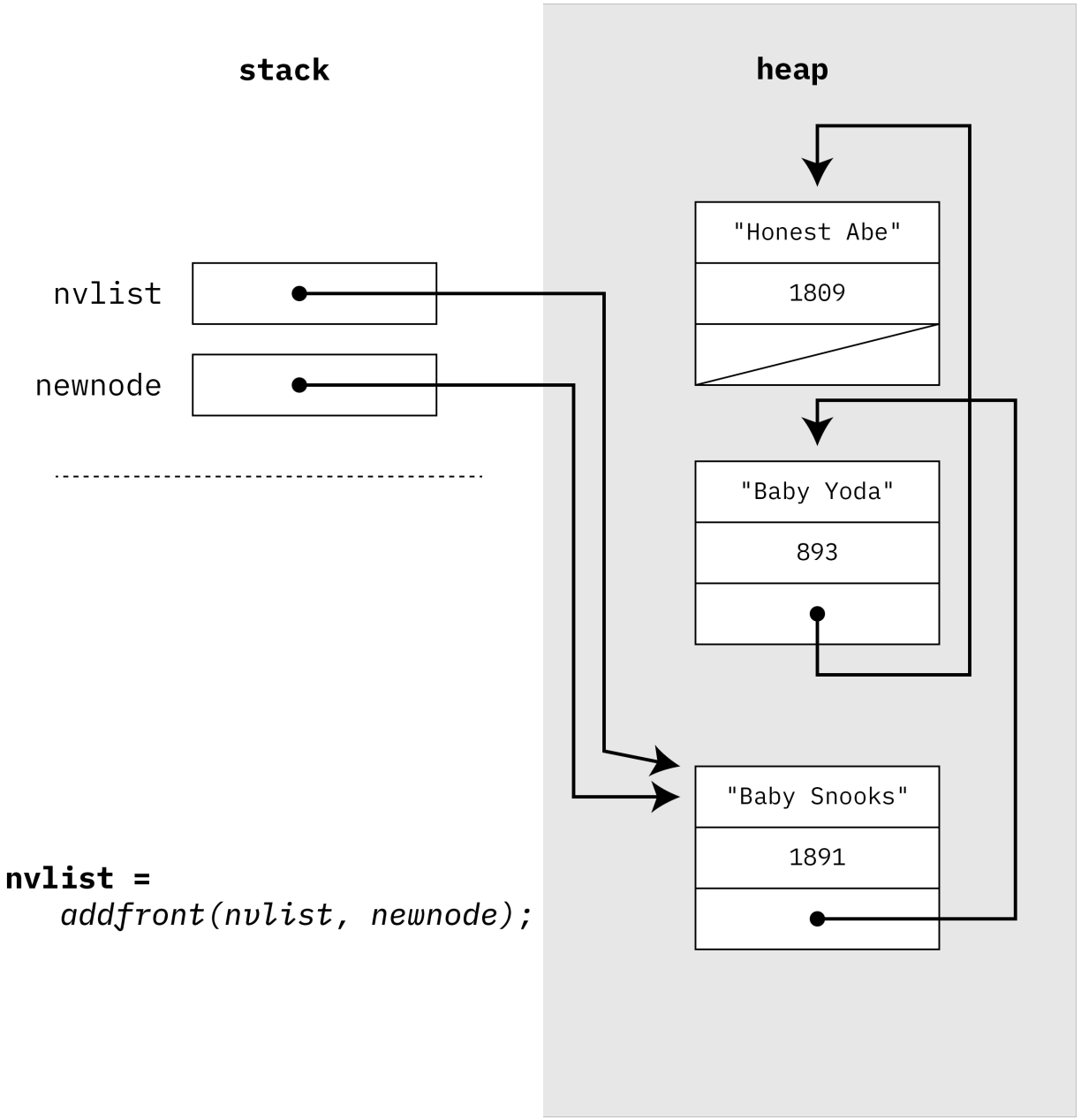

```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```




```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```




```
Nameval *addfront(Nameval *listp, Nameval *newp)
{
    newp->next = listp;
    return newp;
}
```



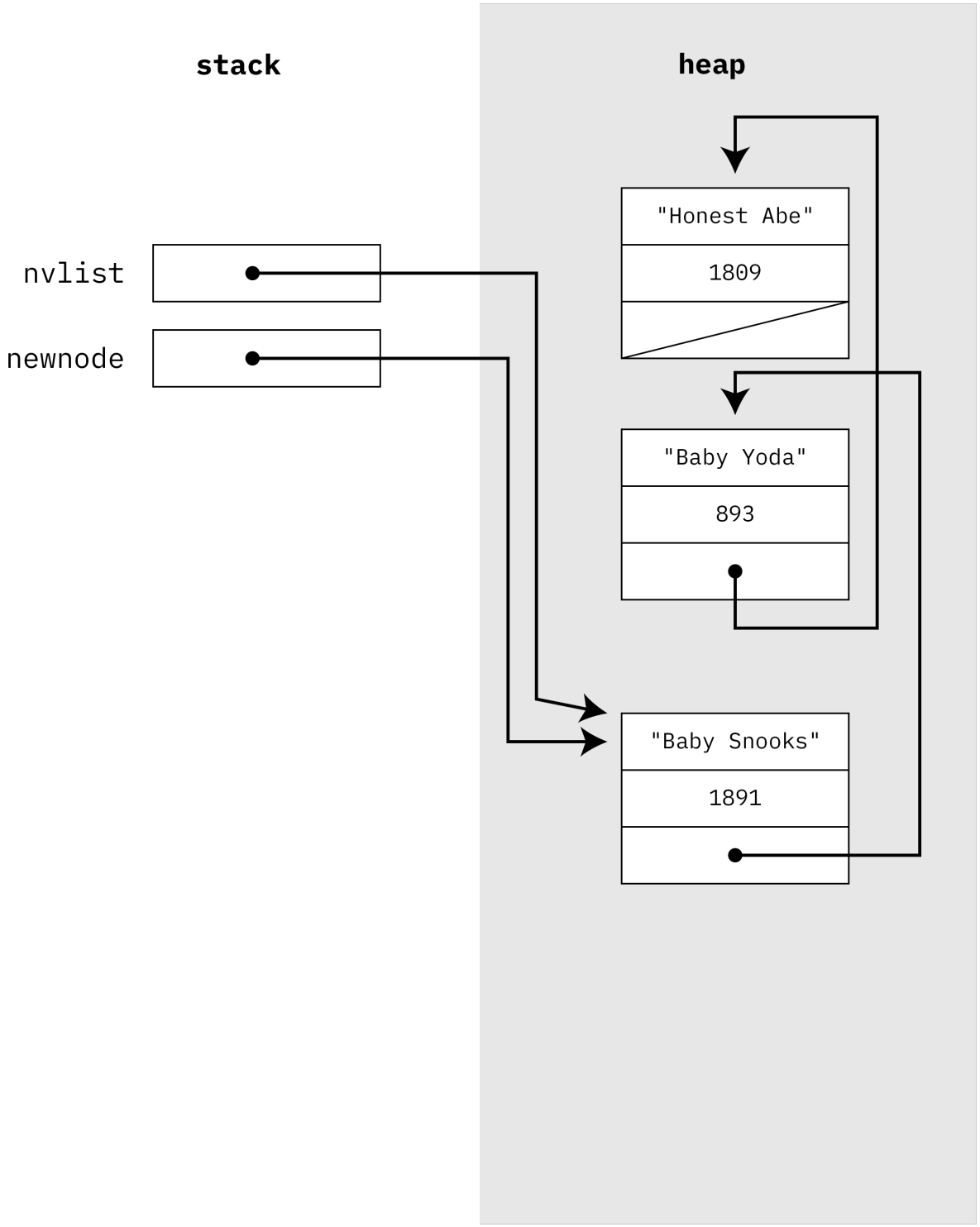
nvlist =
addfront(nvlist, newnode);

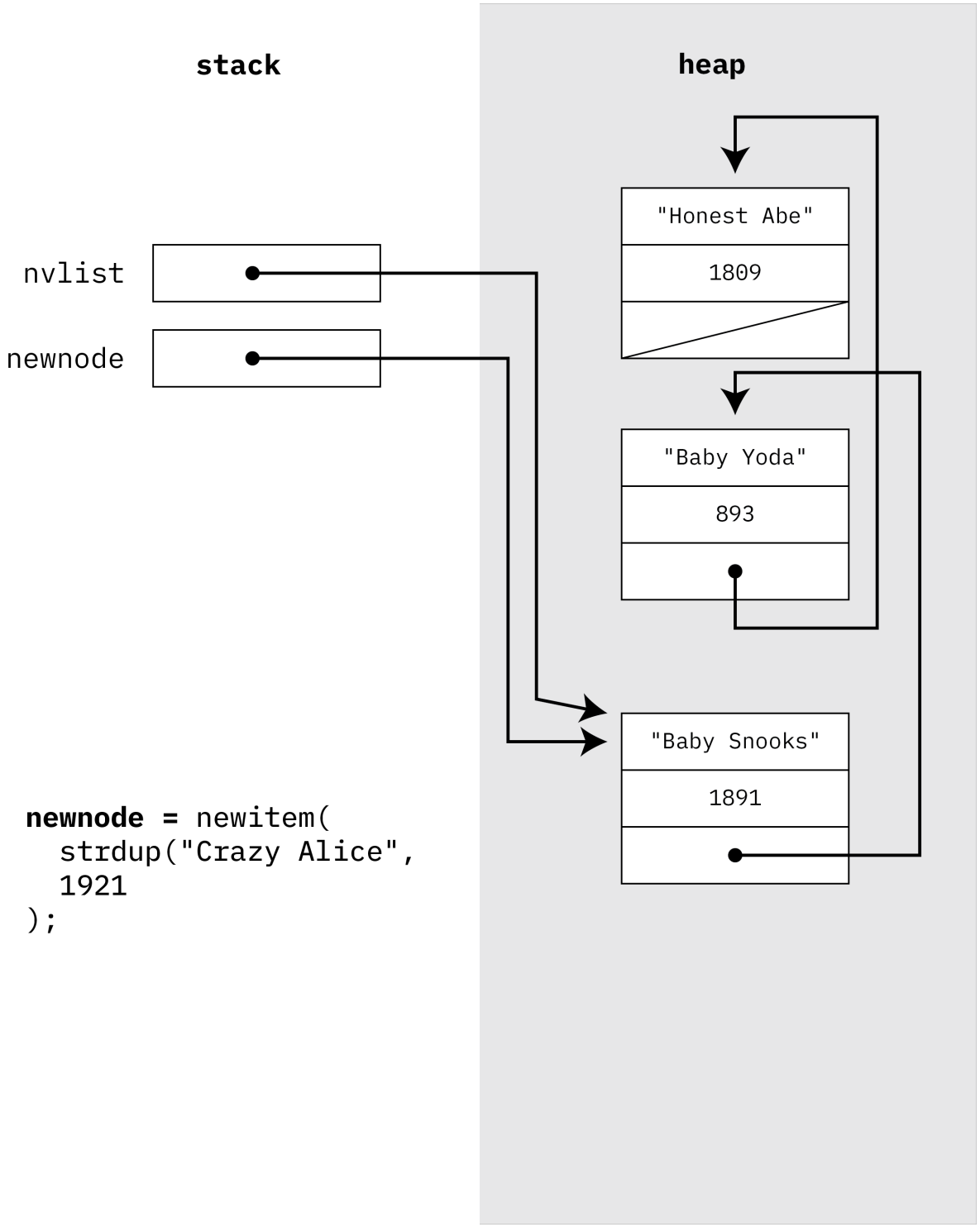
Adding an item to the end

- With a singly-linked list this is an O(n) operation
  - Traverse list until we reach the last node
  - Adjust that node's pointer to indicate the new node.
  - Note that the next field of node created by newitem is already set to NULL.

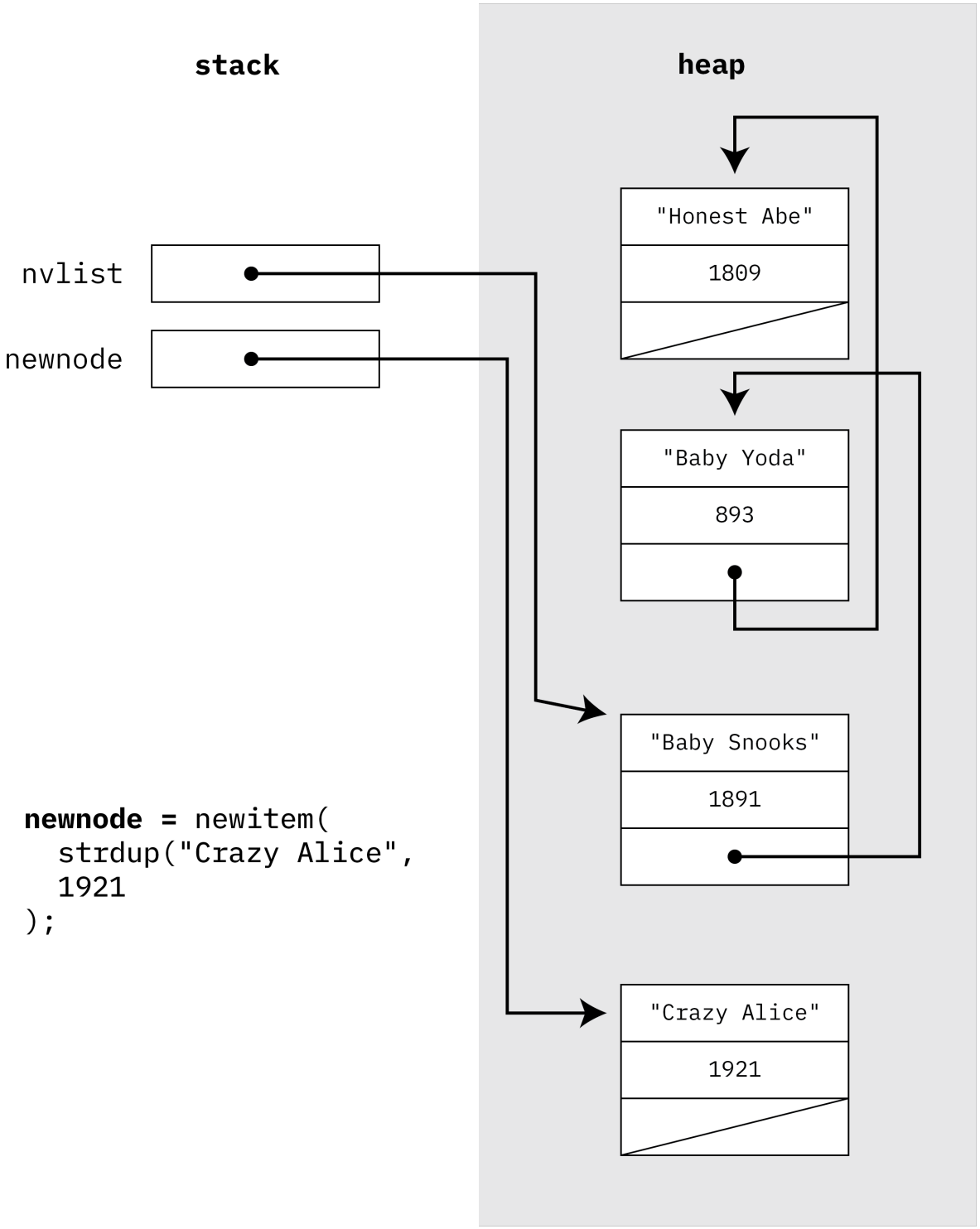
```
Nameval *addend(Nameval *listp, Nameval *newp)
{
    Nameval *p;

    if (listp == NULL) {
        return newp;
    }
    for (p = listp; p->next != NULL; p = p->next)
        ;
    p->next = newp;
    return listp;
}
```

```
...
Nameval *newnode = newitem(strdup("Demetri"), 30);
nvlist = addend(nvlist, newnode);
```

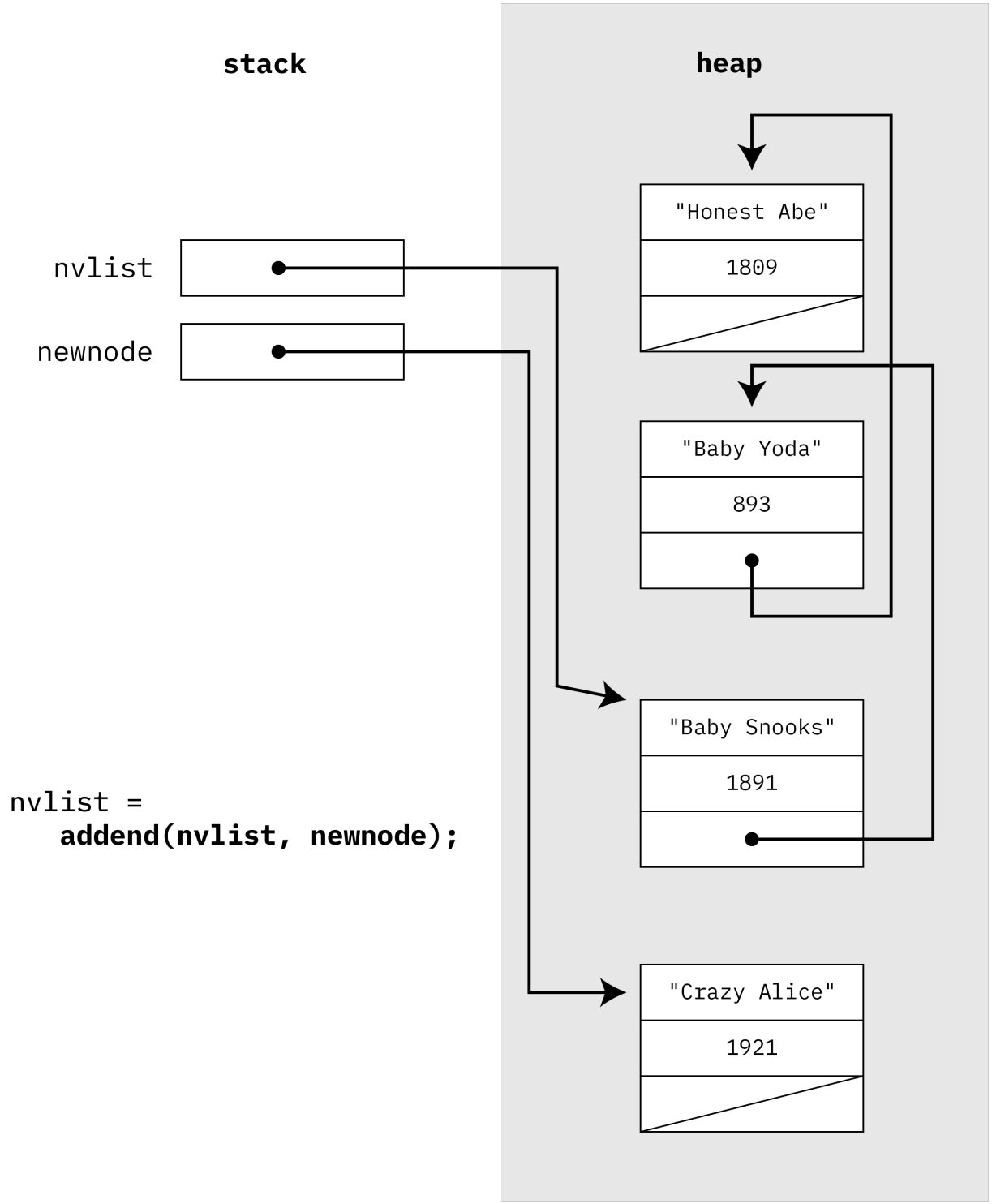

stack
heap
nvlist
newnode
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891

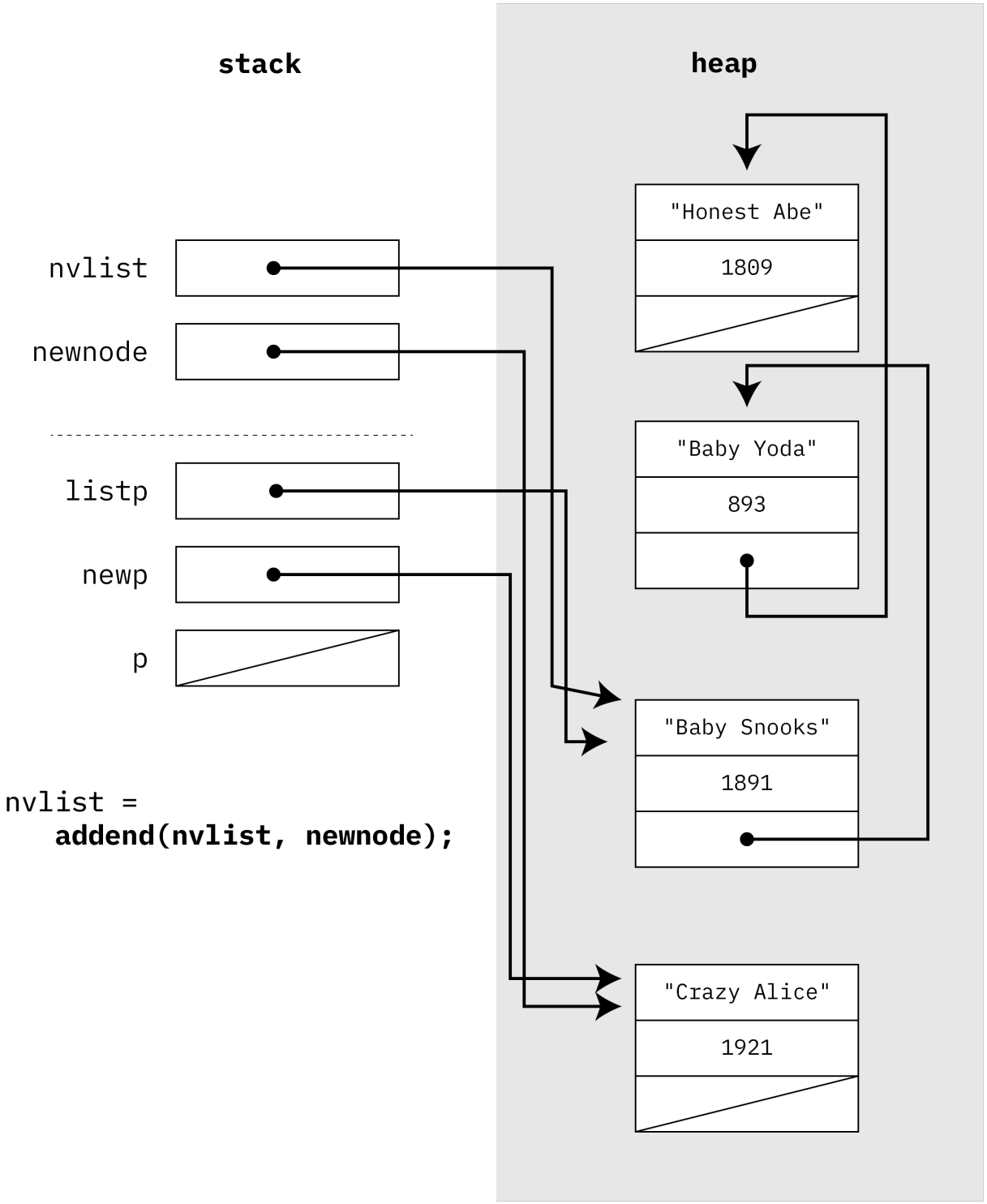


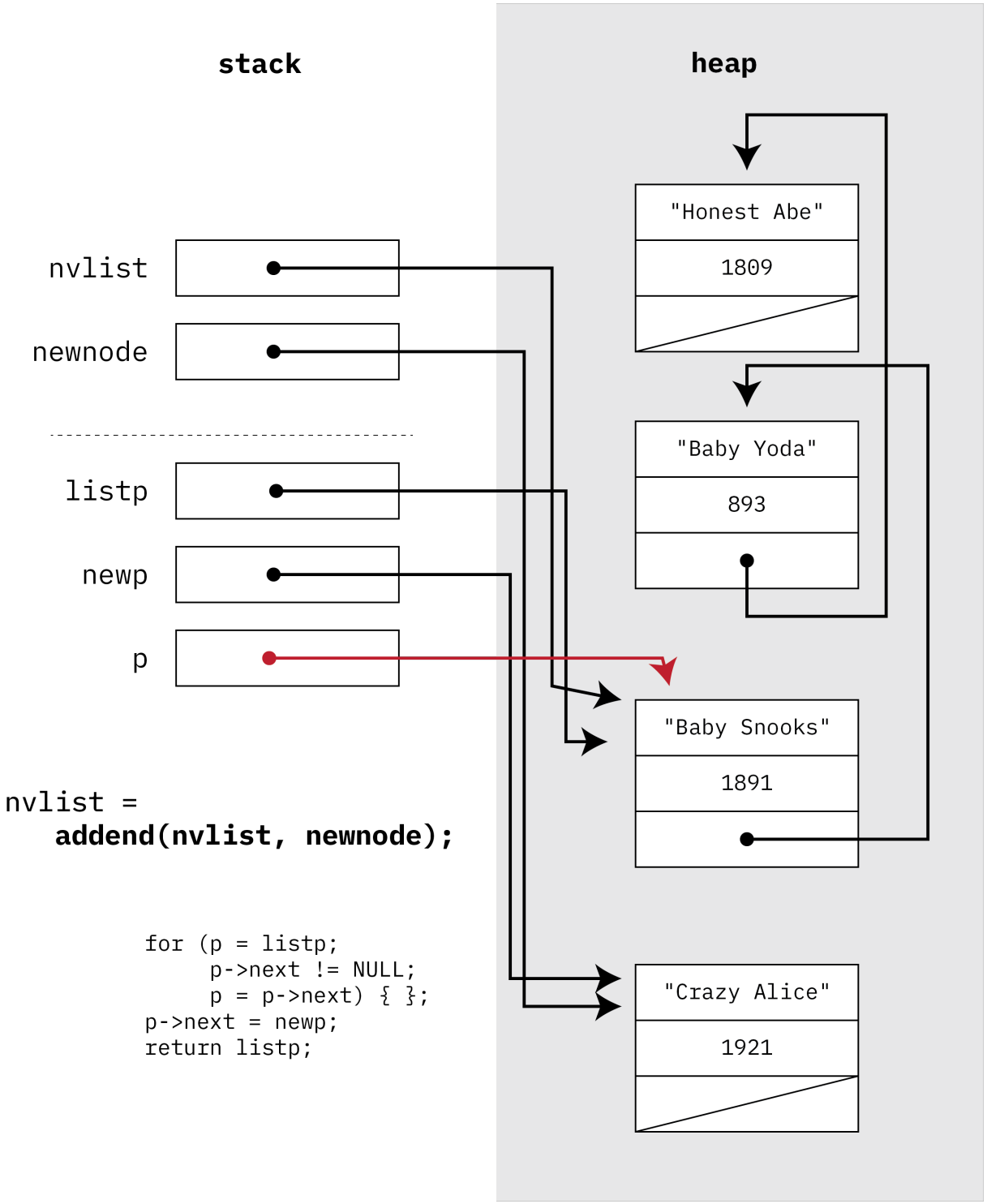

```
newnode = newitem(
  strdup("Crazy Alice",
  1921
);
```

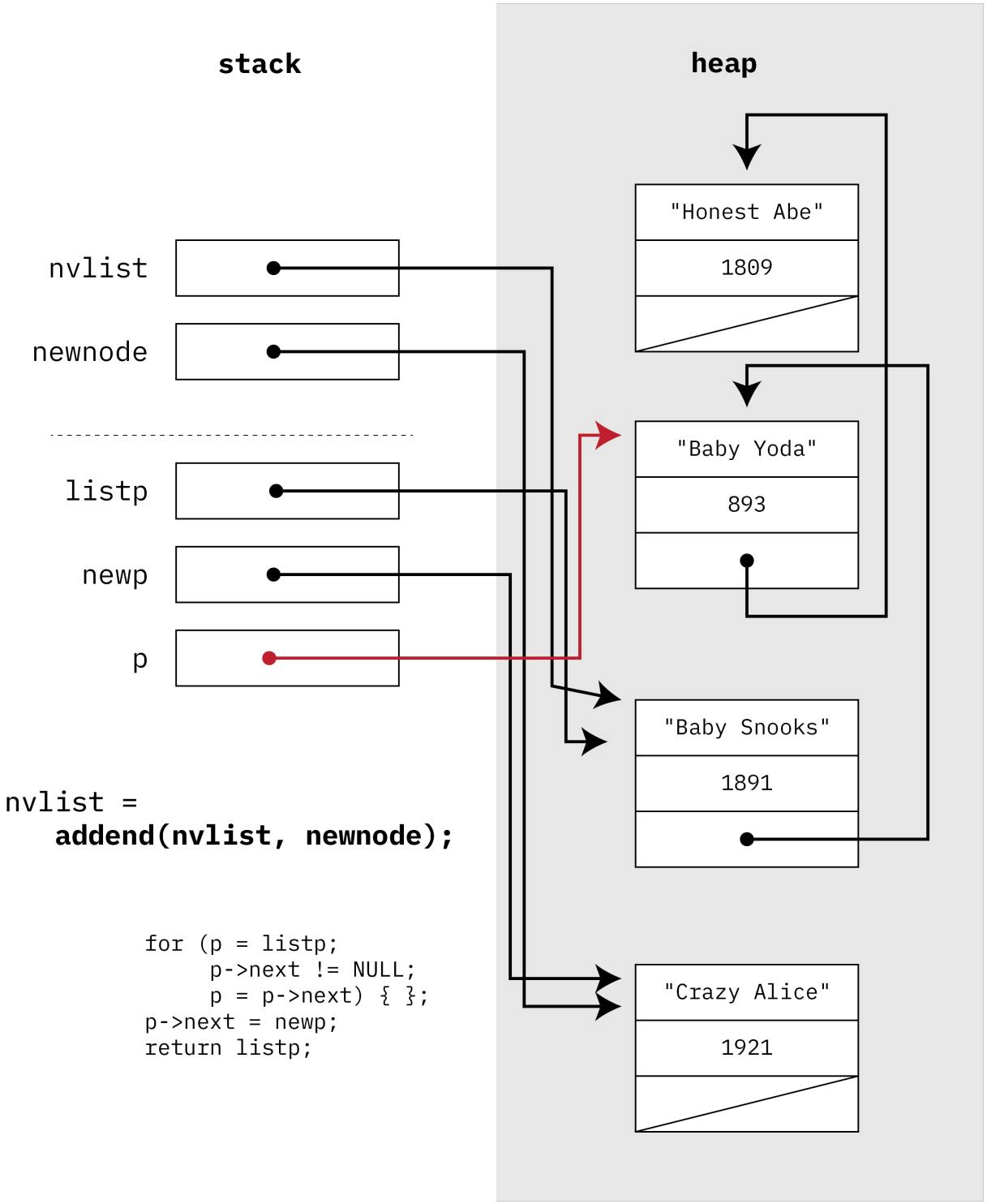


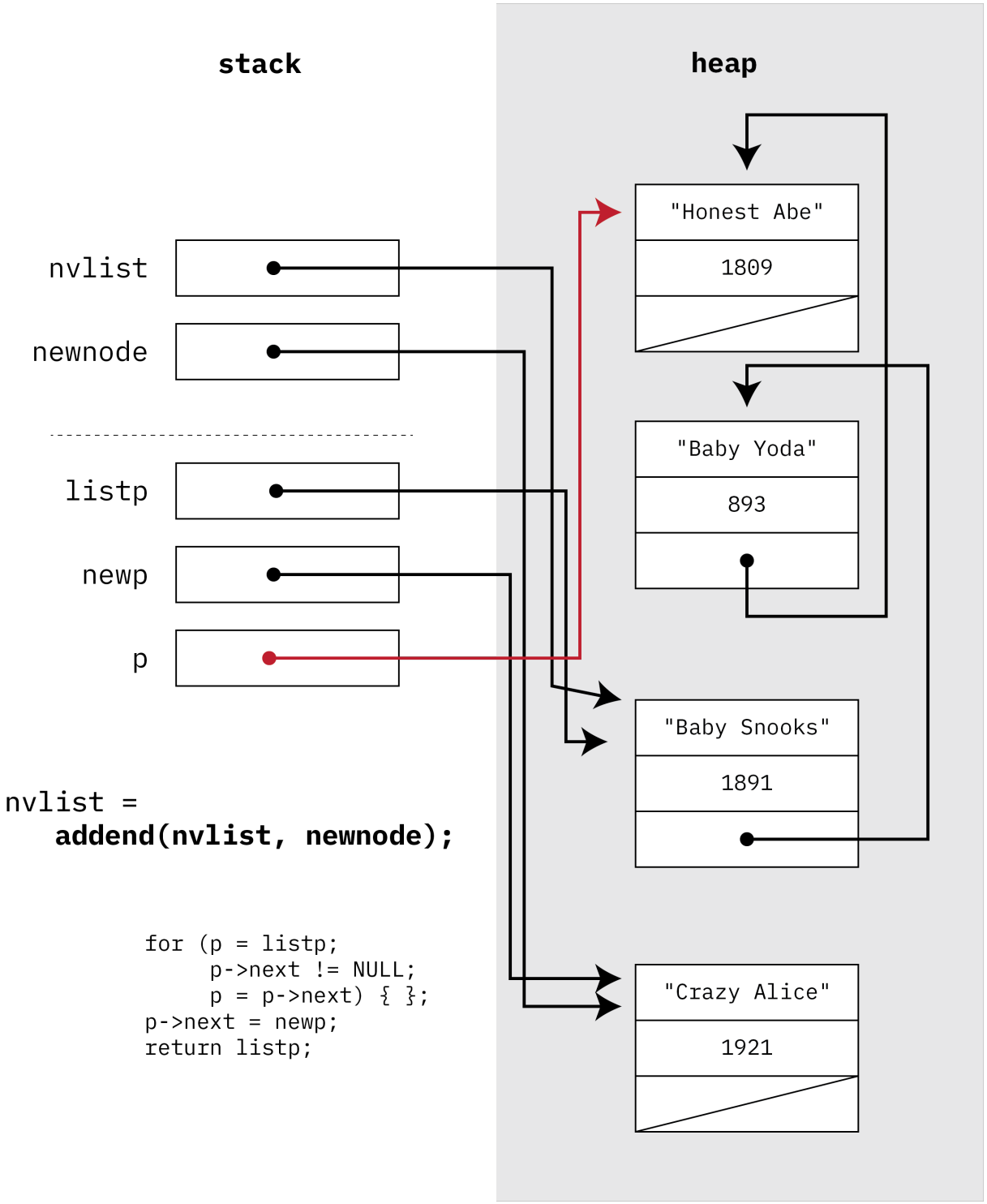

```
newnode = newitem(
  strdup("Crazy Alice",
  1921
);
```

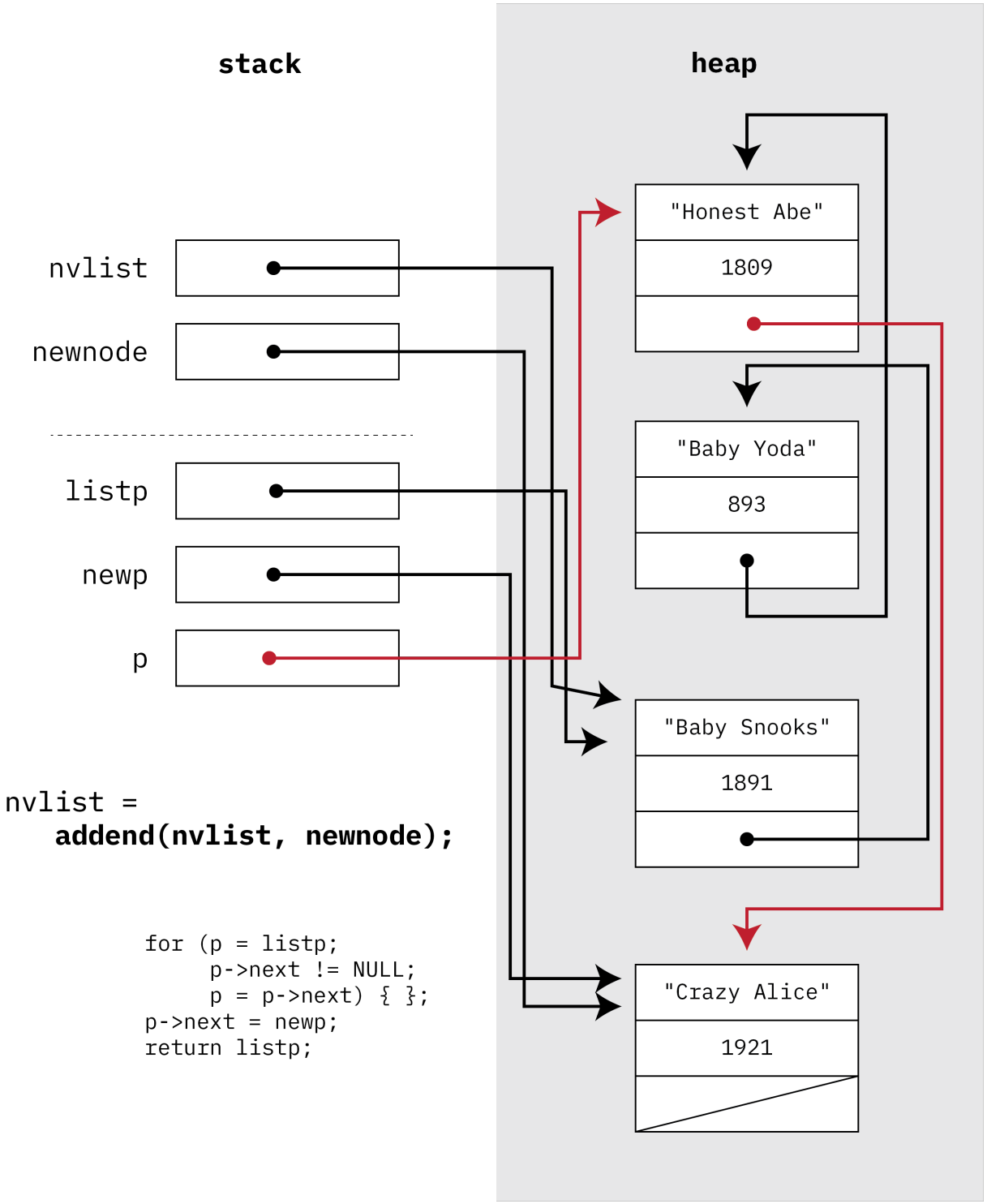

stack
heap
nvlist
newnode
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891
"Crazy Alice"
1921
nvlist =
addend(nvlist, newnode);

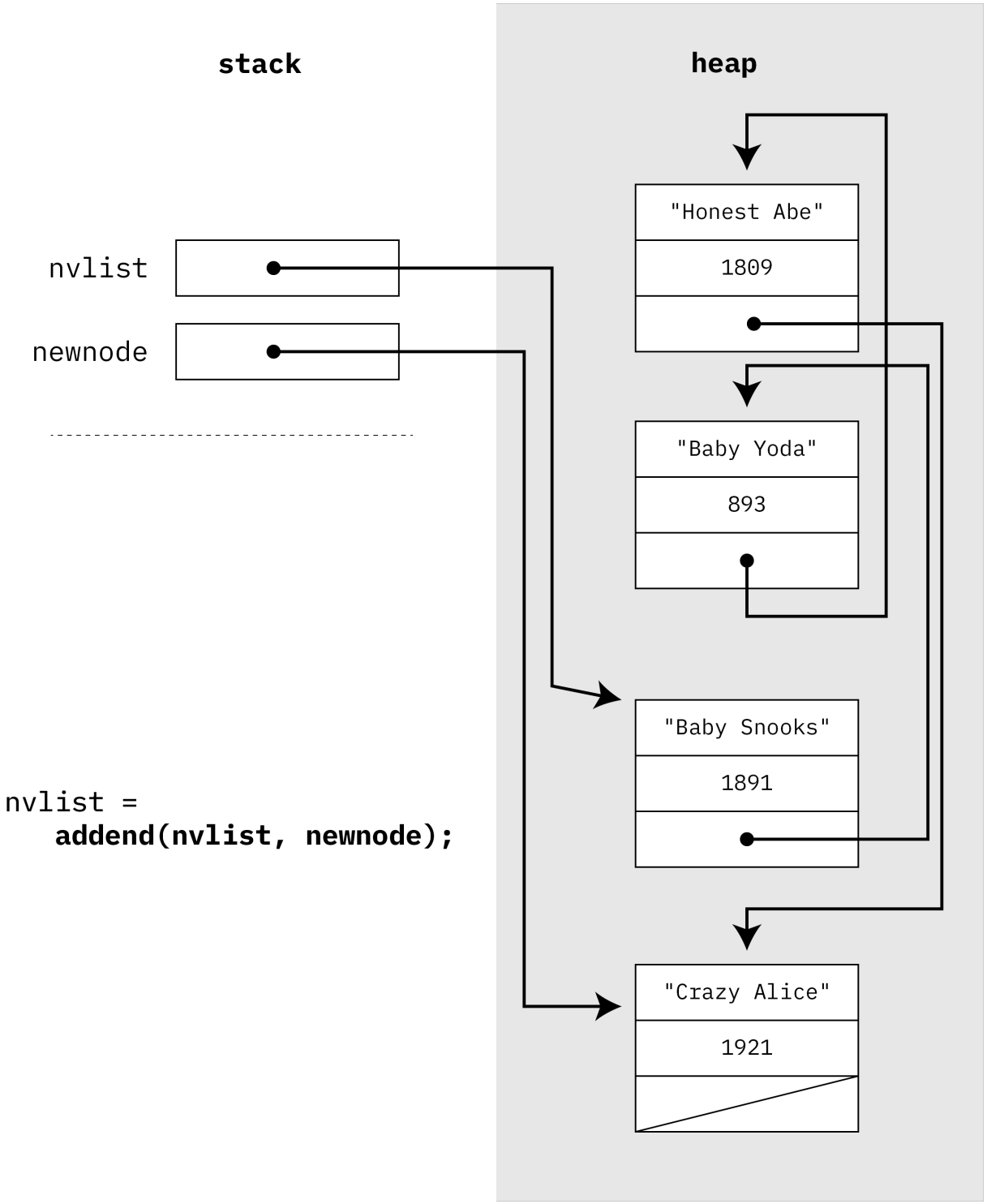

stack
heap
nvlist
newnode
listp
newp
p
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891
"Crazy Alice"
1921
nvlist =
addend(nvlist, newnode);


stack
heap
nvlist
newnode
listp
newp
p
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891
"Crazy Alice"
1921
nvlist =
addend(nvlist, newnode);
for (p = listp;
p->next != NULL;
p = p->next) { };
p->next = newp;
return listp;


stack
heap
nvlist
newnode
listp
newp
p
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891
"Crazy Alice"
1921
nvlist =
addend(nvlist, newnode);
for (p = listp;
p->next != NULL;
p = p->next) { };
p->next = newp;
return listp;


stack
heap
nvlist
newnode
listp
newp
p
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891
"Crazy Alice"
1921
nvlist =
addend(nvlist, newnode);
for (p = listp;
p->next != NULL;
p = p->next) { };
p->next = newp;
return listp;


stack
heap
nvlist
newnode
listp
newp
p
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891
"Crazy Alice"
1921
nvlist =
addend(nvlist, newnode);
for (p = listp;
p->next != NULL;
p = p->next) { };
p->next = newp;
return listp;




```
nvlist =
   addend(nvlist, newnode);
```

Find an item

- As with adding to the end, we have an operation that is O(n)
  - Unlike a sorted array, binary search does not work on list.
  - However, the code is uncomplicated and its main loop is similar to that in addend.
- The function returns the node even though it is searching on the name
  - If the function succeeds, the return value will be a memory location on the list which can be dereferenced.
  - Otherwise the return value is NULL (i.e., the lookup failed)

```
Nameval *lookup(Nameval *listp, char *name)
{
    for ( ; listp != NULL; listp = listp->next) {
        if (strcmp(name, listp->name) == 0) {
            return listp;
        }
    }
    return NULL;
}
```

```
Nameval *t = lookup(nvlist, "Bobby");
if (t) {
    printf("%d\n", t->value);
} else {
    printf("Couldn't find the value\n");
}
```

An observation about lists

- Many other operations on list have a similar structure
  - Traverse through the list...
  - ... and while doing so, compute some value / perform some comparison / etc.
  - After traversing the list, return some node address
- One approach is to write many such functions with this structure.
- Another approach is to write a more general-purpose function…
  - which traverses through the list…
  - … and applies some function to each element in the list.
  - Let's call this function **apply**
  - It will take three arguments (the list; a function to be applied to each element on the list; and an argument for that function)

apply

```
/* apply: execute fn for each element of listp */

void apply(Nameval *listp, void (*fn)(Nameval*, void*), void *arg)
{
    for ( ; listp != NULL; listp = listp->next) {
        (*fn)(listp, arg);  /* call the function */
    }
}
```

```
void (*fn)(Nameval*, void*),

  Declare fn to be a pointer to a void-valued function
  (i.e., it is a variable that holds the address of a function
  that returns void).

  Such a function takes two arguments: an address to a Nameval
  (list element) and a void * (a generic point to an argument
  for the function being passed in).
```

example: printing out all elements

```
/* apply: execute fn for each element of listp */

void apply(Nameval *listp, void (*fn)(Nameval*, void*), void *arg)
{
    for ( ; listp != NULL; listp = listp->next) {
        (*fn)(listp, arg);  /* call the function */
    }
}
void printnv(Nameval *p, void *arg)
{
    char *fmt;

    fmt = (char *) arg;
    printf(fmt, p->name, p->value);
}
```

```
apply(nvlist, printnv, "%s: %x\n");
```

example: count of all elements

```
void inccounter(Nameval *p, void *arg)
{
    int *ip;

    /* p is not used -- all we care about is that this function
     * is called once per node.
     */
    ip = (int *)arg;
    (*ip)++;   /* Note the parentheses!!! */
}
```

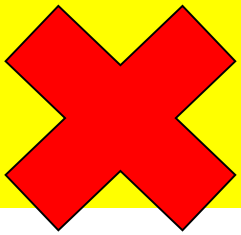
```
int n;

n = 0;
apply(nvlist, inccounter, &n);
printf("%d elements in nvlist\n", n);
```

Deleting elements from the list

- We have yet to see the use of `free` in the management of our lists
- Let's take the simplest case first: deleting the whole list
  - Here we must be rather careful
  - We cannot free an element if we need to dereference that same element later.
  - Also: `free` may itself modify the newly deallocated memory
- Must make good use of temporary variables

freeing the list

```
void bad_freeall(Nameval *listp)
{
    for ( ; listp != NULL; listp = listp->next ) {
        /* What is the value of listp->next after the next
         * operation?
         */
        free(listp);
    }
}
```



```
void freeall(Nameval *listp)
{
    Nameval *next;

    for ( ; listp != NULL; listp = next ) {
        next = listp->next;
        /* assume here the listp->name is freed someplace else */
        free(listp);
    }
}
```

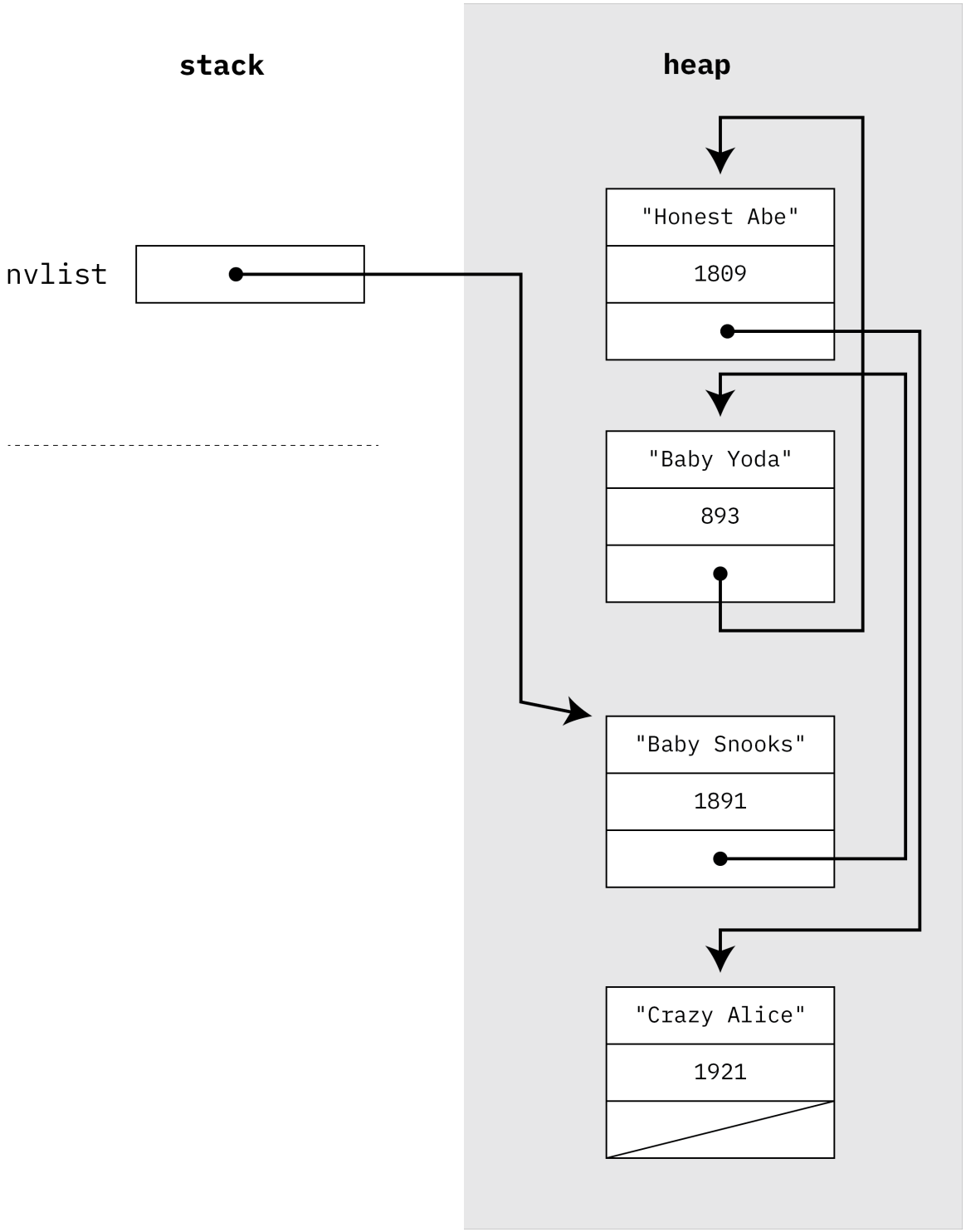
Deleting elements from the list

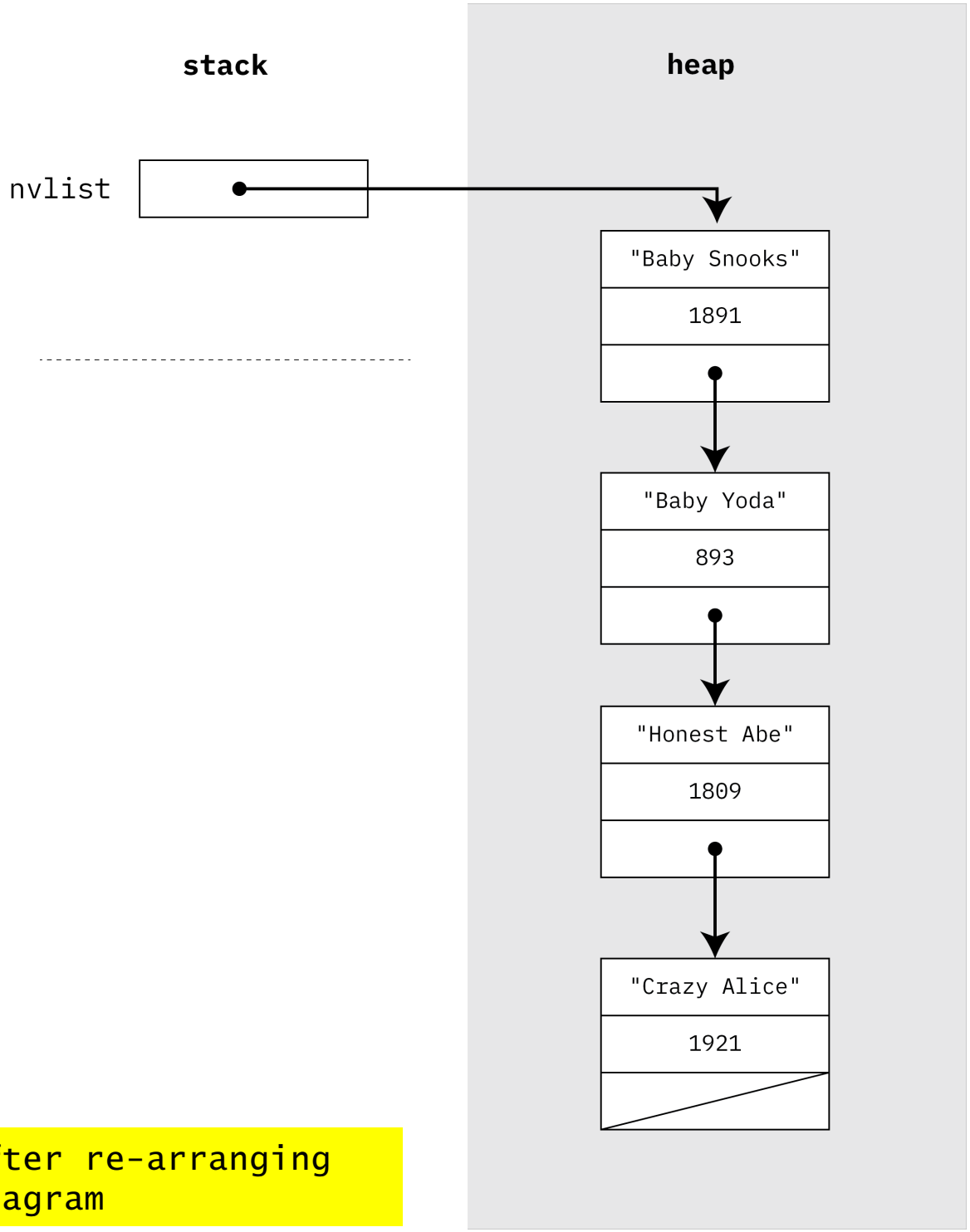
- Deleting a single element requires more work than adding an element
  - Part of this is due to the consequences of using a singly-linked list.
  - It would be much easier with a doubly-linked list—but then again, such a list does require twice as many pointers to be maintained.
- This is the place where bugs are often introduced
  - Yet if we are careful—and correctly diagram what we intend to do—then we can get it right the first time.
  - Recall the two main cases: are we deleting the first element? or one past the first

Deleting a single element

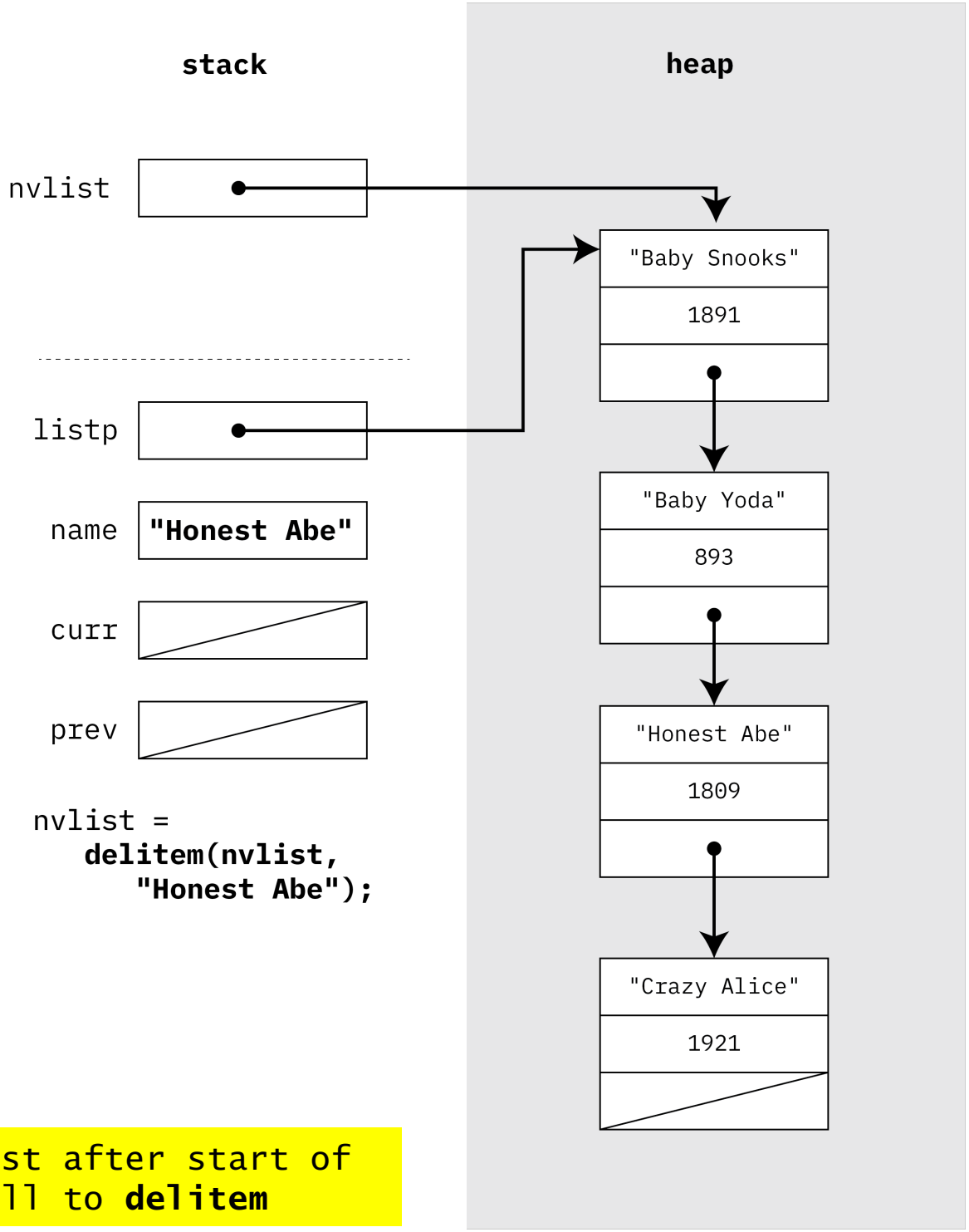
```
Nameval *delitem (Nameval *listp, char *name)
{
    Nameval *curr, *prev;

    prev = NULL;
    for (curr = listp; curr != NULL; curr = curr-> next) {
        if (strcmp(name, curr->name) == 0) {
            if (prev == NULL) {
                listp = curr->next;
            } else {
                prev->next = curr->next;
            }
            free(curr);
            return listp;
        }
        prev = curr;
    }
    /* Ungraceful error handling, but gets the point across. */
    fprintf(stderr, "delitem: %s not in list", name);
    exit(1);
}
```

```
/* typical usage */
Nameval *nvlist = ...
... operations on list ...
nvlist = delitem(nvlist, "Boris");
```

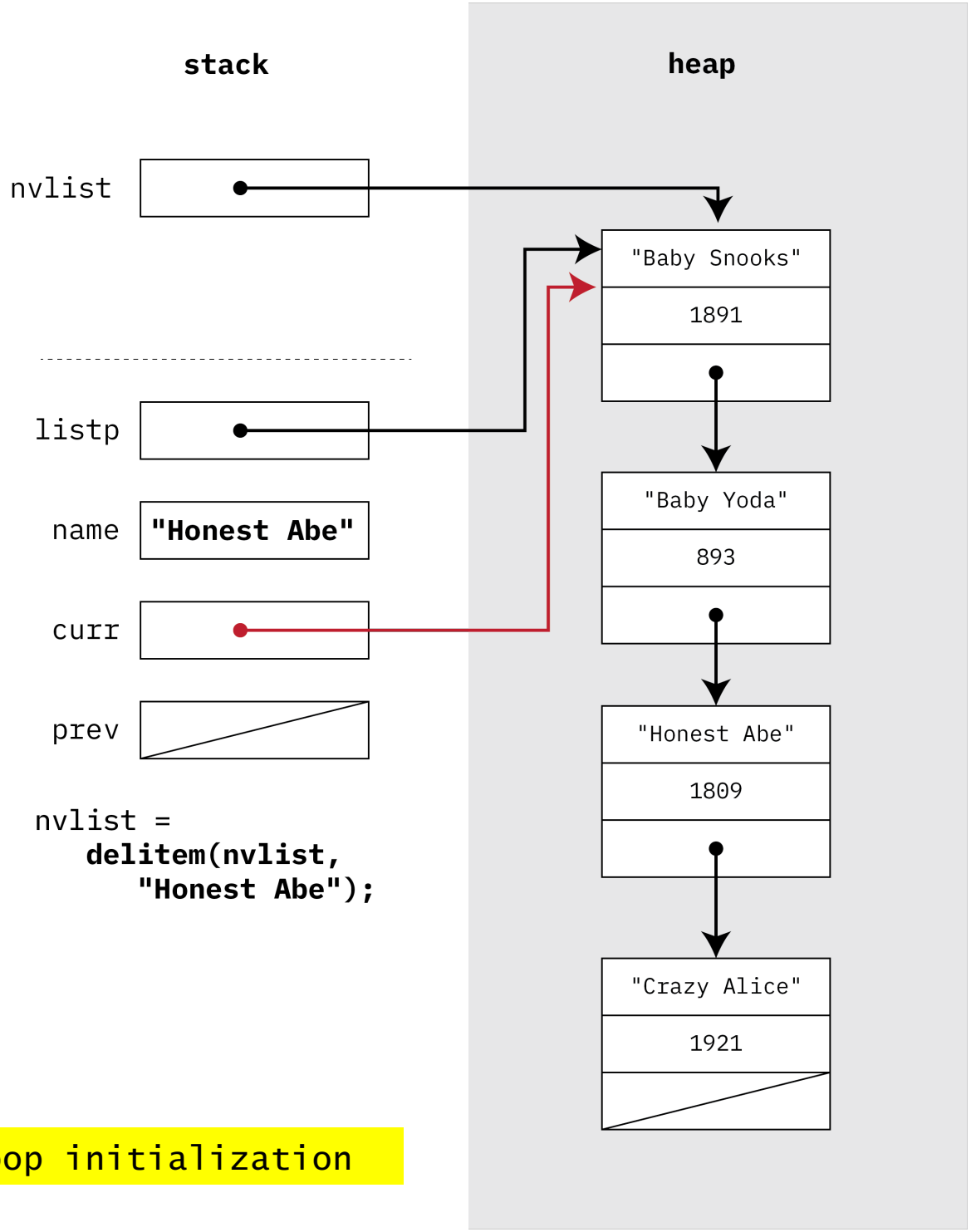

stack
heap
nvlist
"Honest Abe"
1809
"Baby Yoda"
893
"Baby Snooks"
1891
"Crazy Alice"
1921



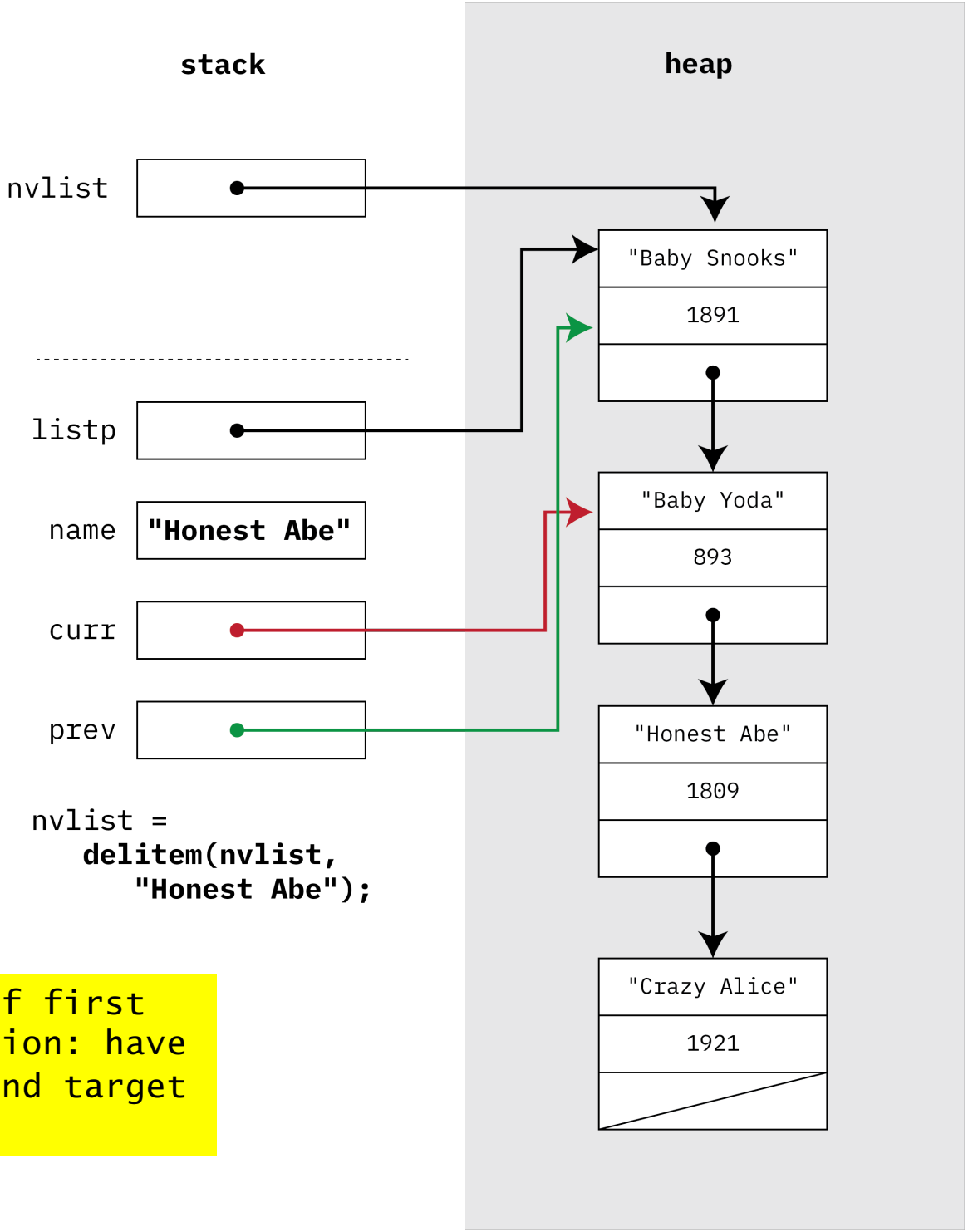
After re-arranging diagram



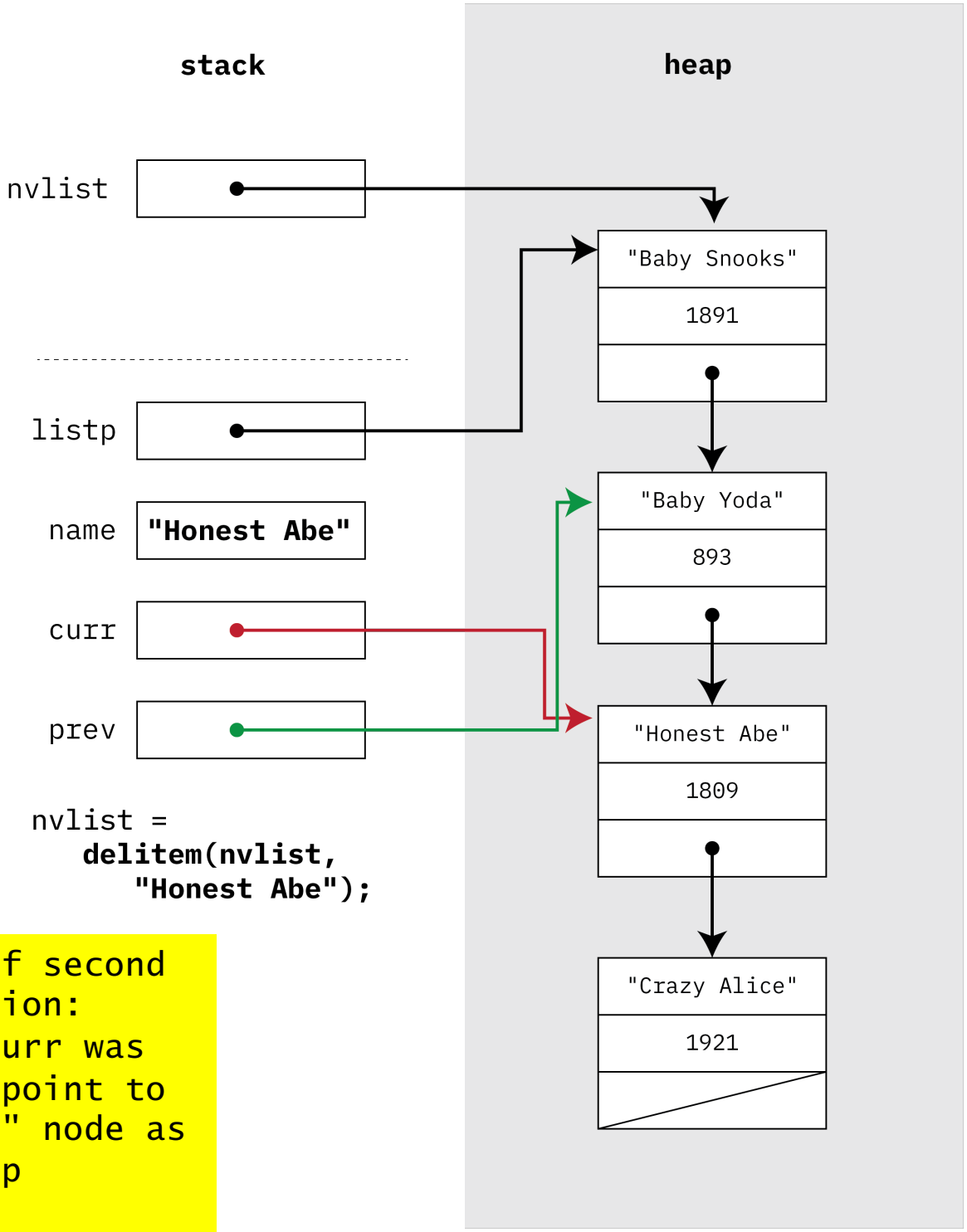
Just after start of call to **delitem**



Loop initialization

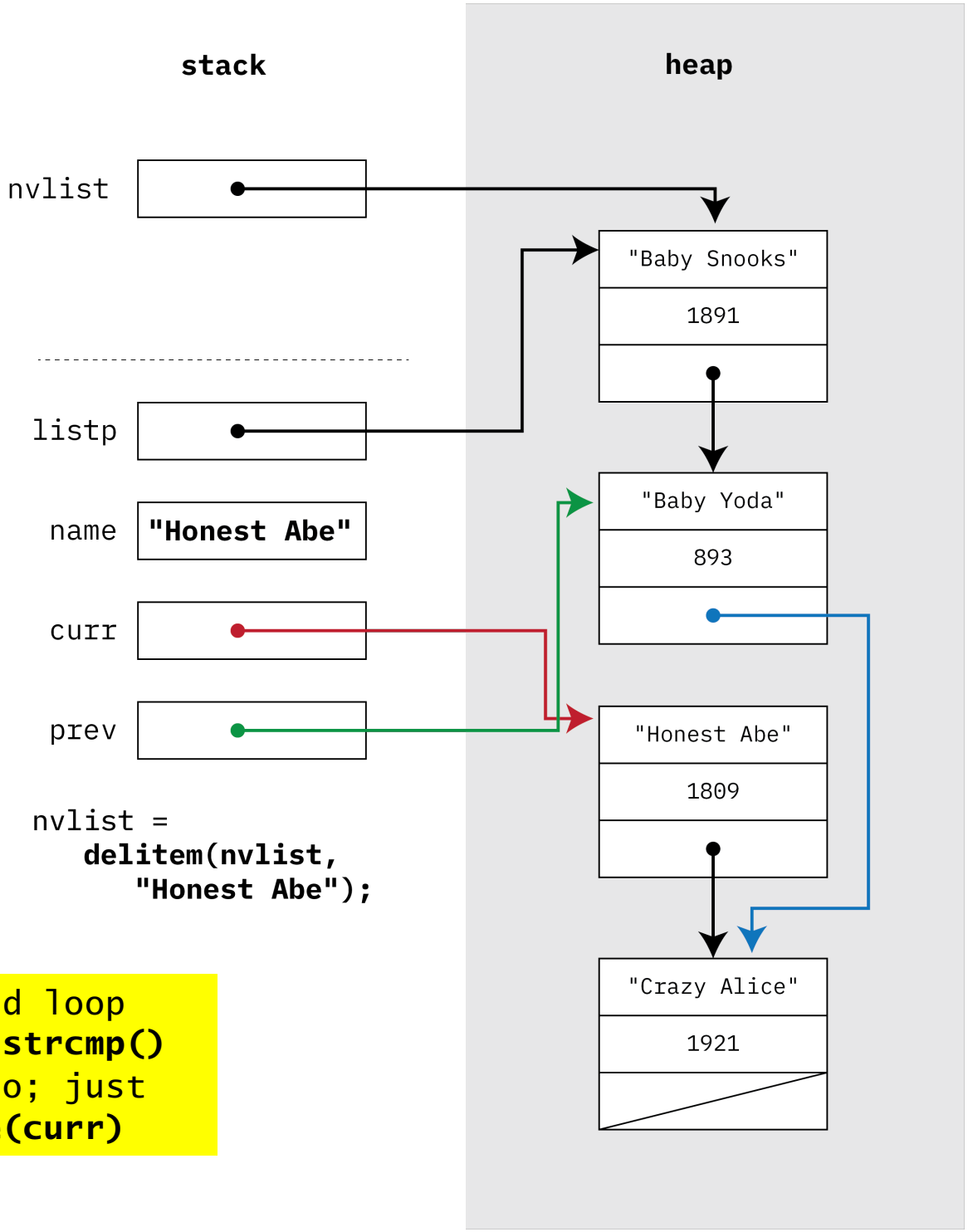


After end of first loop iteration: have not yet found target node.



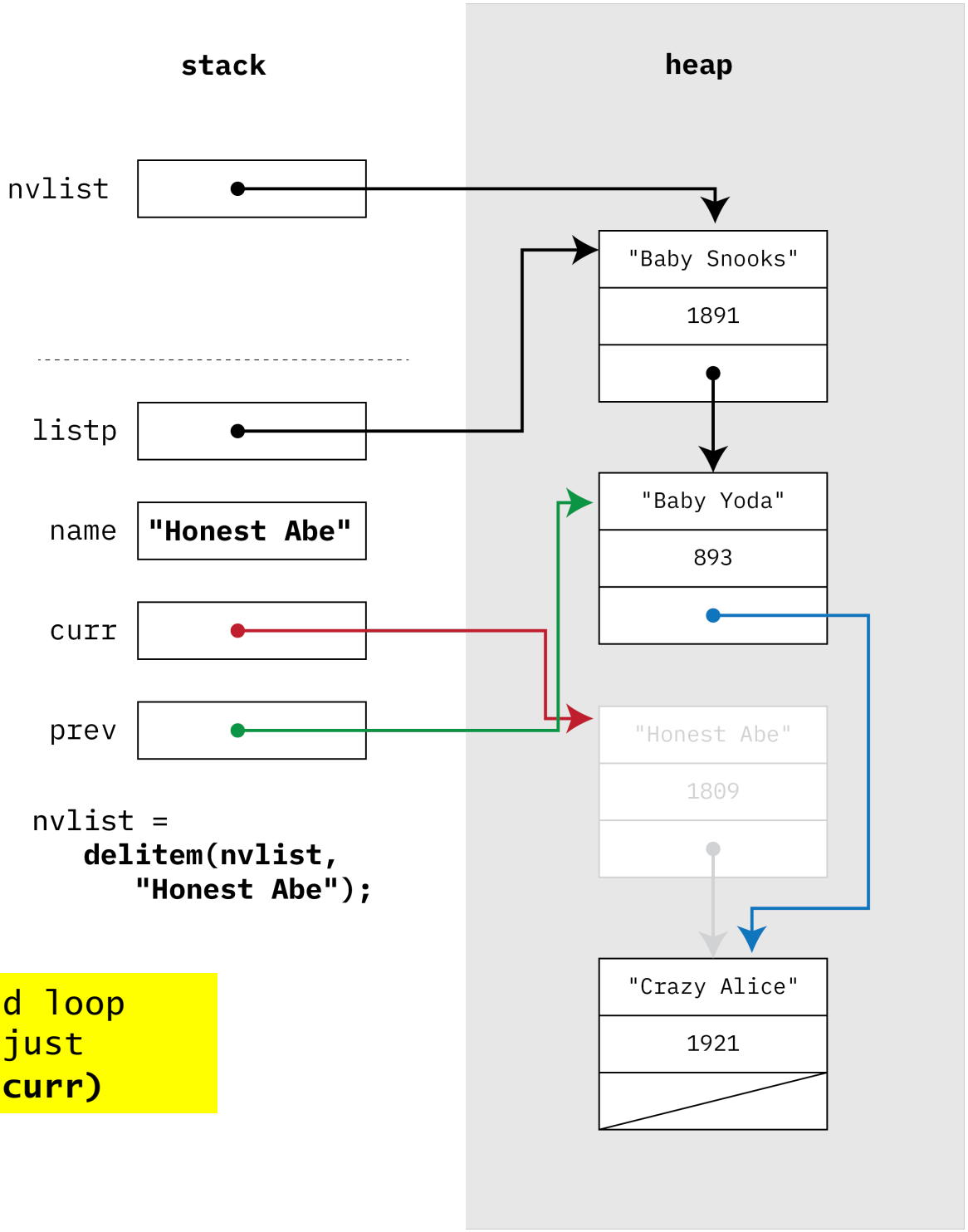

```
nvlist =
   delitem(nvlist,
      "Honest Abe");
```

After end of second loop iteration: (note the curr was updated to point to "Honest Abe" node as part of loop iteration.



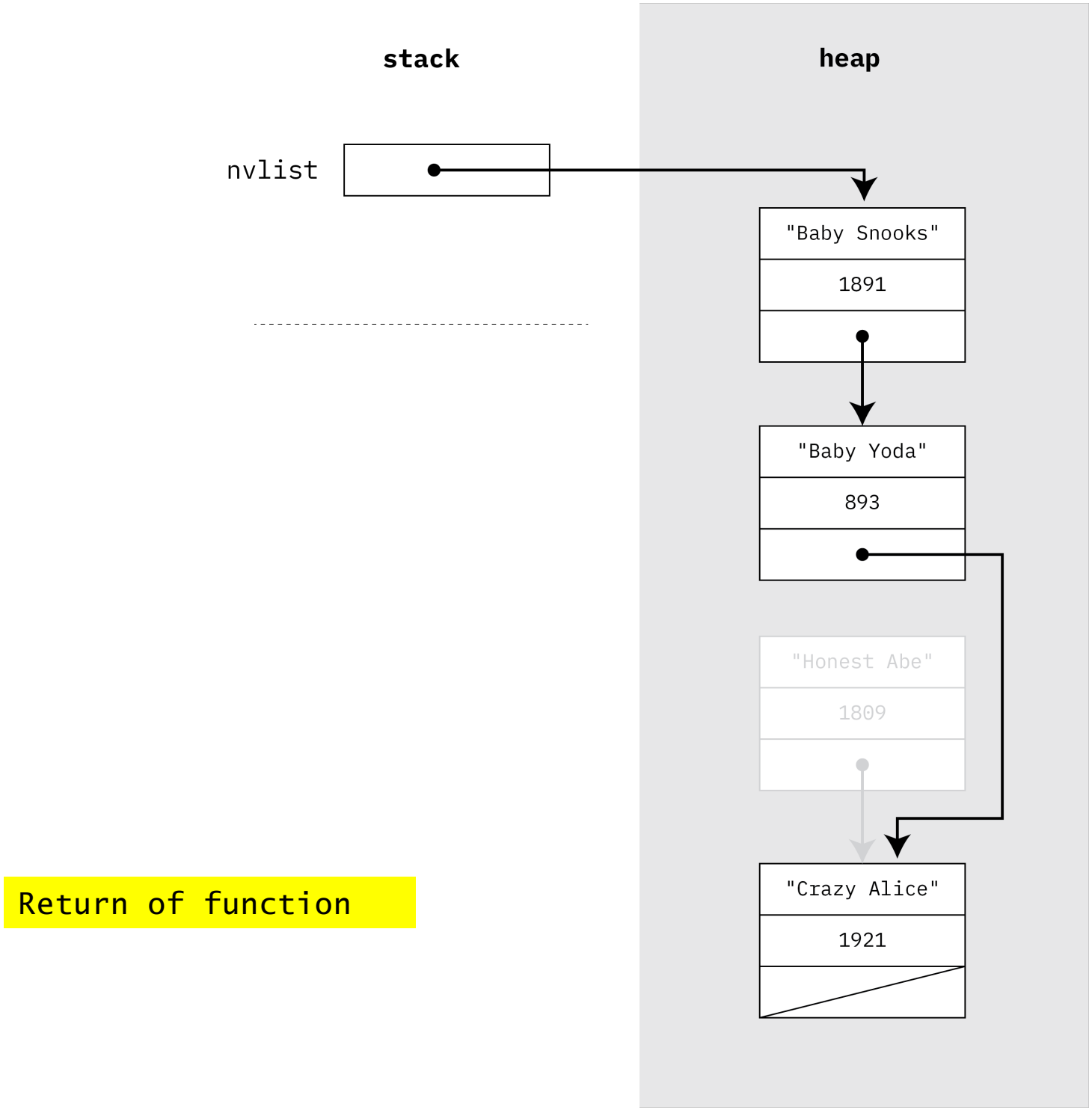

```
nvlist =
   delitem(nvlist,
      "Honest Abe");
```

During third loop iteration: **strcmp()** equaled zero; just before **free(curr)**




```
nvlist =
   delitem(nvlist,
      "Honest Abe");
```

During third loop iteration: just *after* **free(curr)**

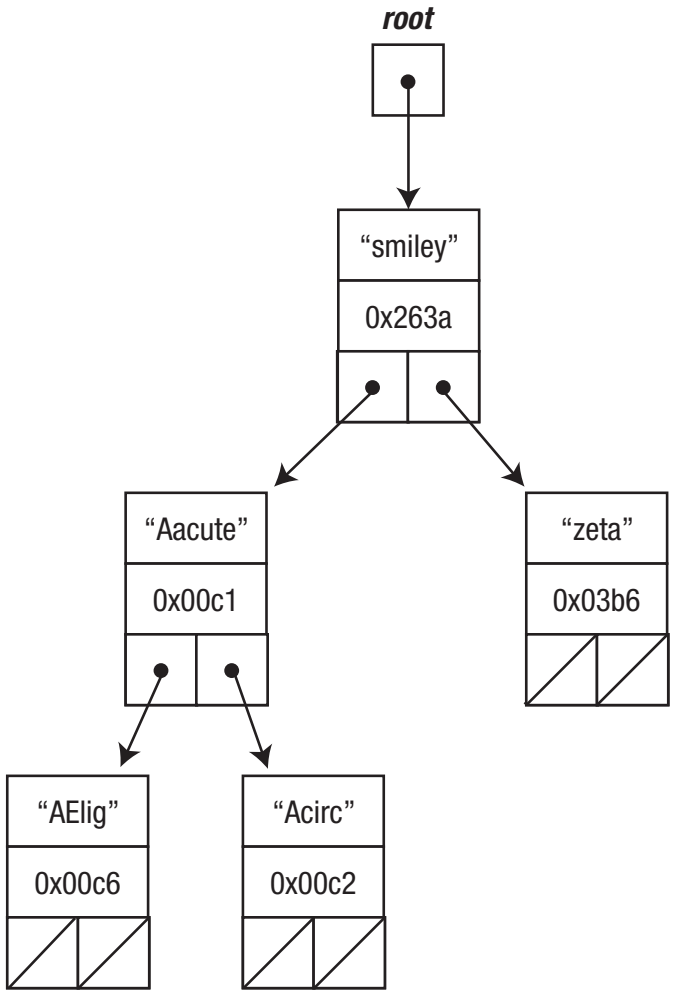


Return of function

Trees

- Hierarchical data structure
  - We use them implicitly when navigating through the Unix file system
  - Also used in compilers (e.g., parse trees)
  - We also construct trees programmatically to get O(lg n) behavior rather than O(n) for our algorithms (after some assumptions)
- **Binary search tree**
  - Simpler tree flavour, straightforward to implement
  - Node in a binary search tree has a **value** and two pointers, **left** and **right**
  - The pointers lead to the node's children
  - All children to the left of a particular node have lower values than the node.
  - All children to the right of a particular node have greater values than the node.

Binary search tree example



Tree node

- We'll again re-use the same problem as shown earlier (<name, value> pairs are stored in nodes)
- We now need links to the left and right subtree
- Code to create such a node is left as an exercise.

```
typedef struct Nameval Nameval;
struct Nameval {
    char    *name;
    int      value;
    Nameval *left;  /* lesser */
    Nameval *right; /* greater */
};
```

Construction

- Although iterative node insertion is possible, we will focus on the recursive version
- Constructing a tree means descending into the tree recursively.
  - At insertion time, each new node ends up as a leaf node.
  - As other items are inserted later, a leaf node above a new leaf node will become the new node's parent.
- The algorithm must choose the left or right branch until the correct place for node is found.
  - But watch for how the left and right links are always updated!
- As with the linked-list routines, the insertion algorithm returns the root of the tree as the result.

Inserting node into tree

```
/* Assume newp has been already initialized. */
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) {
        return newp;
    }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) {
        fprintf(stderr, "insert: ignoring duplicate entry %s\n",
            newp->name);
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```

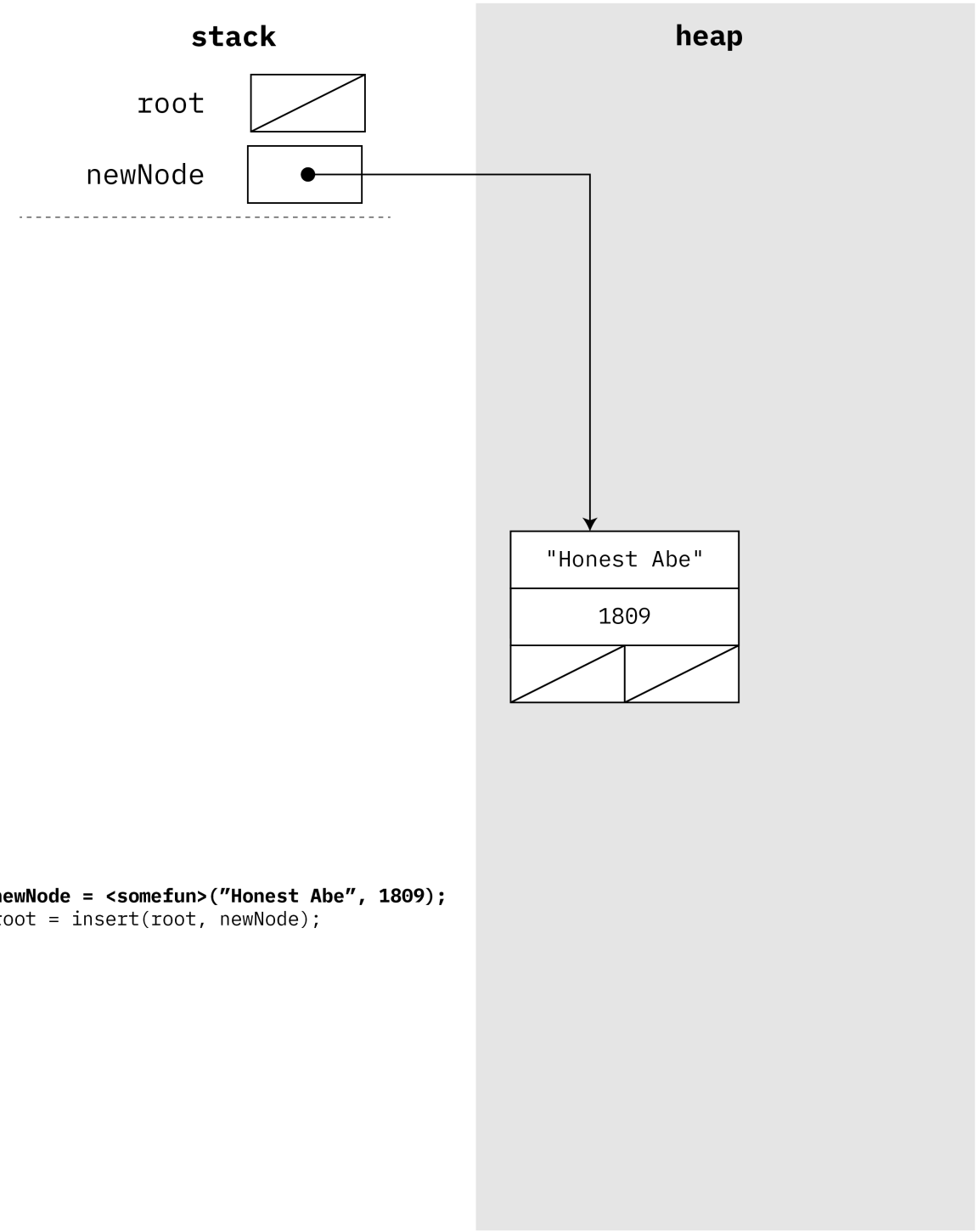
```
Nameval *root = NULL;
...
Nameval *newNode = ... code to malloc a tree node, assign field values, etc. ...
...
root = insert(root, newNode);
```

Example

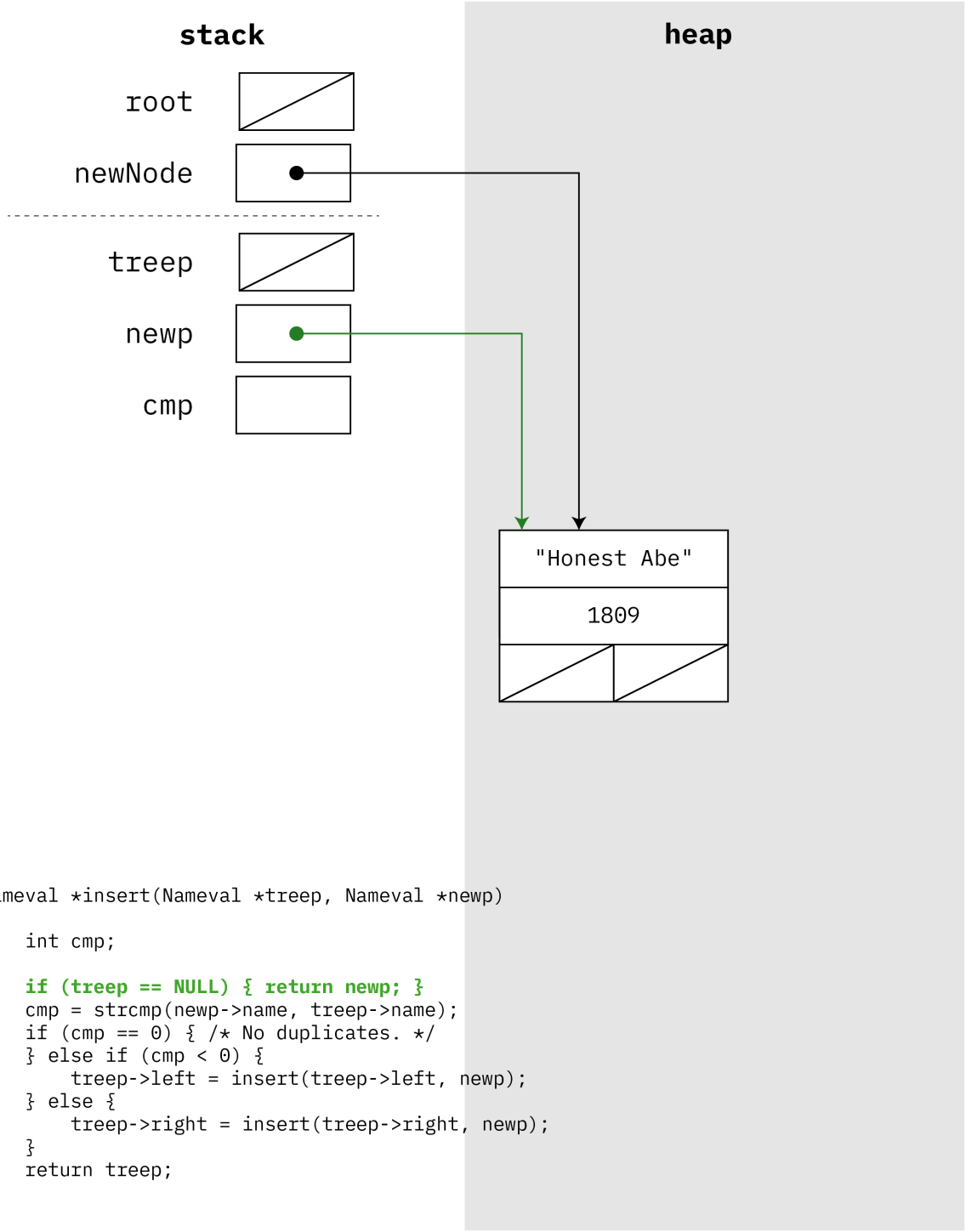
- Let us consider the following example:
  - Root of tree is initialized
  - Name/value node for ("Honest Abe", 1809) created then inserted ...
  - ... then name/value node for ("Baby Yoda", 893) (ditto) ...
  - ... and finally name/value node for ("Crazy Alice", 1921) (ditto).
- To simplify explication, code omits sanity checks
  - Normally we would want to write code that verifies the success of node-creation

```
Nameval *newNode;
Nameval *root = NULL;

newNode = some_node_creation_function("Honest Abe", 1809);
root = insert(root, newNode);

newNode = some_node_creation_function("Baby Yoda", 893);
root = insert(root, newNode);

newNode = some_node_creation_function("Crazy Alice", 1921);
root = insert(root, newNode);
```

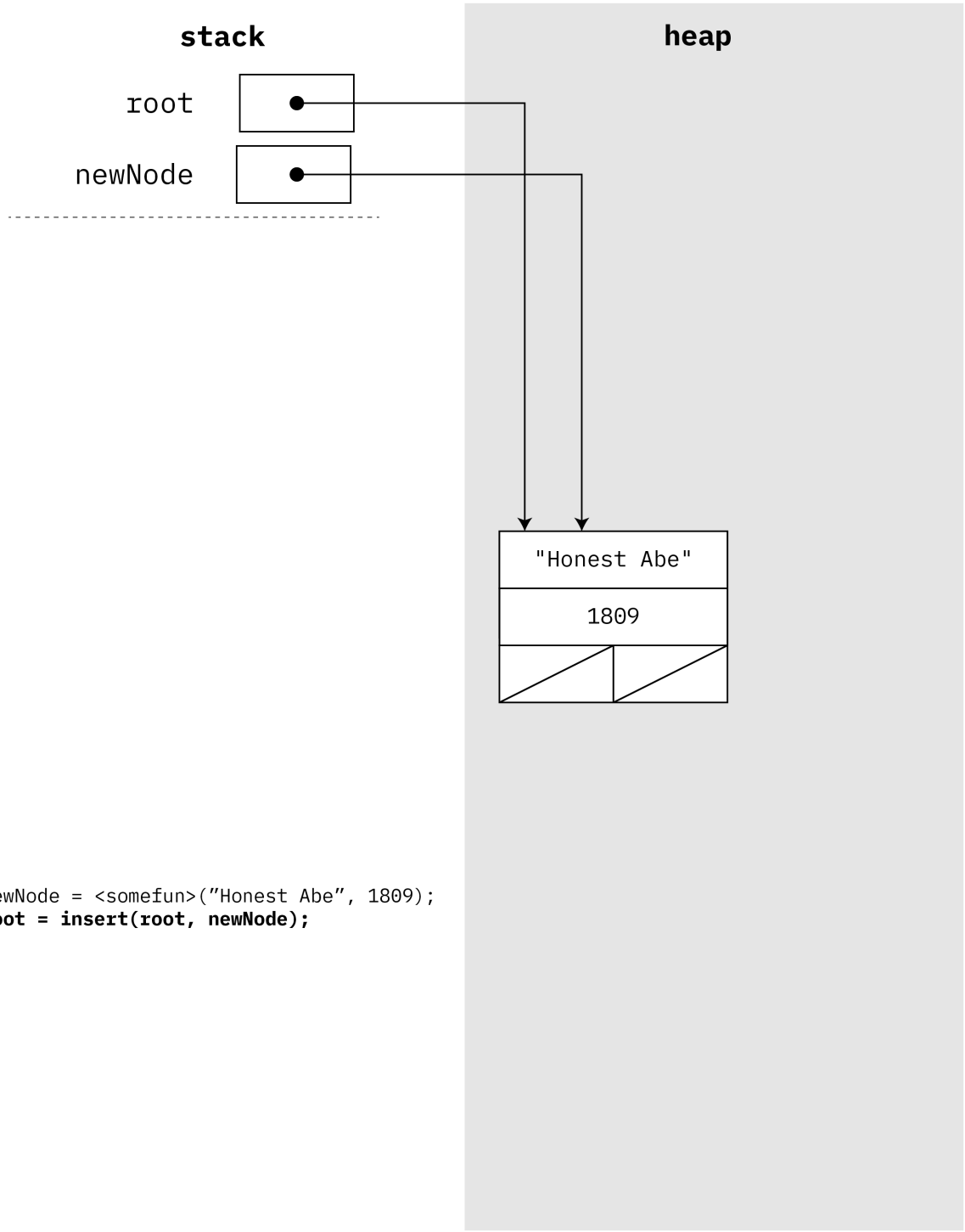

stack
heap
root
newNode
root = null;



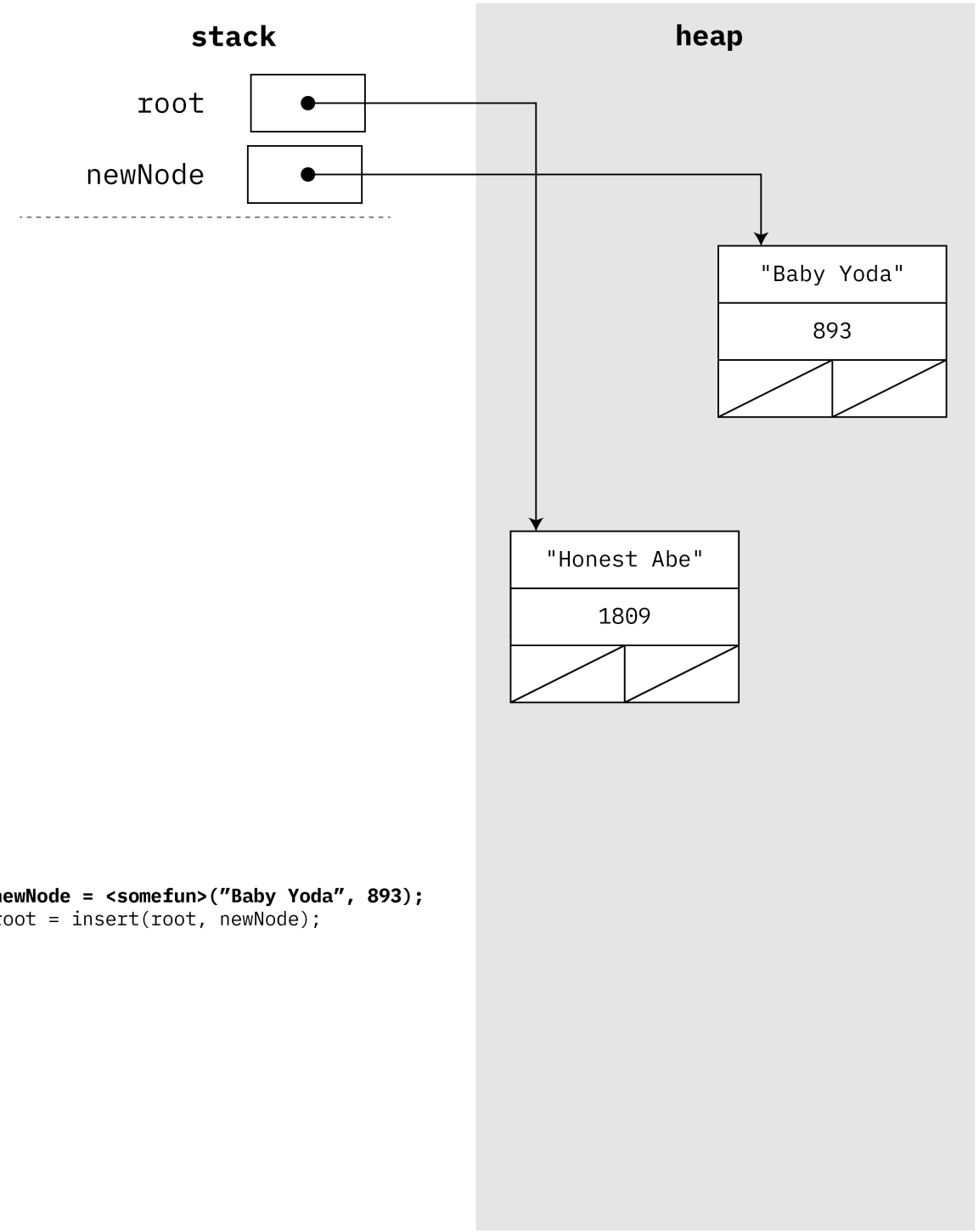

```
newNode = <somefun>(”Honest Abe”, 1809);
root = insert(root, newNode);
```



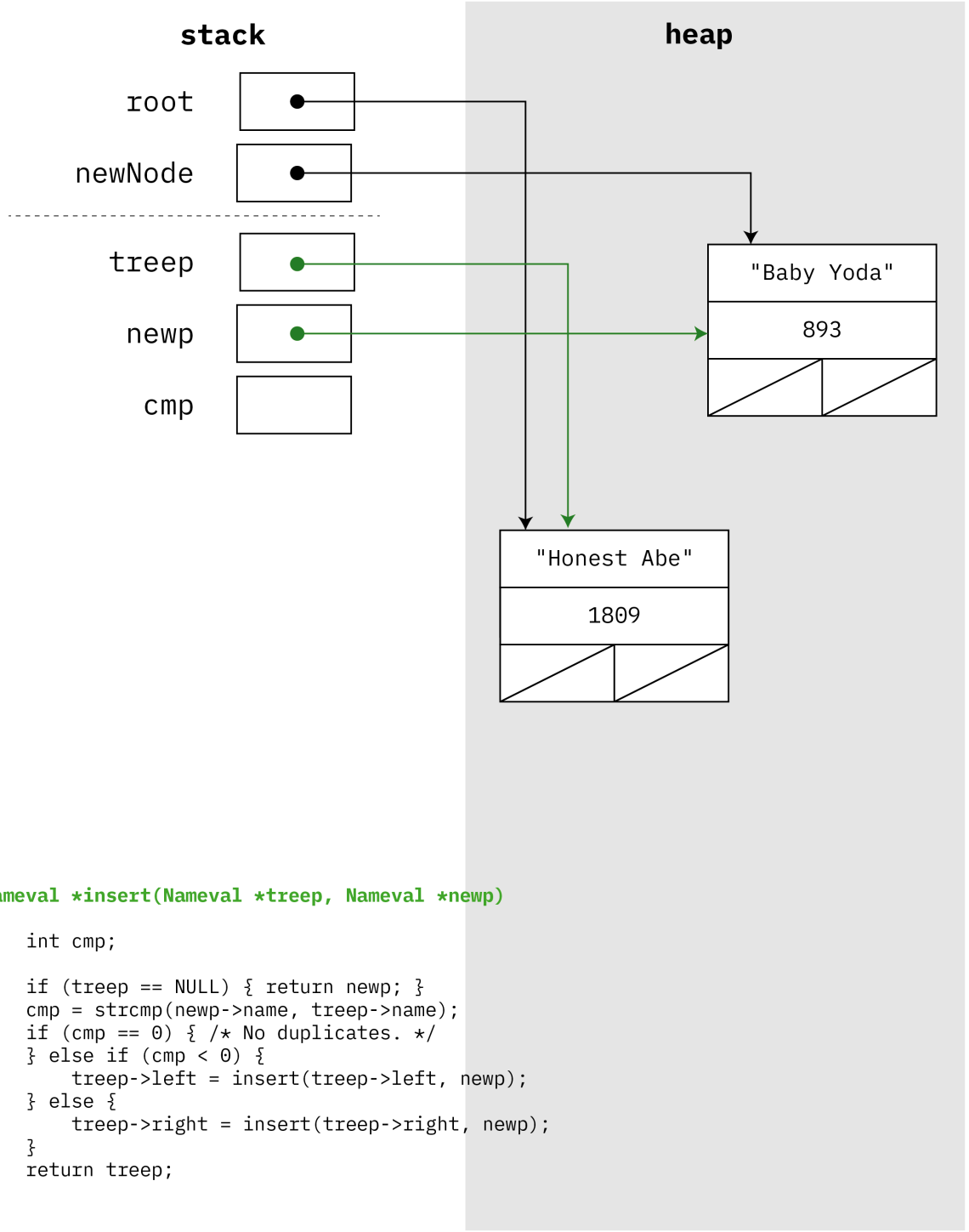

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



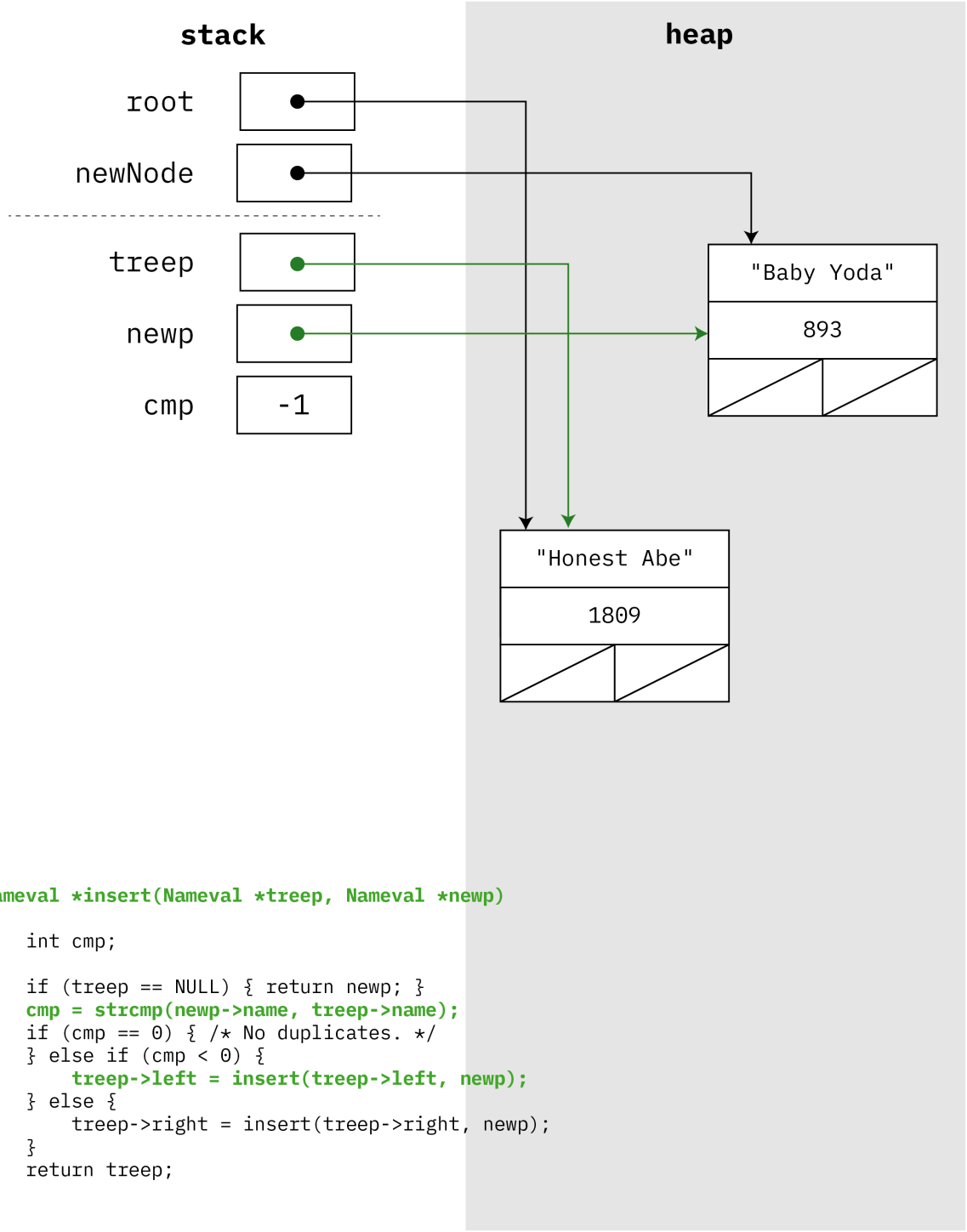

```
newNode = <somefun>(”Honest Abe”, 1809);
root = insert(root, newNode);
```



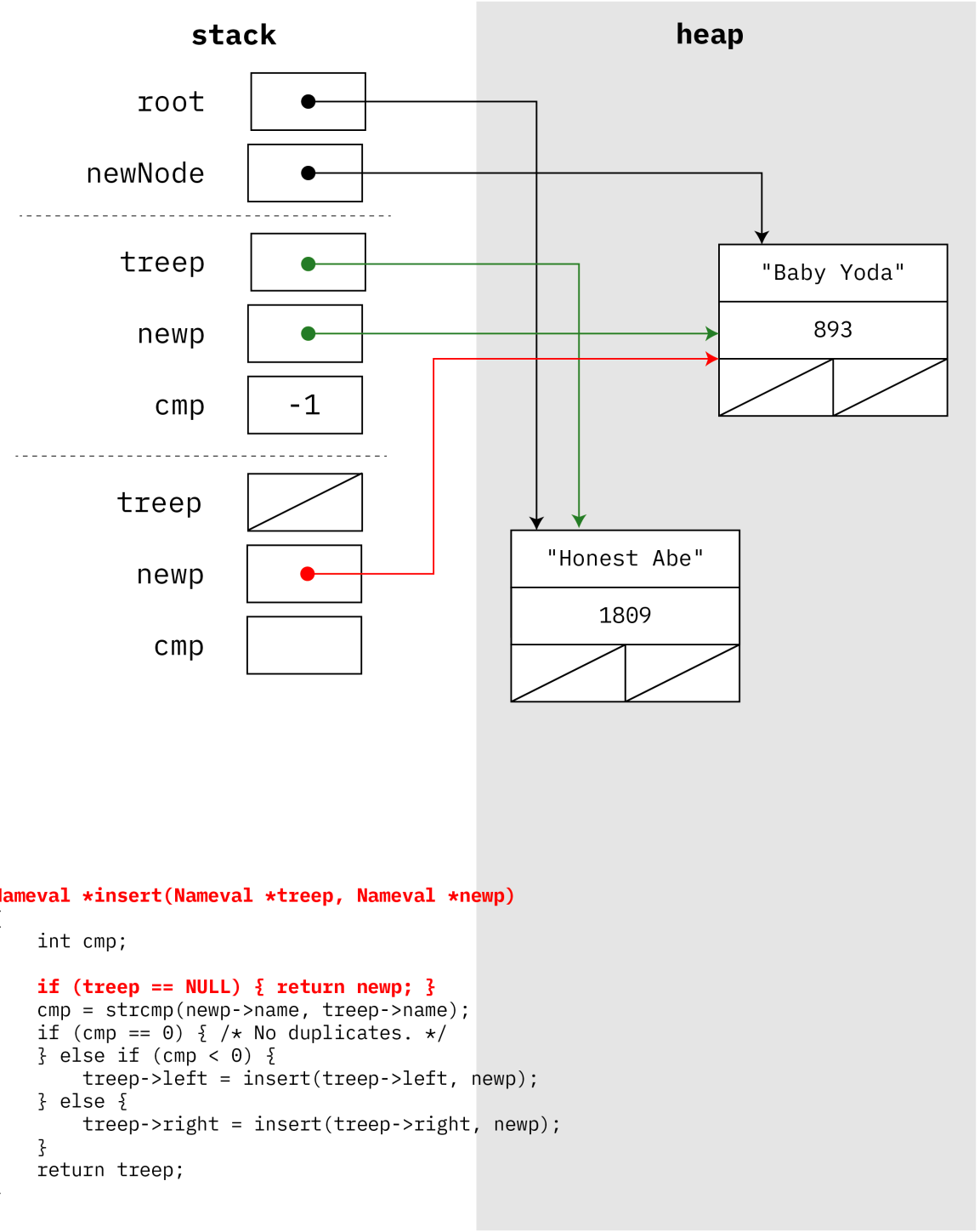
newNode = <somefun>(”Baby Yoda”, 893);
root = insert(root, newNode);



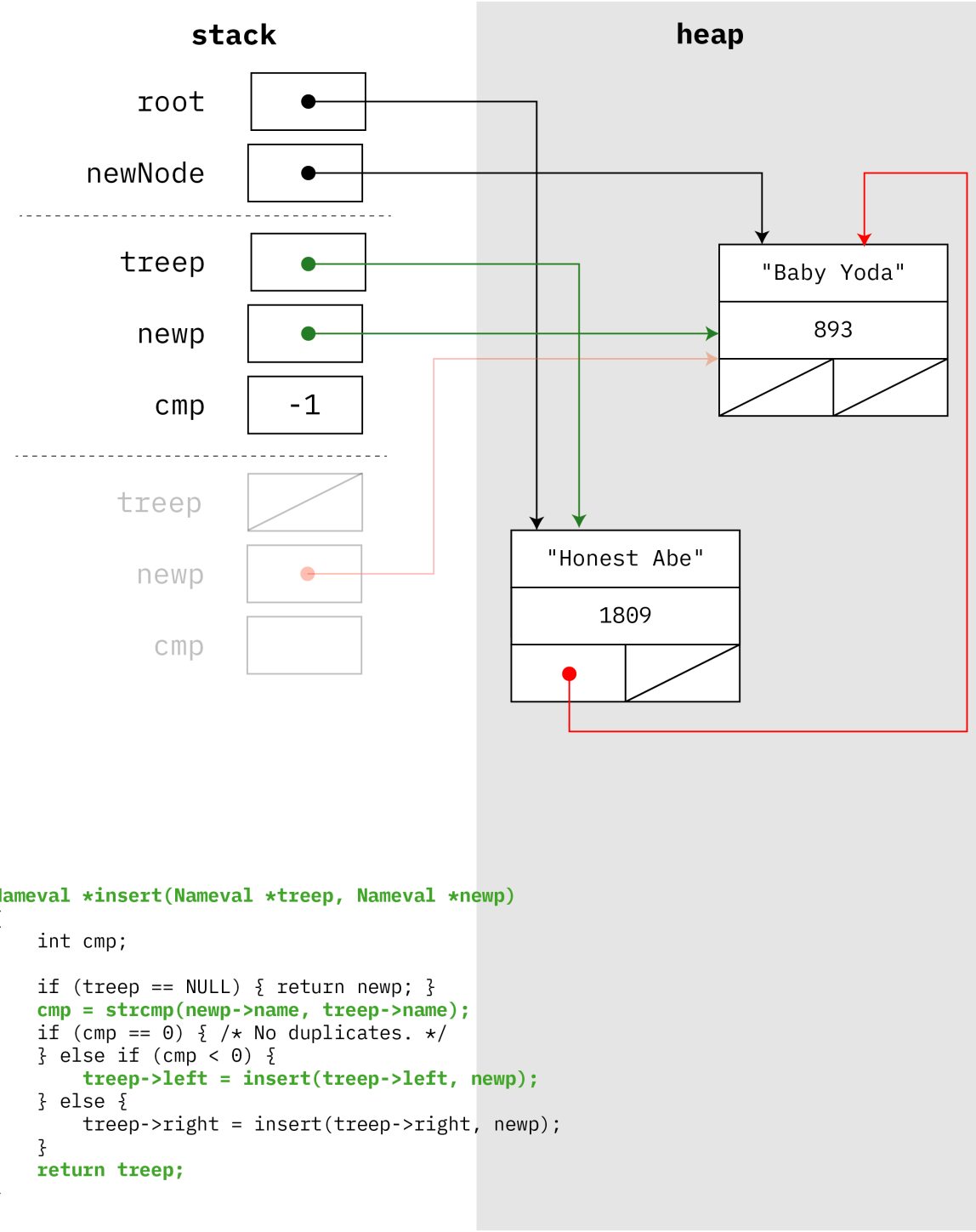

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



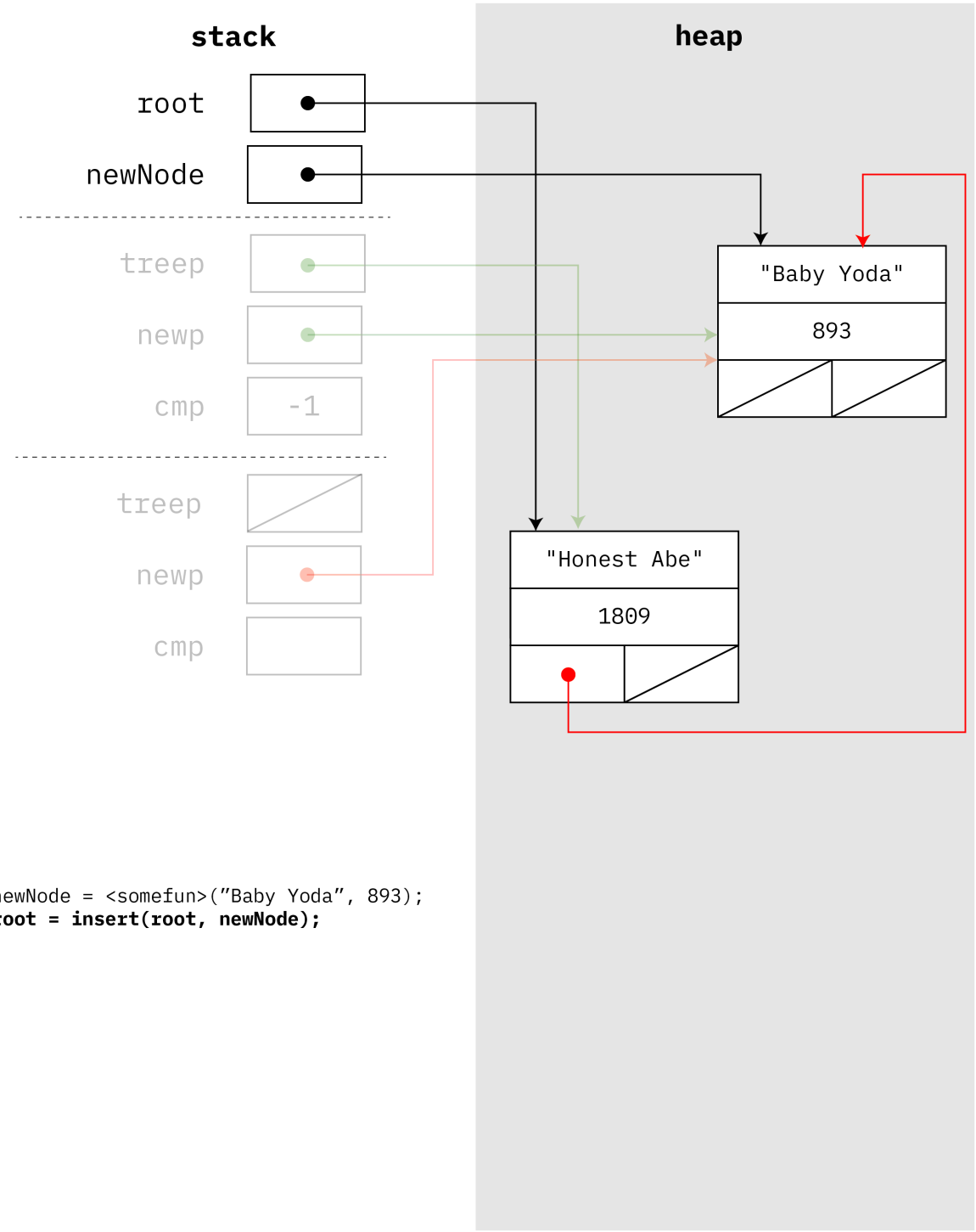

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



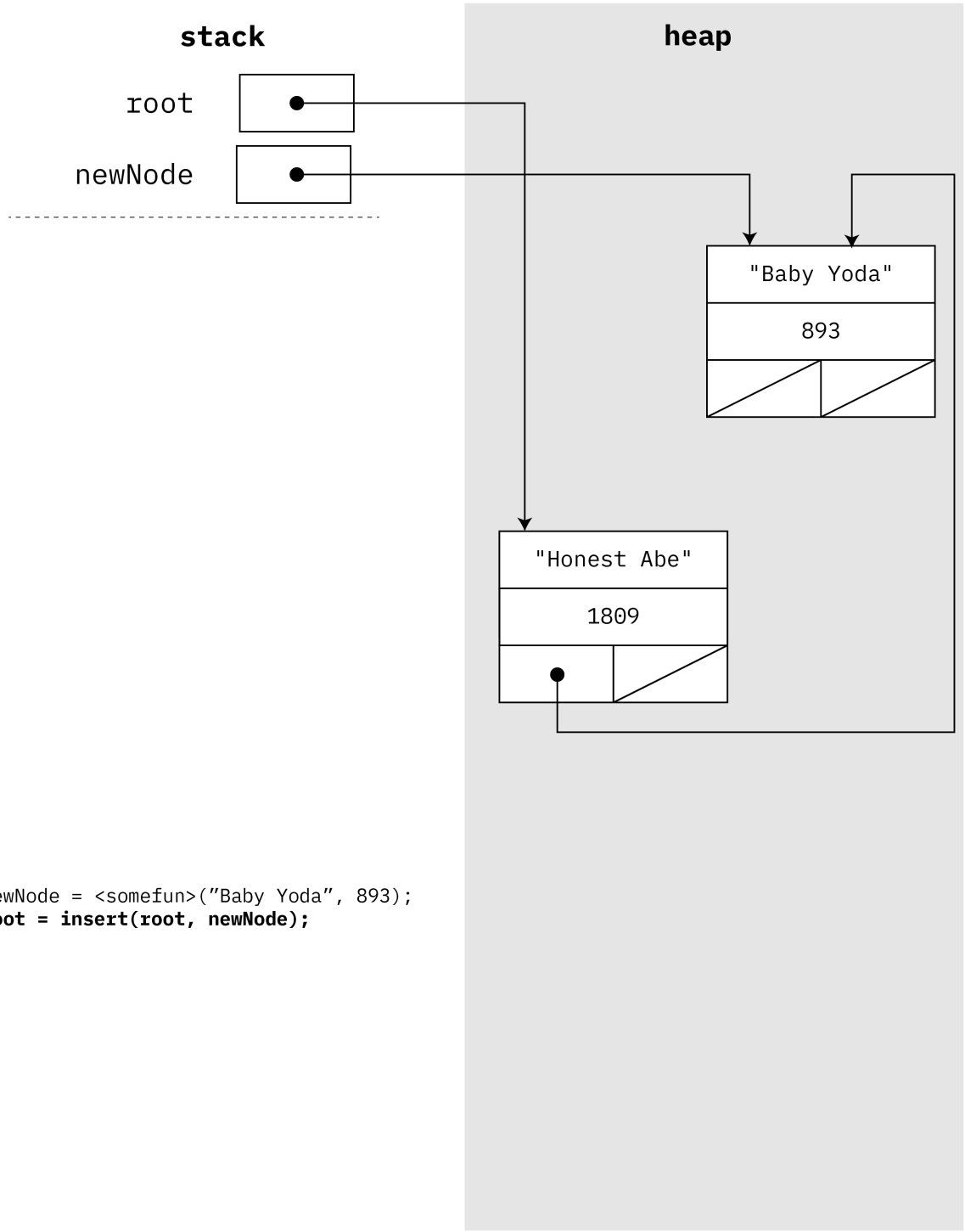

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



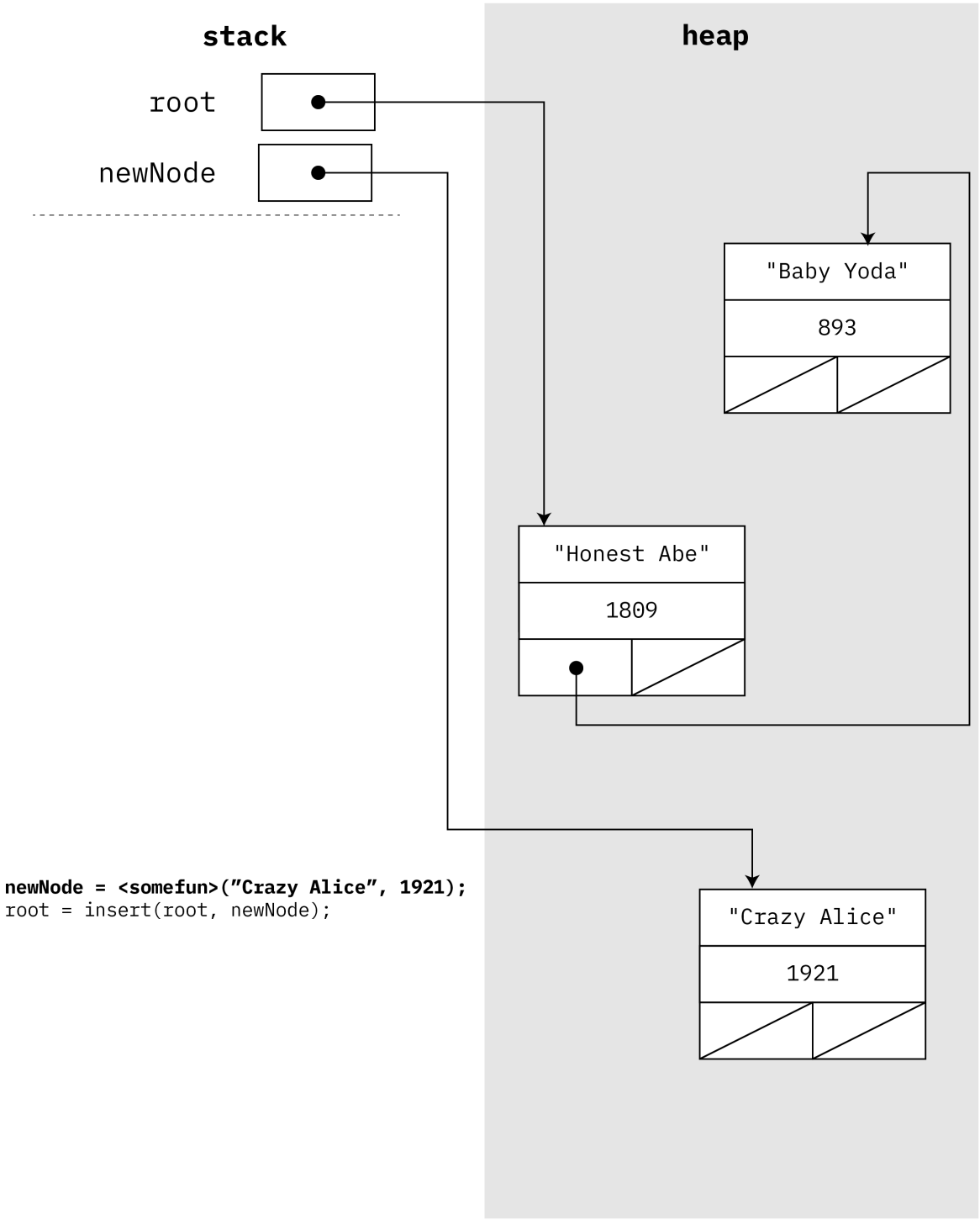

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```

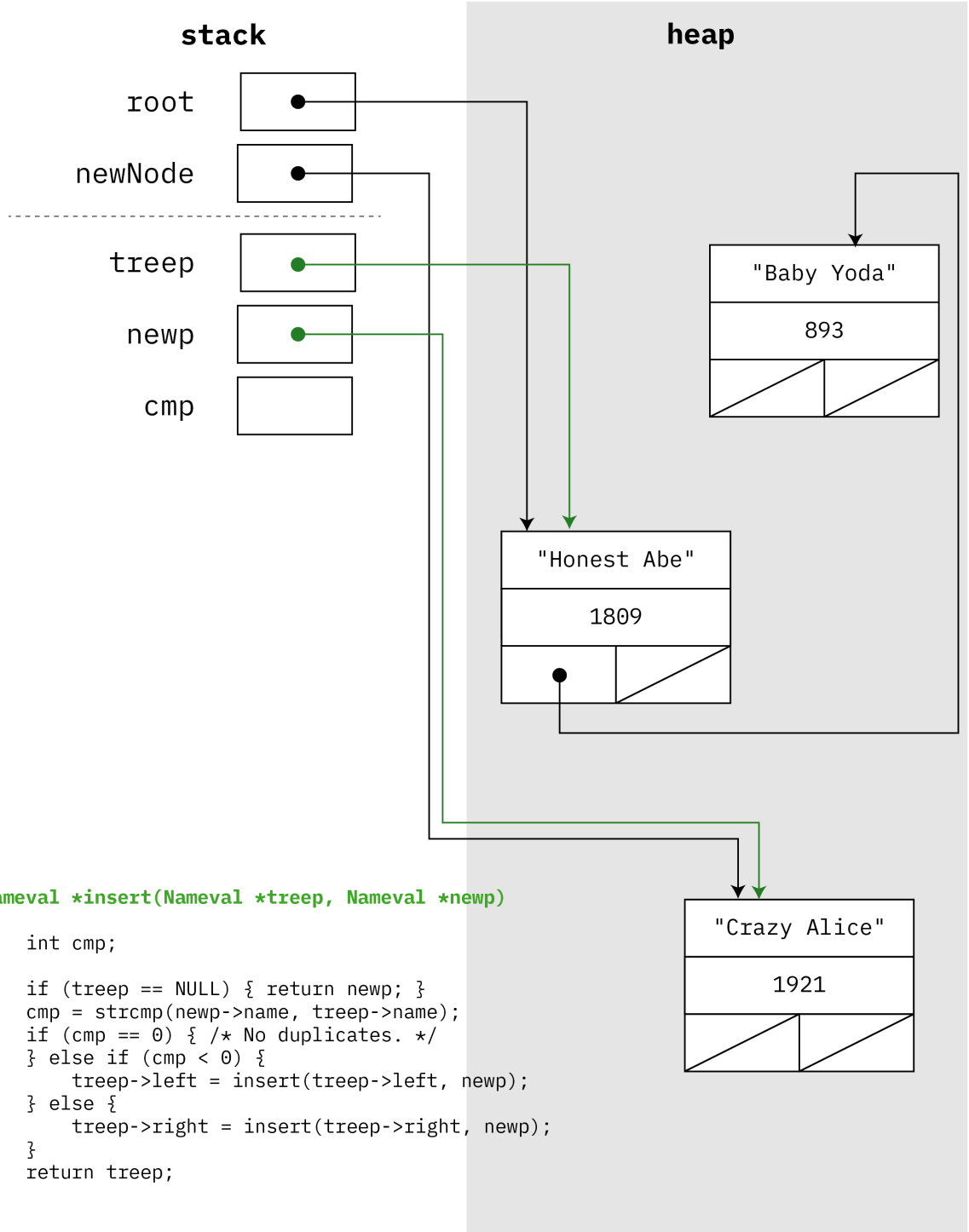



```
newNode = <somefun>(”Baby Yoda”, 893);
root = insert(root, newNode);
```

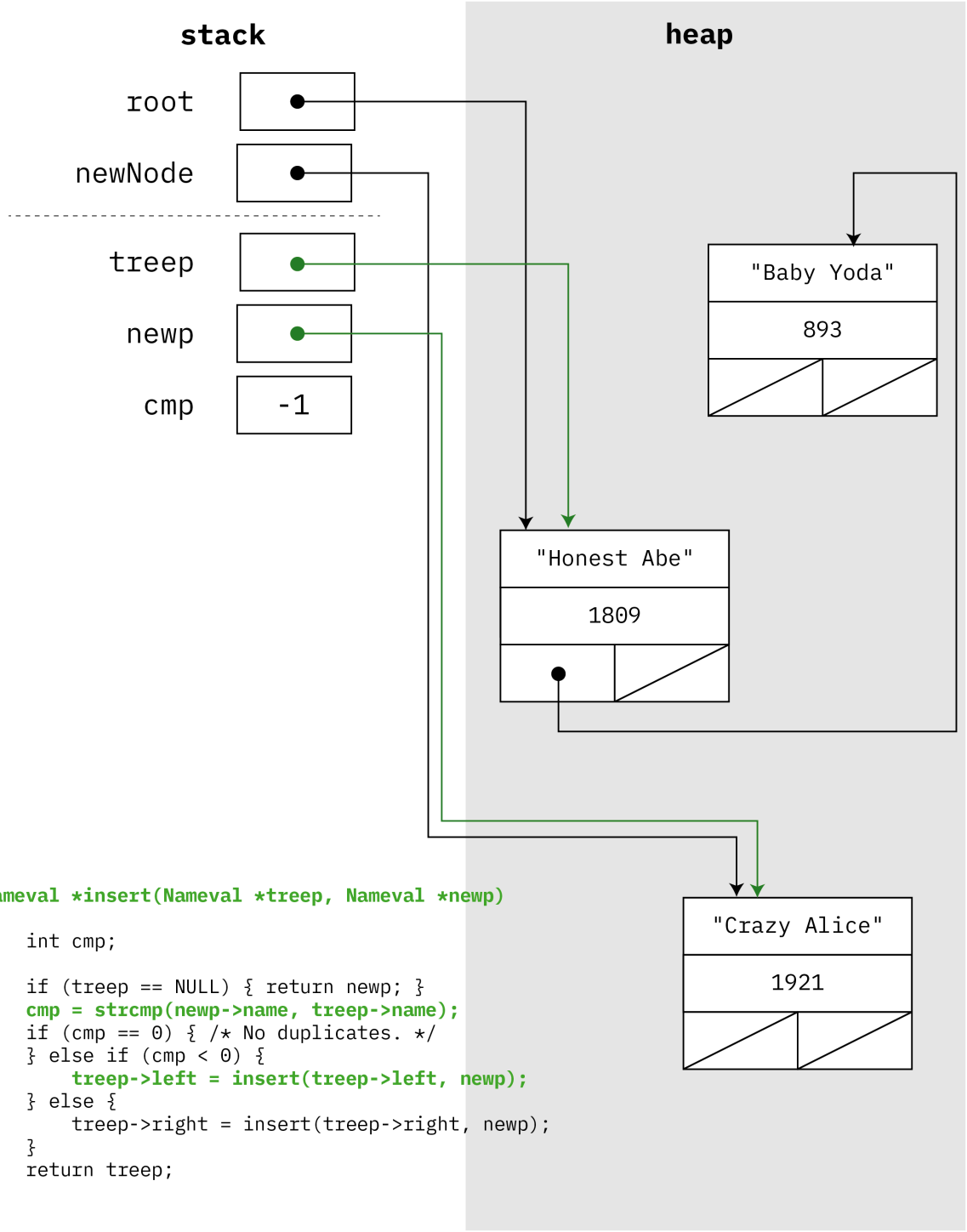



```
newNode = <somefun>(”Baby Yoda”, 893);
root = insert(root, newNode);
```

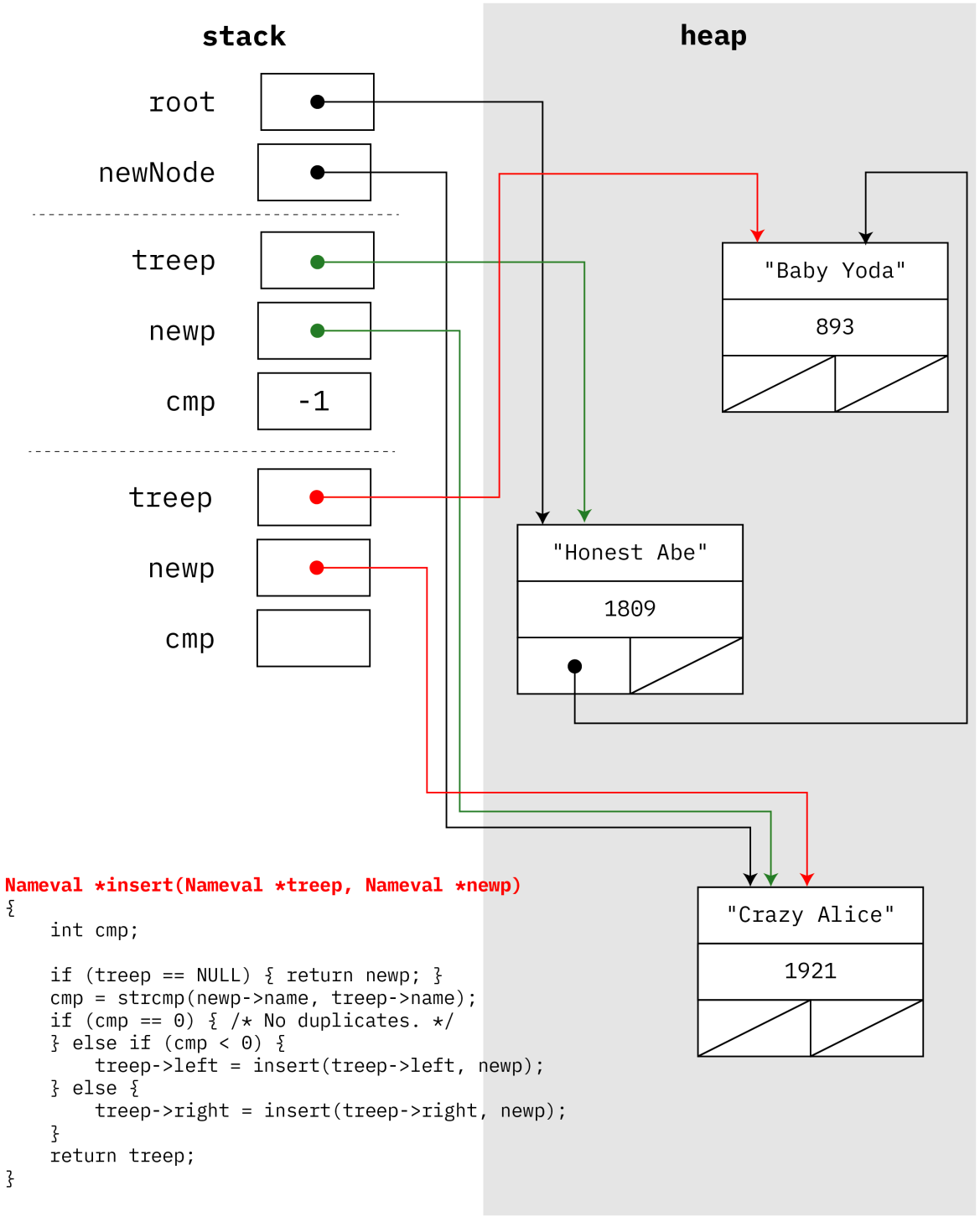

stack
heap
root
newNode
"Baby Yoda"
893
"Honest Abe"
1809
"Crazy Alice"
1921
newNode = <somefun>(”Crazy Alice”, 1921);
root = insert(root, newNode);



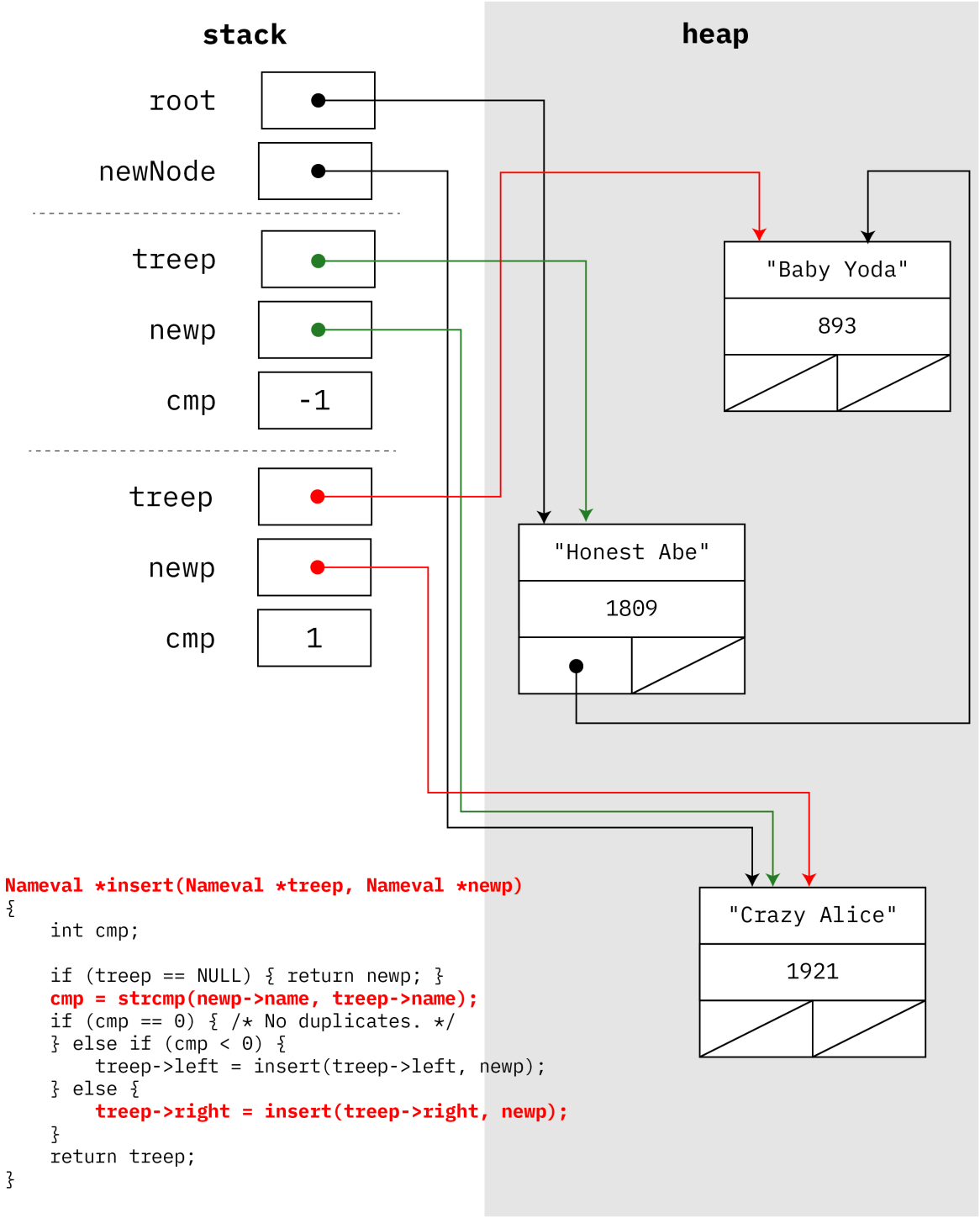

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



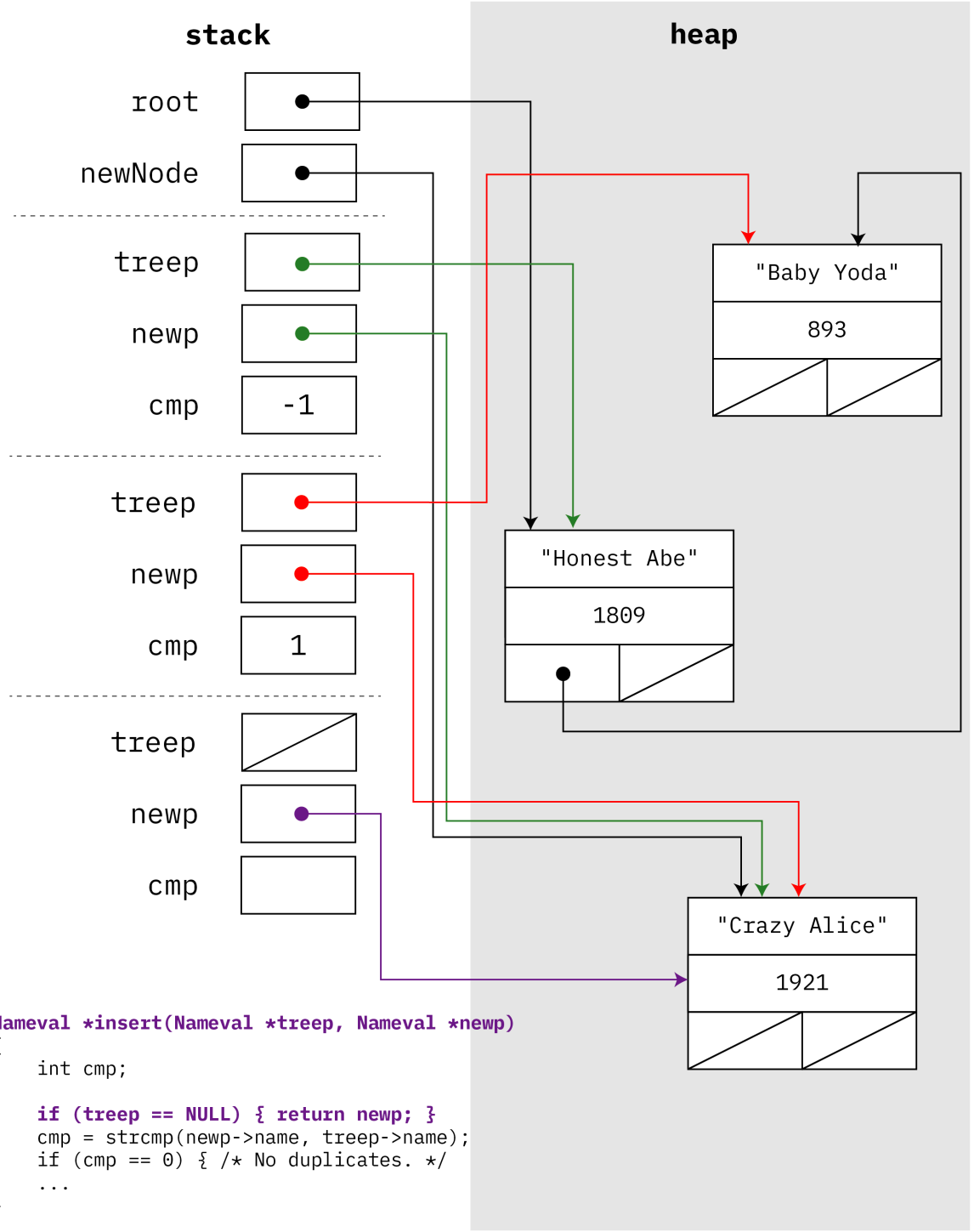

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



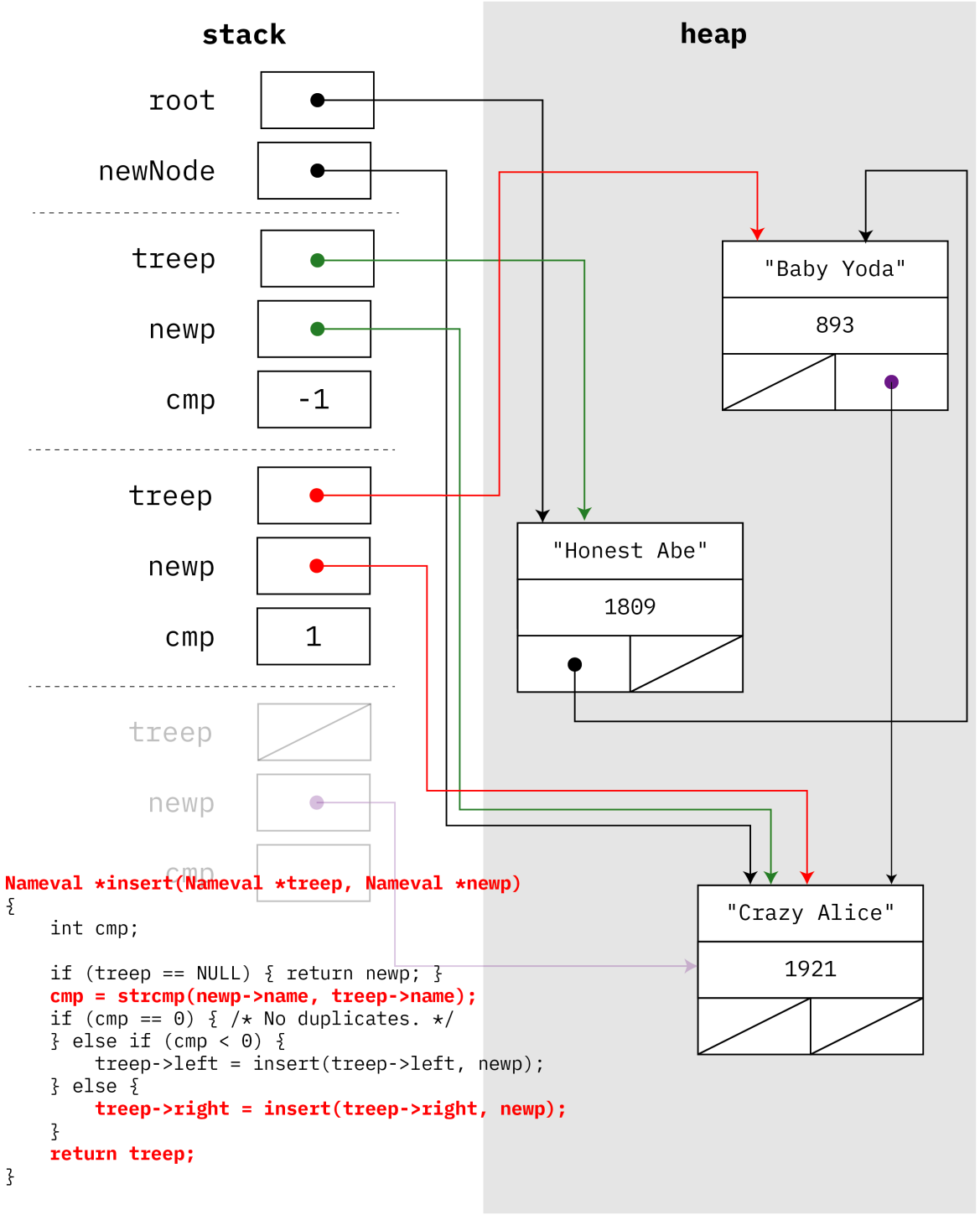

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



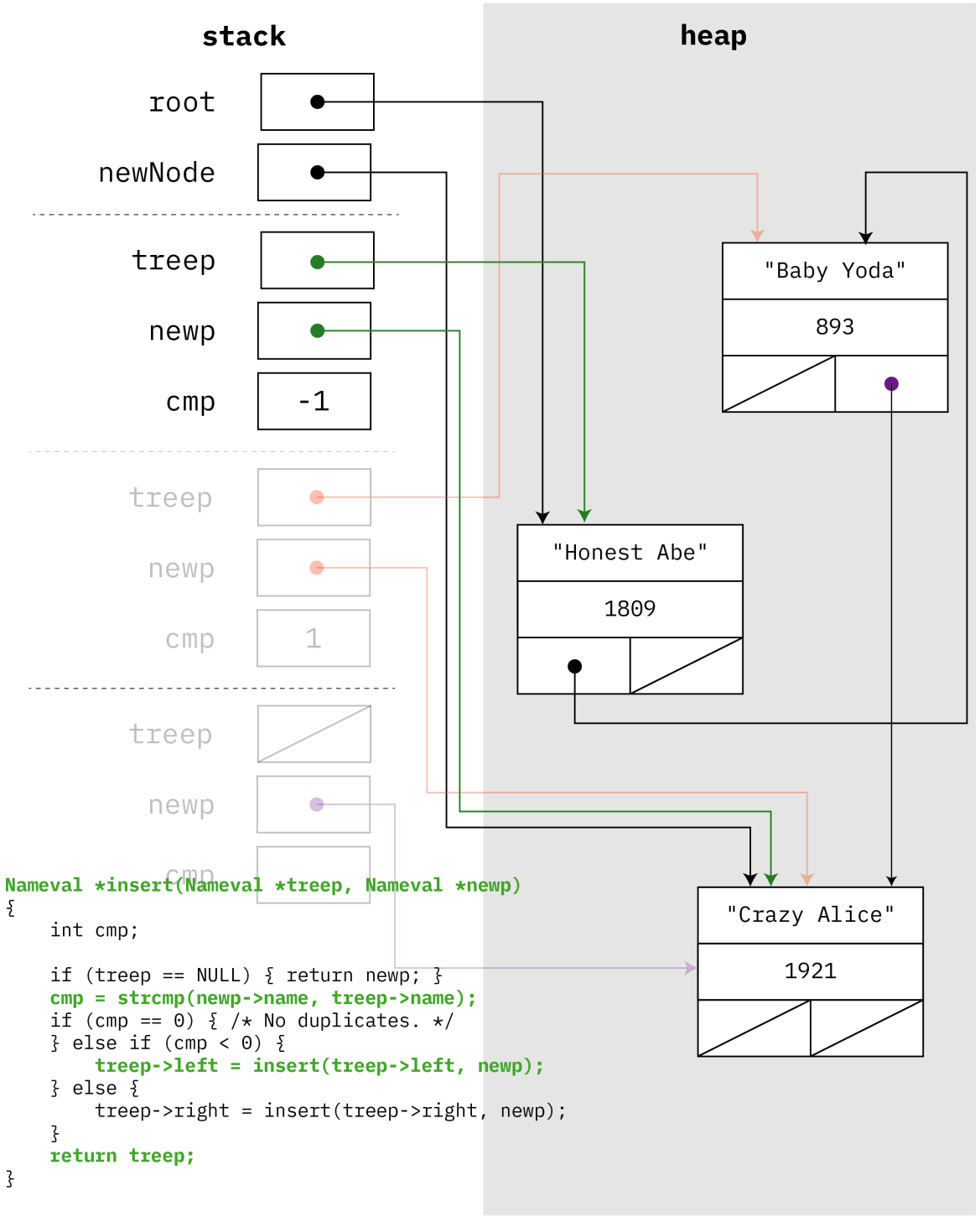

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```



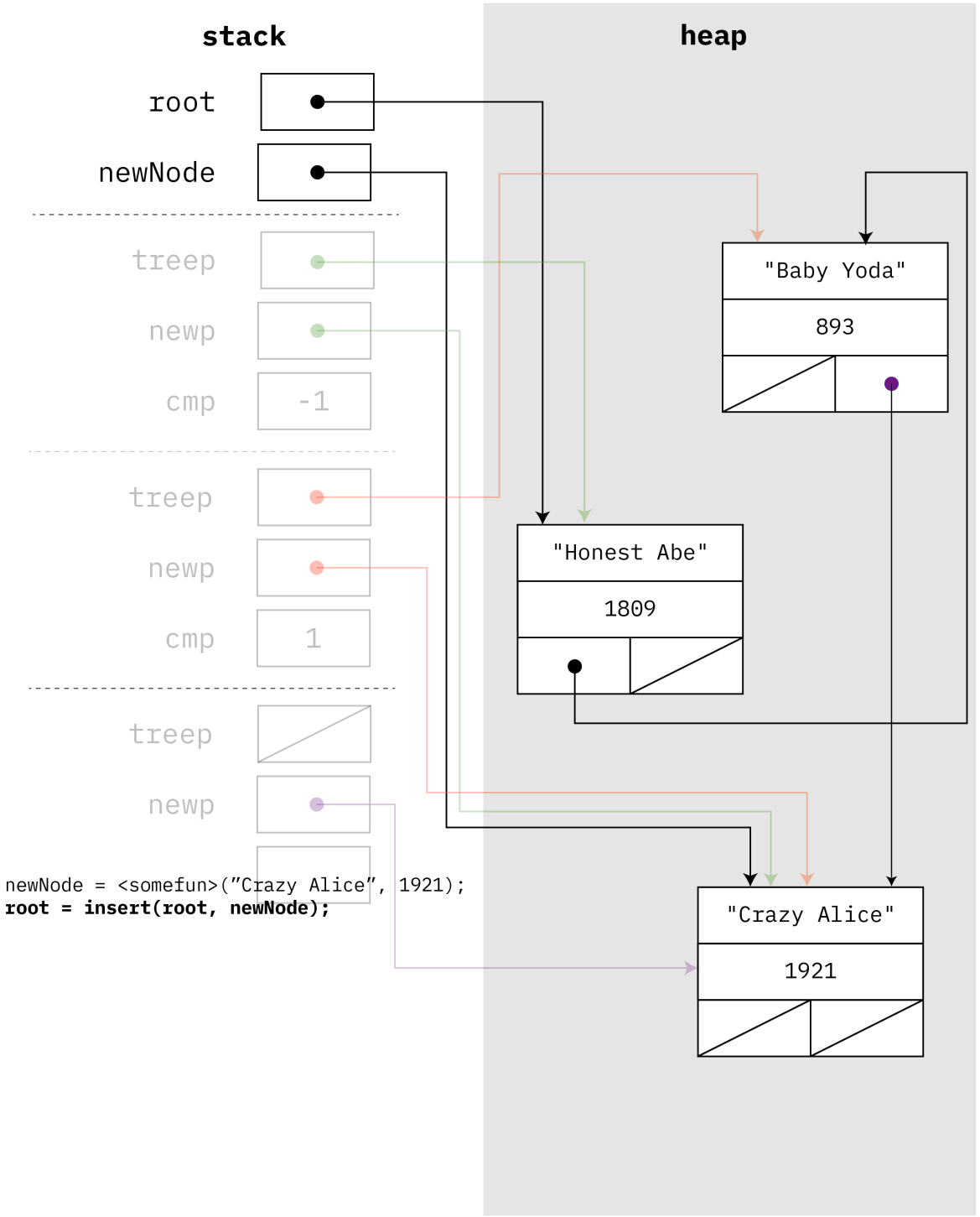

```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    ...
}
```

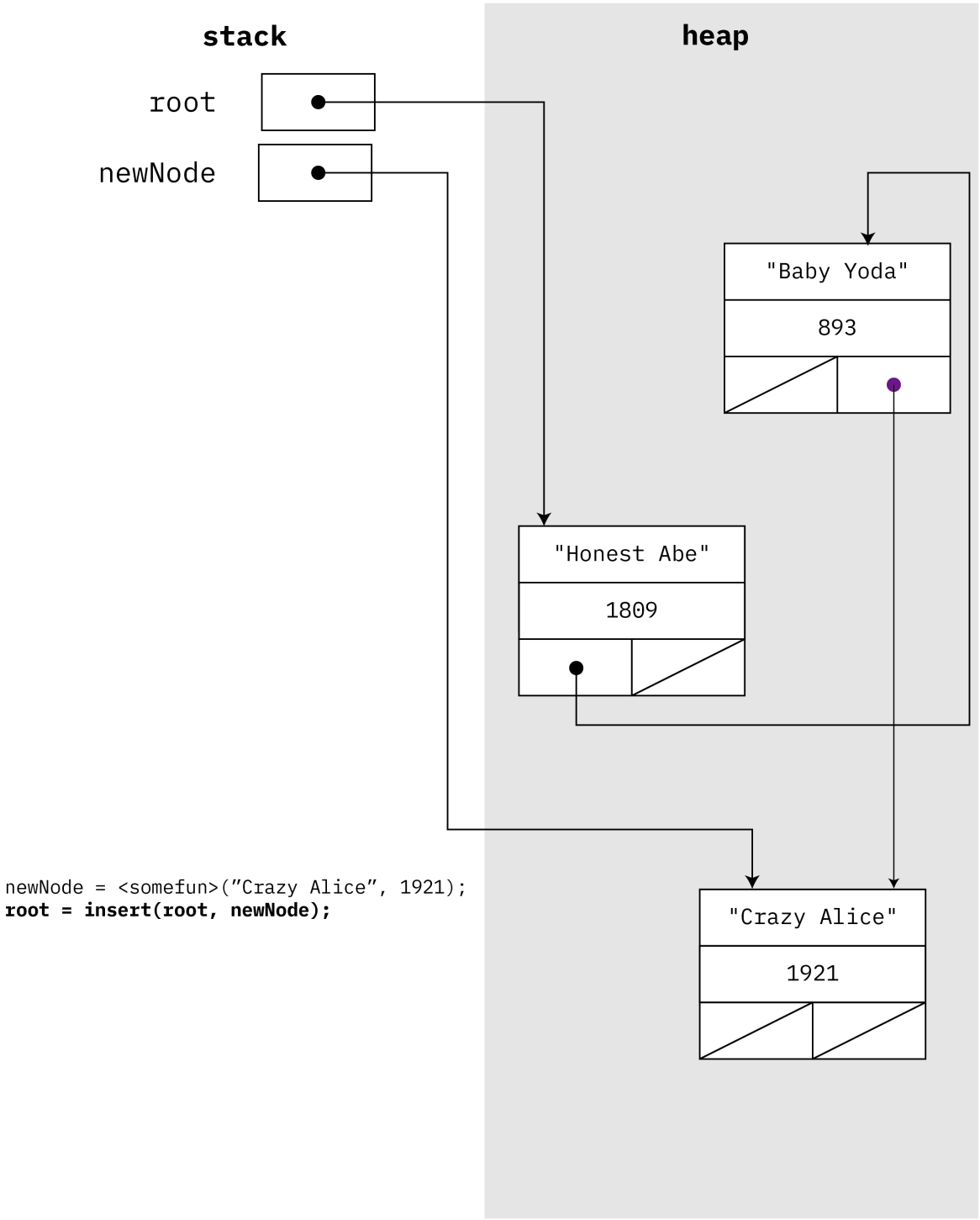



```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```




```
Nameval *insert(Nameval *treep, Nameval *newp)
{
    int cmp;

    if (treep == NULL) { return newp; }
    cmp = strcmp(newp->name, treep->name);
    if (cmp == 0) { /* No duplicates. */
    } else if (cmp < 0) {
        treep->left = insert(treep->left, newp);
    } else {
        treep->right = insert(treep->right, newp);
    }
    return treep;
}
```


stack
heap
root
newNode
treep
newp
cmp
-1
treep
newp
cmp
1
treep
newp
"Baby Yoda"
893
"Honest Abe"
1809
"Crazy Alice"
1921
newNode = <somefun>("Crazy Alice", 1921);
root = insert(root, newNode);


stack
heap
root
newNode
"Baby Yoda"
893
"Honest Abe"
1809
"Crazy Alice"
1921
newNode = <somefun>(”Crazy Alice”, 1921);
root = insert(root, newNode);

Some observations

- The tree routines just shown do not permit duplicate entries.
- **The insertion routine does not try to keep the tree balanced**
  - It is possible that a sequence of inserts could yield a linear list instead of a tree (i.e., inserting a sequence of items that are already sorted).
  - However, this means our routines are a lot simpler (although it is not an oppressive amount of work to implement an AVL tree; rather, it is just a bit complicated!)
- The code for a lookup is similar to that for insertion
  - Recursively search by choosing the left or right subtrees
  - Return the correct node if matching lookup criteria, NULL otherwise.

lookup

```
Nameval *lookup(Nameval *treep, char *name)
{
    int cmp;

    if (treep == NULL) {
        return NULL;
    }
    cmp = strcmp(name, treep->name);
    if (cmp == 0) {
        return treep;
    } else if (cmp < 0) {
        return lookup(treep->left, name);
    } else {
        return lookup(treep->right, name);
    }
}
```

```
Nameval *temp;
temp = lookup(root, "Trudeau");
if (temp) {
    /* found it */
} else {
    /* NULL was returned;
}
```

Must routines be recursive?

- Both insert and lookup were recursive
  - The routines were defined in terms of themselves.
  - Base case: empty tree
  - Inductive step: left tree, and/or right tree
- However, not all routines with recursive definitions need to be recursive
  - **Tail recursion**: When the recursive step (i.e., invocation of the recursive function) is the last step of the function...
  - ... we can transform such tail-recursive functions into iterative ones.
  - All we require is some patching up of arguments (via assignments) and need a way to restart the body of the routine (via some loop)

Non-recursive lookup

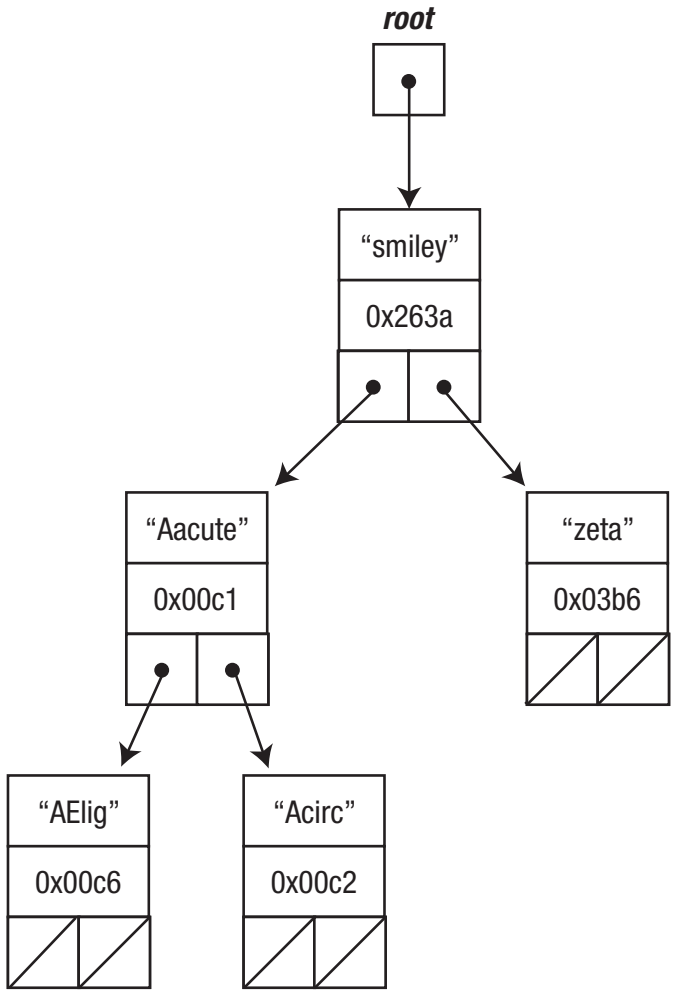
```
Nameval *lookup(Nameval *treep,
    char *name)
{
    int cmp;

    if (treep == NULL) {
        return NULL;
    }
    cmp = strcmp(name, treep->name);
    if (cmp == 0) {
        return treep;
    } else if (cmp < 0) {
        return lookup(treep->left,
            name);
    } else {
        return lookup(treep->right,
            name);
    }
}
```

```
Nameval *nrlookup(Nameval *treep,
    char *name)
{
    int cmp;

    while (treep != NULL) {
        cmp = strcmp(name, treep->name);
        if (cmp == 0) {
            return treep;
        } else if (cmp < 0) {
            treep = treep -> left;
        } else {
            treep = treep->right;
        }
    }
    return NULL;
}
```

An observation about trees

- The same observations we made about operations on lists can also be made with respect to operations on trees
  - Traverse through the tree in some order
  - While doing so, compute some value / perform some comparison / etc.
  - After traversing the tree, return some value
- If we want to rewrite **apply** for a binary search tree, we must decide on some order
  - **inorder** traversal?
  - **pre-order** traversal?
  - **post-order** traversal?
- In effect we will have one **apply** function for each ordering, and each of these functions will take arguments similar to what we had for the list version of **apply**.

Binary search tree example




```
inorder:
    AElig
    Aacute
    Acirc
    smiley
    zeta

post-order:
    AElig
    Acirc
    Aacute
    aeta
    smiley

pre-order:
    ???
```

applyinorder

```
void applyinorder(Nameval *treep,
    void (*fn)(Nameval*, void*), void *arg)
{
    if (treep == NULL) {
        return;
    }
    applyinorder(treep->left, fn, arg);
    (*fn)(treep, arg);
    applyinorder(treep->right, fn arg);
}
```

```
/* We can even use some of the functions we passed as arguments
 * to the "list" version of apply!
 */

applyinorder(treep, printnv, "%s: %x\n");
```

```
/* Could you build a sort based on the tree routines +
 * a function (that you would write) given to applyinorder?
 */
```

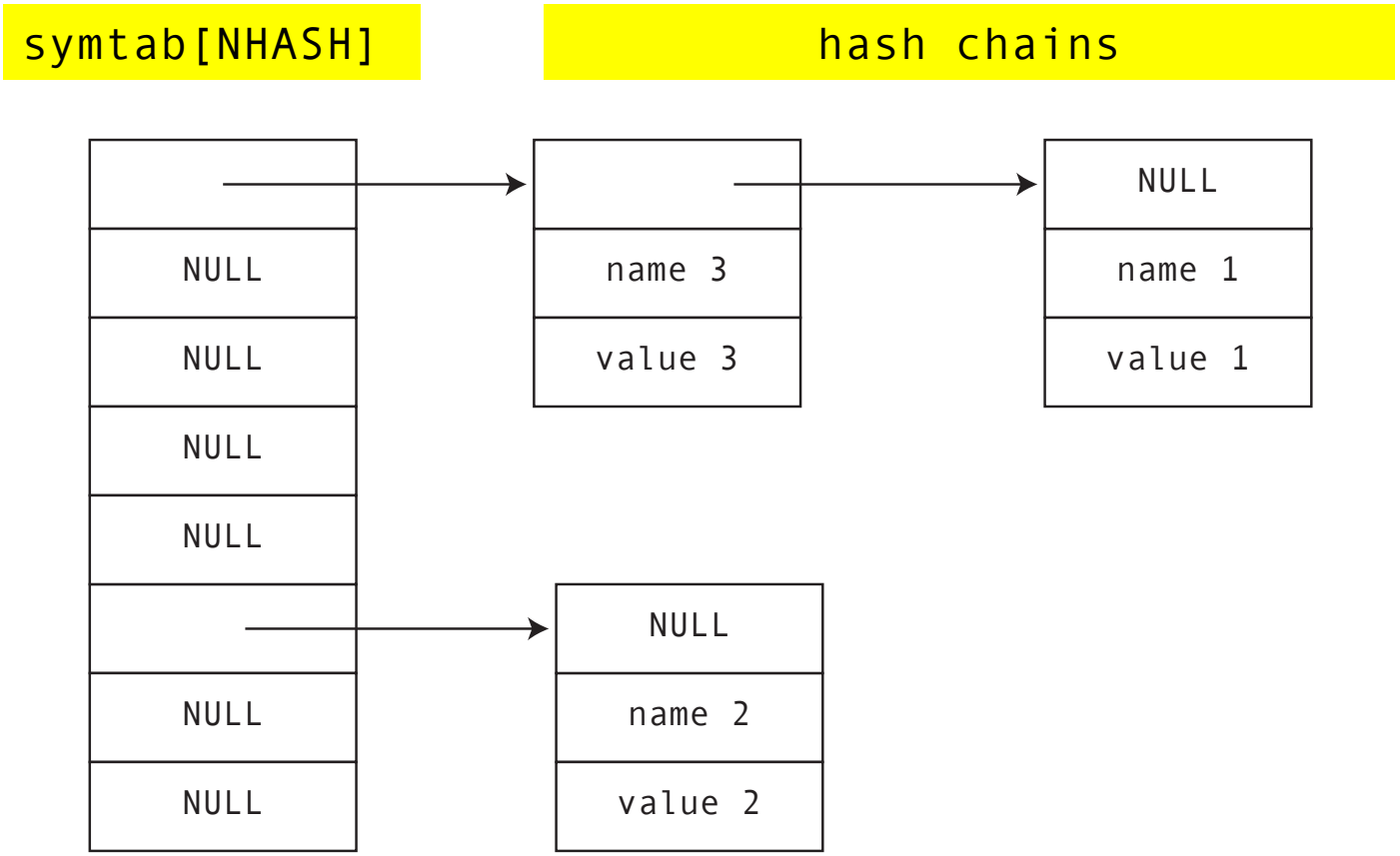
Hash tables

- These combine:
  - **arrays** ...
  - ... and possibly some **linked lists** ....
  - ... along with **some mathematics**
- Result is an efficient structure for storing and retrieving dynamic data
- Typical application for hash tables: **symbol tables**
  - Associates a key string (e.g., a variable name)...
  - with some value that is an attribute of that string (e.g. the variable's type)
  - Symbol tables are used heavily by compilers
- Lots of other places where hash tables are useful

The idea

- Hash tables work on the following principle
  - **First** pass key to the **hash function**
  - The hash function produces a **hash value**
  - These values will be **evenly distributed** through a modest-sized integer range
- The hash value is then used as an array index
  - **Then** use the hash value to index into some structure.
  - In C the usual style is to associate each hash value / array index with a list of items that share the hash
  - Each such list (sometimes called a **hash chain**) is known as a **bucket**
- Collision handling:
  - Separate chaining (we'll use this)
  - Open addressing (linear or quadratic probing; ignore for now)

Example


symtab[NHASH]
hash chains
NULL
NULL
NULL
NULL
NULL
NULL
NULL
name 3
value 3
NULL
name 1
value 1
NULL
name 2
value 2

The practice

- Hash functions are pre-defined by programmer
- Array is sized appropriately (usually at compile time)
- Each element of the array is a list that **chains** together the items that share a hash value (i.e., hash chain)
- Equivalently:
  - A hash table of n items ...
  - ... is an array of lists whose average length is (n/array size)
- Retrieving an item is an O(1) operation provided the following two conditions hold:
  - **we pick a good hash function**
  - **the lists do not grow too long**

Element type

- A hash table is an array of lists...
  - ... therefore we can re-use the element type used for lists
- Maintaining individual hash chains is similar to maintaining individual lists
- Once we have a good hash function, the code falls out easily
  - just pick the hash bucket...
  - ... and walk along the list looking for a perfect match

```
typedef struct Nameval Nameval;
struct Nameval {
    char    *name;
    int      value;
    Nameval *next; /* in chain */
};

/* symbol table */
Nameval *symtab[NHASH];
```

Lookup / insertion routine

- If item is found:
  - It is returned
- If item is not found and create flag is set:
  - add item to the table.

```
Nameval *lookup (char *name, int create, int value)
{
    int h
    Nameval *sym;

    h = hash(name);
    for (sym = symtab[h]; sym != NULL; sym = sym->next) {
        if (strcmp(name, sym->name) == 0) { return sym; }
    if (create) {
        sym = (Nameval *) emalloc(sizeof(Nameval));
        sym->name = name; /* assumed allocated elsewhere */
        sym->value = value;
        sym->next = symtab[h];
        symtab[h] = sym;
    }
    return sym;
}
```

Why combine lookup & insertion?

- This is a common combination
- Without it we often duplicate effort
- (Without it the hash function to be executed twice for the same item.)
- This is a stylistic point (but one which can save a bit of tedium and reduce possibility of buggy code)

```
/*
 * The code that might result if we
 * keep lookup and insertion separate.
 */

if (lookup("name") == NULL) {
    additem(newitem("name", value));
}
```

Two more questions

- How big should the array be?
  - In general: make it large enough that each hash chain will have at most a few elements
  - Example: A compiler might have an array size of a few thousand
- How is the hash function computed?
  - Must be deterministic (i.e., produce same value each time for same key)
  - Must be fast
  - Must distribute data uniformly through the array
  - Lots of research exists that investigates these properties of hash functions

Possible hash function

- Common hashing algorithm for strings:
  - Build a value by adding each byte of the string to a multiple of the hash so far
  - Multiplication spreads bits from the new byte through the value so far
- Empirically: the values 31 and 37 have proven to be good choices for ASCII strings

```
#define MULTIPLIER 31

/* hash: compute hash value of string */
unsigned int hash (char *str) {
    unsigned int h;
    unsigned char *p;

    h = 0;
    for (p = (unsigned char *) str; *p != '\0'; p++) {
        h = MULTIPLIER * h + *p;
    }
    return h % NHASH;
}
```

Summary

- malloc() is an important tool
  - but it can be tricky at first to use correctly
  - is usually paired with free()
- dynamically-allocated memory needed for implementing many kinds of data structures
- four big takeaways
  - arrays can be resized (and that's handy as arrays are easy to use)
  - lists are used in many data structures (so it is important to know how to write routines that add to, traverse through, and remove from lists)
  - binary search trees can be constructed in a way familiar to us from theory
  - hash tables (i.e. maps) can make use of either arrays + linked lists or of dynamically-sized arrays

Colophon

- Some code examples are from "The Practice of Programming" (Addison-Wesley) © 1999 Brian W. Kernighan and Rob Pike