The Code Expander Generator

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1. Introduction

A **code expander** (**ce** for short) is a part of the Amsterdam Compiler Kit[1] (**ACK**) and provides the user with high-speed generation of medium-quality code. Although conceptually equivalent to the more usual **code generator**, it differs in some aspects.

Normally, a program to be compiled with **ACK** is first fed to the preprocessor. The output of the preprocessor goes into the appropriate front end, which produces EM[2] (a machine independent low level intermediate code). The generated EM code is fed into the peephole optimizer, which scans it with a window of a few instructions, replacing certain inefficient code sequences by better ones. After the peephole optimizer a back end follows, which produces high-quality assembly code. The assembly code goes via the target optimizer into the assembler and the object code then goes into the linker/loader, the final component in the pipeline.

For various applications this scheme is too slow. When debugging, for example, compile time is more important than execution time of a program. For this purpose a new scheme is introduced:

1: The code generator and assembler are replaced by a library, the **code expander**, consisting of a set of routines, one for every EM-instruction. Each routine expands its EM-instruction into relocatable object code. In contrast, the usual ACK code generator uses expensive pattern matching on sequences of EM-instructions. The peephole and target optimizer are not used.

2: These routines replace the usual EM-generating routines in the front end; this eliminates the overhead of intermediate files.

This results in a fast compiler producing object file, ready to be linked and loaded, at the cost of unoptimized object code.

Because of the simple nature of the code expander, it is much easier to build, to debug, and to test. Experience has demonstrated that a code expander can be constructed, debugged, and tested in less than two weeks.

This document describes the tools for automatically generating a **ce** (a library of C files) from two tables and a few machine-dependent functions. A thorough knowledge of EM is necessary to understand this document.

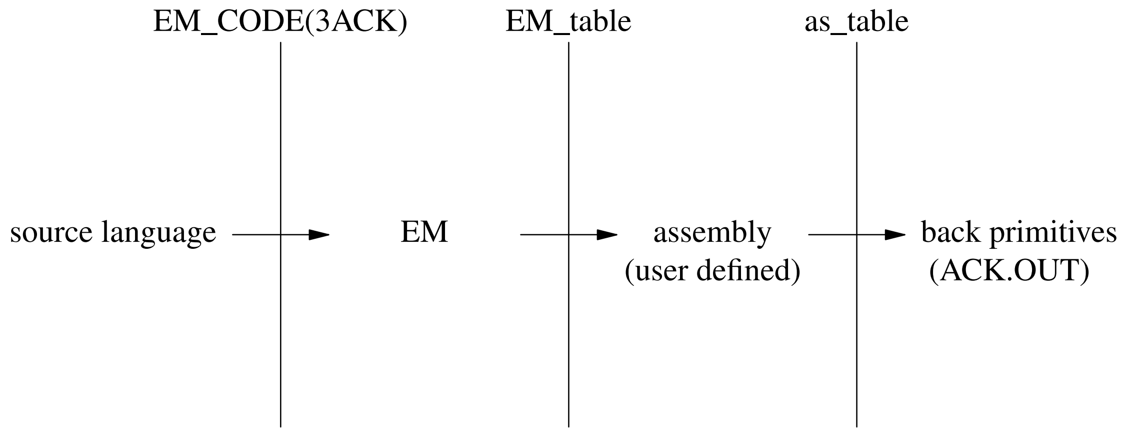
2. The code expander generator

The code expander generator (**ceg**) generates a code expander from two tables and a few machine-dependent functions. This section explains how **ceg** works. The first half describes the transformations that are done on the two tables. The second half tells how these transformations are done by the **ceg**.

A code expander consists of a set of routines that convert EM-instructions directly to relocatable object code. These routines are called by a front end through the EM_CODE(3ACK)[3] interface. To free the table writer of the burden of building an object file, we supply a set of routines that build an object file in the ACK.OUT(5ACK)[4] format (see appendix B). This set of routines is called the **back**-primitives (see appendix A). In short, a code expander consists of a set of routines that map the EM_CODE interface on the **back**-primitives interface.

To avoid repetition of the same sequences of **back**-primitives in different EM-instructions and to improve readability, the EM-to-object information must be supplied in two tables. The EM_table maps EM to an assembly language, and the as_table maps assembly code to **back**-primitives. The assembly language is chosen by the table writer. It can either be an actual assembly language or his ad-hoc designed language.

The following picture shows the dependencies between the different components:



The picture suggests that, during compilation, the EM instructions are first transformed into assembly instructions and then the assembly instructions are transformed into object-generating calls. This is not what happens in practice, although the user is free to think it does. Actually, however the EM_table and the as_table are combined during code expander generation time, yielding an imaginary compound table that results in routines from the EM_CODE interface that generate object code directly.

As already indicated, the compound table does not exist either. Instead, each assembly instruction in the as_table is converted to a routine generating C[5] code to generate C code to call the **back**-primitives. The EM_table is converted into a program that for each EM instruction generates a routine, using the routines generated from the as_table. Execution of the latter program will then generate the code expander.

This scheme allows great flexibility in the table writing, while still resulting in a very efficient code expander. One implication is that the as_table is interpreted twice and the EM_table only once. This has consequences for their structure.

To illustrate what happens, we give an example. The example is an entry in the tables for the VAX-machine. The assembly language chosen is a subset of the VAX assembly language.

One of the most fundamental operations in EM is “loc c”, load the value of c on the stack. To expand this instruction the tables contain the following information:

EM_table :

```
   C_loc    ==>    "pushl $$$1".
     /* $1 refers to the first argument of C_loc.
      * $$ is a quoted $. */
```

as_table :

```
   pushl  src : CONST    ==>
                          @text1( 0xd0);
                          @text1( 0xef);
                          @text4( %$( src->num)).
```

The as_table is transformed in the following routine:

```
pushl_instr(src)
t_operand *src;
/* ''t_operand'' is a struct defined by the
 * table writer. */
{
   printf("swtxt();");
   printf("text1( 0xd0 );");
   printf("text1( 0xef );");
   printf("text4(%s);", substitute_dollar( src->num));
}
```

Using “pushl_instr()”, the following routine is generated from the EM_table:

```
C_loc( c)
arith c;
/* text1() and text4() are library routines that fill the
 * text segment. */
{
    swtxt();
    text1( 0xd0);
    text1( 0xef);
    text4( c);
}
```

A compiler call to “C_loc()” will cause the 1-byte numbers “0xd0” and “0xef” and the 4-byte value of the variable “c” to be stored in the text segment.

The transformations on the tables are done automatically by the code expander generator. The code expander generator is made up of two tools: **emg** and **asg**. **Asg** transforms each assembly instruction into a C routine. These C routines generate calls to the **back**-primitives. The generated C routines are used by **emg** to generate the actual code expander from the EM_table.

The link between **emg** and **asg** is an assembly language. We did not enforce a specific syntax for the assembly language; instead we have given the table writer the freedom to make an ad-hoc assembly language or to use an actual assembly language suitable for his purpose. Apart from a greater flexibility this has another advantage; if the table writer adopts the assembly language that runs on the machine at hand, he can test the EM_table independently from the as_table. Of course there is a price to pay: the table writer has to do the decoding of the operands himself. See section 4 for more details.

Before we describe the structure of the tables in detail, we will give an overview of the four main phases.

phase 1:
: The as_table is transformed by **asg**. This results in a set of C routines. Each assembly-opcode generates one C routine. Note that a call to such a routine does not generate the corresponding object code; it generates C code, which, when executed, generates the desired object code.

phase 2:
: The C routines generated by **asg** are used by emg to expand the EM_table. This results in a set of C routines, the code expander, which conform to the procedural interface EM_CODE(3ACK). A call to such a routine does indeed generate the desired object code.

phase 3:
: The front end that uses the procedural interface is linked/loaded with the code expander generated in phase 2 and the **back**-primitives (a supplied library). This results in a compiler.

phase 4:
: The compiler runs. The routines in the code expander are executed and produce object code.

3. Description of the EM_table

This section describes the EM_table. It contains four subsections. The first 3 sections describe the syntax of the EM_table, the semantics of the EM_table, and the functions and constants that must be present in the EM_table, in the file ‘‘mach.c’’ or in the file ‘‘mach.h’’. The last section explains how a table writer can generate assembly code instead of object code. The section on semantics contains many examples.

3.1. Grammar

The following grammar describes the syntax of the EM_table.

```
TABLE      ::=   ( RULE)*
RULE       ::=   C_instr   ( COND_SEQUENCE | SIMPLE)
```

```
COND_SEQUENCE    ::=   ( condition  SIMPLE)*  “default”  SIMPLE
SIMPLE           ::=   “==>” ACTION_LIST
ACTION_LIST      ::=   [ ACTION  ( “;” ACTION)* ]  “.”
ACTION           ::=   AS_INSTR
                  |    function-call
AS_INSTR         ::=   “"” [ label “:”]  [ INSTR] “"”
INSTR            ::=   mnemonic  [ operand  ( “,”  operand)* ]
```

The “(” “)” brackets are used for grouping, “[” ... “]” means ... 0 or 1 time, a “*” means zero or more times, and a “|” means a choice between left or right. A **C_instr** is a name in the EM_CODE(3ACK) interface. **condition** is a C expression. **function-call** is a call of a C function. **label**, **mnemonic**, and **operand** are arbitrary strings. If an **operand** contains brackets, the brackets must match. There is an upper bound on the number of operands; the maximum number is defined by the constant MAX_OPERANDS in de file “const.h” in the directory assemble.c. Comments in the table should be placed between “/*” and “*/”. The table is processed by the C preprocessor, before being parsed by **emg**.

3.2. Semantics

The EM_table is processed by **emg**. **Emg** generates a C function for every instruction in the EM_CODE(3ACK). For every EM-instruction not mentioned in the EM_table, a C function that prints an error message is generated. It is possible to divide the EM_CODE(3ACK)-interface into four parts :

1: text instructions (e.g., C_loc, C_adi, ..)

2: pseudo instructions (e.g., C_open, C_df_ilb, ..)

3: storage instructions (e.g., C_rom_icon, ..)

4: message instructions (e.g., C_mes_begin, ..)

This section starts with giving the semantics of the grammar. The examples are text instructions. The section ends with remarks on the pseudo instructions and the storage instructions. Since message instructions are not useful for a code expander, they are ignored.

3.2.1. Actions

The EM_table is made up of rules describing how to expand a **C_instr** defined by the EM_CODE(3ACK)-interface (corresponding to an EM instruction) into actions. There are two kinds of actions: assembly instructions and C function calls. An assembly instruction is defined as a mnemonic followed by zero or more operands separated by commas. The semantics of an assembly instruction is defined by the table writer. When the assembly language is not expressive enough, then, as an escape route, function calls can be made. However, this reduces the speed of the actual code expander. Finally, actions can be grouped into a list of actions; actions are separated by a semicolon and terminated by a “.”.

```
C_nop    ==> .
       /* Empty action list : no operation. */

C_inc    ==> "incl (sp)".
       /* Assembler instruction, which is evaluated
        * during expansion of the EM_table */

C_slu    ==> C_sli( $1).
       /* Function call, which is evaluated during
        *  execution of the compiler. */
```

3.2.2. Labels

Since an assembly language without instruction labels is a rather weak language, labels inside a contiguous block of assembly instructions are allowed. When using labels two rules must be observed:

1: The name of a label should be unique inside an action list.

2: The labels used in an assembler instruction should be defined in the same action list.

The following example illustrates the usage of labels.

```
   /* Compare the two top elements on the stack. */
C_cmp      ==>      "pop bx";
                    "pop cx";
                    "xor ax, ax";
                    "cmp cx, bx";
                 /* Forward jump to local label */
                    "je 2f";
                    "jb 1f";
                    "inc ax";
                    "jmp 2f";
                    "1: dec ax";
                    "2: push ax".
```

We will come back to labels in the section on the as_table.

3.2.3. Arguments of an EM instruction

In most cases the translation of a **C_instr** depends on its arguments. The arguments of a **C_instr** are numbered from 1 to *n*, where *n* is the total number of arguments of the current **C_instr** (there are a few exceptions, see Implicit arguments). The table writer may refer to an argument as $*i*. If a plain $-sign is needed in an assembly instruction, it must be preceded by a extra $-sign.

There are two groups of **C_instr**s whose arguments are handled specially:

1: Instructions dealing with local offsets

The value of the $*i* argument referring to a parameter ($*i* >= 0) is increased by “EM_BSIZE”. “EM_BSIZE” is the size of the return status block and must be defined in the file "mach.h" (see section 3.3). For example :

```
C_lol    ==>     "push $1(bp)".
               /* automatic conversion of $1 */
```

2: Instructions using global names or instruction labels
All the arguments referring to global names or instruction labels will be transformed into a unique assembly name. To prevent name clashes with library names the table writer has to provide the conversions in the file "mach.h". For example :

```
C_bra    ==>     "jmp $1".
                /* automatic conversion of $1 */
                /* type arith is converted to string */
```

3.2.4. Conditionals

The rules in the EM_table can be divided into two groups: simple rules and conditional rules. The simple rules are made up of a **C_instr** followed by a list of actions, as described above. The conditional rules (COND_SEQUENCE) allow the table writer to select an action list depending on the value of a condition.

A CONDITIONAL is a list of a boolean expression with the corresponding simple rule. If the expression evaluates to true then the corresponding simple rule is carried out. If more than one condition evaluates to true, the first one is chosen. The last case of a COND_SEQUENCE of a **C_instr** must handle the default case. The boolean expressions in a COND_SEQUENCE must be C expressions. Besides the ordinary C operators and constants, $*i*$ references can be used in an expression.

```
    /* Load address of LB $1 levels back. */
C_lxl
    $1 == 0     ==>    "pushl fp".
    $1 == 1     ==>    "pushl 4(ap)".
    default     ==>    "movl $$$1, r0";
                       "jsb .lxl";
                       "pushl r0".
```

3.2.5. Abbreviations

EM instructions with an external as an argument come in three variants in the EM_CODE(3ACK) interface. In most cases it will be possible to take these variants together. For this purpose the ".." notation is introduced. For the code expander there is no difference between the following instructions.

```
C_loe_dlb    ==>    "pushl $1 + $2".
C_loe_dnam   ==>    "pushl $1 + $2".
C_loe        ==>    "pushl $1 + $2".
```

So it can be written in the following way.

```
C_loe..      ==>    "pushl $1 + $2".
```

3.2.6. Implicit arguments

In the last example ‘‘C_loe’’ has two arguments, but in the EM_CODE interface it has one argument. This argument depends on the current ‘‘hol’’ block; in the EM_table this is made explicit. Every **C_instr** whose argument depends on a ‘‘hol’’ block has one extra argument; argument 1 refers to the ‘‘hol’’ block.

3.2.7. Pseudo instructions

Most pseudo instructions are machine independent and are provided by **ceg**. The table writer has only to supply the following functions, which are used to build a stack-frame:

```
C_prolog()
/* Performs the prolog, for example save
 * return address */

C_locals( n)
arith n;
/* Allocate n bytes for locals on the stack */

C_jump( label)
char *label;
/* Generates code for a jump to ''label'' */
```

These functions can be defined in ‘‘mach.c’’ or in the EM_table (see section 3.3).

3.2.8. Storage instructions

The storage instructions ‘‘C_bss_*cstp()*’’, ‘‘C_hol_*cstp()*’’, dealing with constants of type string (C_..._icon, C_..._ucon, C_..._fcon), are generated automatically. No information is needed in the table. To generate the C_..._icon, C_..._ucon, C_..._fcon instructions **ceg** only has to know how to convert a number of type string to bytes; this can be defined with the constants ONE_BYTE, TWO_BYTES, and FOUR_BYTES. C_rom_icon, C_con_icon, C_bss_icon, C_hol_icon can be abbreviated by ..icon. This also holds for ..ucon and ..fcon. For example :

```
\.\.icon
    $2 == 1   ==>  gen1( (ONE_BYTE) atoi( $1)).
    $2 == 2   ==>  gen2( (TWO_BYTES) atoi( $1)).
    $2 == 4   ==>  gen4( (FOUR_BYTES) atol( $1)).
    default   ==>   arg_error( "..icon", $2).
```

Gen1(), gen2() and gen4() are **back**-primitives (see appendix A), and generate one, two, or four byte constants. Atoi() is a C library function that converts strings to integers. The constants ‘‘ONE_BYTE’’, ‘‘TWO_BYTES’’, and ‘‘FOUR_BYTES’’ must be defined in the file ‘‘mach.h’’.

3.3. User supplied definitions and functions

If the table writer uses all the default functions he has only to supply the following constants and functions :

C_prolog()	:	Do prolog
C_jump(l)	:	Perform a jump to label l
C_locals(n)	:	Allocate n bytes on the stack
NAME_FMT	:	Print format describing name to a unique name conversion. The format must contain %s.
DNAM_FMT	:	Print format describing data-label to a unique name conversion. The format must contain %s.
DLB_FMT	:	Print format describing numerical-data-label to a unique name conversion. The format must contain a %ld.
ILB_FMT	:	Print format describing instruction-label to a unique name conversion. The format must contain %d followed by %ld.
HOL_FMT	:	Print format describing hol-block-number to a unique name conversion. The format must contain %d.
EM_WSIZE	:	Size of a word in bytes on the target machine
EM_PSIZE	:	Size of a pointer in bytes on the target machine
EM_BSIZE	:	Size of base block in bytes on the target machine
ONE_BYTE	:	\C suitable type that can hold one byte on the machine where the **ce** runs
TWO_BYTES	:	\C suitable type that can hold two bytes on the machine where the **ce** runs
FOUR_BYTES	:	\C suitable type that can hold four bytes on the machine where the **ce** runs
BSS_INIT	:	The default value that the loader puts in the bss segment
BYTES_REVERSED	:	Must be defined if the byte order must be reversed. By default the least significant byte is outputted first.†
WORDS_REVERSED	:	Must be defined if the word order must be reversed. By default the least significant word is outputted first.

An example of the file ‘‘mach.h’’ for the vax4.

```
#define    ONE_BYTE      int
#define    TWO_BYTES     int
#define    FOUR_BYTES    long
```

† When both byte orders are used, for example NS 16032, the table writer has to supply his own set of routines.

```
#define     EM_WSIZE      4
#define     EM_PSIZE      4
#define     EM_BSIZE      0

#define     BSS_INIT      0

#define     NAME_FMT      "_%s"
#define     DNAM_FMT      "_%s"
#define     DLB_FMT       "_%ld"
#define     ILB_FMT       "I%03d%ld"
#define     HOL_FMT       "hol%d"
```

Notice that EM_BSIZE is zero. The vax “call” instruction takes automatically care of the base block.

There are three primitives that have to be defined by the table writer, either as functions in the file “mach.c” or as rules in the EM_table. For example, for the 8086 they look like this:

```
C_jump          ==>        "jmp $1".

C_prolog        ==>        "push bp";
                         "mov bp, sp".

C_locals
  $1   == 0     ==>      .
  $1   == 2     ==>      "push ax".
  $1   == 4     ==>      "push ax";
                         "push ax".
  default       ==>      "sub sp, $1".
```

3.4. Generating assembly code

When the code expander generator is used for generating assembly instead of object code (see section 5), additional print formats have to be defined in “mach.h”. The following table lists these formats.

BYTE_FMT	:	Print format to allocate and initialize one byte. The format must contain %ld.
WORD_FMT	:	Print format to allocate and initialize one word. The format must contain %ld.
LONG_FMT	:	Print format to allocate and initialize one long. The format must contain %ld.
BSS_FMT	:	Print format to allocate space in the bss segment. The format must contain %ld (number of bytes).
COMM_FMT	:	Print format to declare a "common". The format must contain a %s (name to be declared common), followed by a %ld (number of bytes).

SEGTXT_FMT	:	Print format to switch to the text segment.
SEGDAT_FMT	:	Print format to switch to the data segment.
SEGBSS_FMT	:	Print format to switch to the bss segment.
SYMBOL_DEF_FMT	:	Print format to define a label. The format must contain %s.
GLOBAL_FMT	:	Print format to declare a global name. The format must contain %s.
LOCAL_FMT	:	Print format to declare a local name. The format must contain %s.
RELOC1_FMT	:	Print format to initialize a byte with an address expression. The format must contain %s (name) and %ld (offset).
RELOC2_FMT	:	Print format to initialize a word with an address expression. The format must contain %s (name) and %ld (offset).
RELOC4_FMT	:	Print format to initialize a long with an address expression. The format must contain %s (name) and %ld (offset).
ALIGN_FMT	:	Print format to align a segment.

4. Description of the as_table

This section describes the as_table. Like the previous section, it is divided into four parts: the first two parts describe the grammar and the semantics of the as_table; the third part gives an overview of the functions and the constants that must be present in the as_table (in the file "as.h" or in the file "as.c"); the last part describes the case when assembly is generated instead of object code. The part on semantics contains examples that appear in the as_table for the VAX or for the 8086.

4.1. Grammar

The form of the as_table is given by the following grammar :

```
TABLE          ::=  ( RULE)*
RULE           ::=  ( mnemonic | "...")  DECL_LIST  "==>"  ACTION_LIST
DECL_LIST      ::=  DECLARATION  ( ","  DECLARATION)*
DECLARATION    ::=  operand  [ ":"  type]
ACTION_LIST    ::=  ACTION  ( ";"  ACTION) "."
ACTION         ::=  IF_STATEMENT
                 |  function-call
                 |  "@"function-call
IF_STATEMENT   ::=  "@if"  "(" condition ")"  ACTION_LIST
                    ( "@elsif"  "(" condition ")"  ACTION_LIST)*
                    [ "@else"  ACTION_LIST]
                    "@fi"
function-call  ::=  function-identifier "(" [arg (,arg)*] ")"
arg            ::=  argument
```

| reference

mnemonic, **operand**, and **type** are all C identifiers; **condition** is a normal C expression; **function-call** must be a C function call. A function can be called with standard C arguments or with a reference (see section 4.2.4). Since the as_table is interpreted during code expander generation as well as during code expander execution, two levels of calls are present in it. A "function-call" is done during code expander generation, a "@function-call" during code expander execution.

4.2. Semantics

The as_table is made up of rules that map assembly instructions onto **back**-primitives, a set of functions that construct an object file. The table is processed by **asg**, which generates a C functions for each assembler mnemonic. The names of these functions are the assembler mnemonics postfixed with "_instr" (e.g., "add" becomes "add_instr()"). These functions will be used by the function assemble() during the expansion of the EM_table. After explaining the semantics of the as_table the function assemble() will be described.

4.2.1. Rules

A rule in the as_table is made up of a left and a right hand side; the left hand side describes an assembler instruction (mnemonic and operands); the right hand side gives the corresponding actions as **back**-primitives or as functions defined by the table writer, which call **back-primitives**. Two simple examples from the VAX as_table and the 8086 as_table, resp.:

```
movl src, dst  ==> @text1( 0xd0);
                   gen_operand( src);
                   gen_operand( dst).
    /* ''gen_operand'' is a function that encodes
     * operands by calling back-primitives. */

rep ens:MOVS   ==>  @text1( 0xf3);
                    @text1( 0xa5).
```

4.2.2. Declaration of types.

In general, a machine instruction is encoded as an opcode followed by zero or more the operands. There are two methods for mapping assembler mnemonics onto opcodes: the mnemonic determines the opcode, or mnemonic and operands together determine the opcode. Both cases can be easily expressed in the as_table. The first case is obvious. The second case is handled by introducing type fields for the operands.

When mnemonic and operands together determine the opcode, the table writer has to give several rules for each combination of mnemonic and operands. The rules differ in the type fields of the operands. The table writer has to supply functions that check the type of the operand. The name of such a function is the name of the type; it has one argument: a pointer to a struct of type *t_operand*; it returns non-zero when the operand is of this type, otherwise it returns 0.

This will usually lead to a list of rules per mnemonic. To reduce the amount of work an abbreviation is supplied. Once the mnemonic is specified it can be referred to in the following rules by “...”. One has to make sure that each mnemonic is mentioned only once in the as_table, otherwise **asg** will generate more than one function with the same name.

The following example shows the usage of type fields.

```
mov dst:REG, src:EADDR  ==>
        @text1( 0x8b);               /* opcode */
        mod_RM( %d(dst->reg), src). /* operands */

... dst:EADDR, src:REG  ==>
        @text1( 0x89);               /* opcode */
        mod_RM( %d(src->reg), dst). /* operands */
```

The table-writer must supply the restriction functions, `REG` and `EADDR` in the previous example, in “as.c” or ”as.h”.

4.2.3. The function of the @-sign and the if-statement.

The right hand side of a rule is made up of function calls. Since the as_table is interpreted on two levels, during code expander generation and during code expander execution, two levels of calls are present in it. A function-call without an “@”-sign is called during code expander generation (e.g., the `gen_operand()` in the first example). A function call with an “@”-sign is called during code expander execution (e.g., the **back**-primitives). So the last group will be part of the compiler.

The need for the “@”-sign construction arises, for example, when implementing push/pop optimization (e.g., “push x” followed by “pop y” can be replaced by “move x, y”). In this case flags need to be set, unset, and tested during the execution of the compiler:

```
PUSH src   ==>    /* save in ax */
                  mov_instr( AX_oper, src);
                  /* set flag */
                  @assign( push_waiting, TRUE).

     POP dst    ==>    @if ( push_waiting)
                              /* ‘‘mov_instr’’ is asg-generated */
                              mov_instr( dst, AX_oper);
                              @assign( push_waiting, FALSE).
                       @else
                              /* ‘‘pop_instr’’ is asg-generated */
                              pop_instr( dst).
                       @fi.
```

Although the @-sign is followed syntactically by a function name, this function can very well be the name of a macro defined in C. This is in fact the case with “@assign()” in the above example.

The case may arise when information is needed that is not known until execution of the compiler. For example one needs to know if a "$*i*" argument fits in one byte. In this case one can use a special if-statement provided by **asg**: @if, @elsif, @else, @fi. This means that the conditions will be evaluated at run time of the **ce**. In such a condition one may of course refer to the "$*i*" arguments. For example, constants can be packed into one or two byte arguments as follows:

```
mov dst:ACCU, src:DATA ==>
                              @if ( fits_byte( %$(dst->expr)))
                                   @text1( 0xc0);
                                   @text1( %$(dst->expr)).
                              @else
                                   @text1( 0xc8);
                                   @text2( %$(dst->expr)).
                              @fi.
```

4.2.4. References to operands

As noted before, the operands of an assembler instruction may be used as pointers to the struct *t_operand* in the right hand side of the table. Because of the free format assembler, the types of the fields in the struct *t_operand* are unknown to **asg**. As these fields can appear in calls to functions, **asg** must know these types. This section explains how these types must be specified.

References to operands come in three forms: ordinary operands, operands that contain "$*i*" references, and operands that refer to names of local labels. The "$*i*" in operands represent names or numbers of a **C_instr** and must be given as arguments to the **back**-primitives. Labels in operands must be converted to a number that tells the distance, the number of bytes, between the label and the current position in the text-segment.

All these three cases are treated in an uniform way. When the table writer makes a reference to an operand of an assembly instruction, he must describe the type of the operand in the following way.

reference	::=	"%" conversion
		"(" operand-name "–>" field-name ")"
conversion	::=	printformat
	|	"$"
	|	"dist"
printformat	::=	see PRINT(3ACK)[6]

The three cases differ only in the conversion field. The printformat conversion applies to ordinary operands. The "%$" applies to operands that contain a "$*i*". The expression between parentheses must result in a pointer to a char. The result of "%$" is of the type of "$*i*". The "%dist" applies to operands that refer to a local label. The expression between the brackets must result in a pointer to a char. The result of "%dist" is of type arith.

The following example illustrates the usage of "%$". (For an example that illustrates the usage of ordinary fields see the section on "User supplied definitions and functions").

```
jmp dst ==>
    @text1( 0xe9);
    @reloc2( %$(dst->lab), %$(dst->off), PC_REL).
```

A useful function concerning $*i*s is arg_type(), which takes as input a string starting with $*i* and returns the type of the *i*"th argument of the current EM-instruction, which can be STRING, ARITH or INT. One may need this function while decoding operands if the context of the $*i* does not give enough information. If the function arg_type() is used, the file arg_type.h must contain the definition of STRING, ARITH and INT.

%dist is only guaranteed to work when called as a parameter of text1(), text2() or text4(). The goal of the %dist conversion is to reduce the number of reloc1(), reloc2() and reloc4() calls, saving space and time (no relocation at compiler run time). The following example illustrates the usage of "%dist".

```
jmp dst:ILB    ==> /* label in an instruction list */
    @text1( 0xeb);
    @text1( %dist( dst->lab)).

... dst:LABEL  ==> /* global label */
    @text1( 0xe9);
    @reloc2( %$(dst->lab), %$(dst->off), PC_REL).
```

4.2.5. The functions assemble() and block_assemble()

The functions assemble() and block_assemble() are provided by **ceg**. If, however, the table writer is not satisfied with the way they work he can supply his own assemble() or block_assemble(). The default function assemble() splits an assembly string into a label, mnemonic, and operands and performs the following actions on them:

1: It processes the local label; it records the name and current position. Thereafter it calls the function process_label() with one argument of type string, the label. The table writer has to define this function.

2: Thereafter it calls the function process_mnemonic() with one argument of type string, the mnemonic. The table writer has to define this function.

3: It calls process_operand() for each operand. Process_operand() must be written by the table-writer since no fixed representation for operands is enforced. It has two arguments: a string (the operand to decode) and a pointer to the struct *t_operand*. The declaration of the struct *t_operand* must be given in the file "as.h", and the table-writer can put all the information needed for encoding the operand in machine format in it.

4: It examines the mnemonic and calls the associated function, generated by **asg**, with pointers to the decoded operands as arguments. This makes it possible to use the decoded operands in the right hand side of a rule (see below).

If the default assemble() does not work the way the table writer wants, he can supply his own version of it. Assemble() has the following arguments:

```
assemble( instruction )
    char *instruction;
```

instruction points to a null-terminated string.

The default function block_assemble() is called with a sequence of assembly instructions that belong to one action list. It calls assemble() for every assembly instruction in this block. But if a special action is required on a block of assembly instructions, the table writer only has to rewrite this function to get a new **ceg** that obliges to his wishes. The function block_assemble has the following arguments:

```
block_assemble( instructions, nr, first, last)
       char   **instruction;
       int      nr, first, last;
```

Instruction point to an array of pointers to strings representing assembly instructions. *Nr* is the number of instructions that must be assembled. *First* and *last* have no function in the default block_assemble(), but are useful when optimizations are done in block_assemble().

Four things have to be specified in ‘‘as.h’’ and ‘‘as.c’’. First the user must give the declaration of struct *t_operand* in ‘‘as.h’’, and the functions process_operand(), process_mnemonic(), and process_label() must be given in ‘‘as.c’’. If the right hand side of the as_table contains function calls other than the **back**-primitives, these functions must also be present in ‘‘as.c’’. Note that both the ‘‘@’’-sign (see 4.2.3) and ‘‘references’’ (see 4.2.4) also work in the functions defined in ‘‘as.c’’.

The following example shows the representative and essential parts of the 8086 ‘‘as.h’’ and ‘‘as.c’’ files.

```
/* Constants and type definitions in as.h */

#define        UNKNOWN                0
#define        IS_REG                 0x1
#define        IS_ACCU                0x2
#define        IS_DATA                0x4
#define        IS_LABEL               0x8
#define        IS_MEM                 0x10
#define        IS_ADDR                0x20
#define        IS_ILB                 0x40

#define AX               0
#define BX               3
#define CL               1
#define SP               4
#define BP               5
#define SI               6
#define DI               7

#define REG( op)          ( op->type & IS_REG)
#define ACCU( op)         ( op->type & IS_REG  &&  op->reg == AX)
#define REG_CL( op)       ( op->type & IS_REG  &&  op->reg == CL)
#define DATA( op)         ( op->type & IS_DATA)
#define LABEL( op)        ( op->type & IS_LABEL)
#define ILB( op)          ( op->type & IS_ILB)
#define MEM( op)          ( op->type & IS_MEM)
#define ADDR( op)         ( op->type & IS_ADDR)
#define EADDR( op)        ( op->type & ( IS_ADDR | IS_MEM | IS_REG))
#define CONST1( op)       ( op->type & IS_DATA  && strcmp( "1", op->expr) == 0)
#define MOVS( op)         ( op->type & IS_LABEL&&strcmp("
#define IMMEDIATE( op)    ( op->type & ( IS_DATA | IS_LABEL))

struct t_operand {
        unsigned type;
        int reg;
        char *expr, *lab, *off;
       };

extern struct t_operand saved_op, *AX_oper;
```

```
/* Some functions in as.c. */

#include "arg_type.h"
#include "as.h"

#define last( s)        ( s + strlen( s) - 1)
#define LEFT            '('
#define RIGHT           ')'
#define DOLLAR          '$'

process_operand( str, op)
char *str;
struct t_operand *op;

/*        expr            ->        IS_DATA en IS_LABEL
 *        reg             ->        IS_REG en IS_ACCU
 *        (expr)          ->        IS_ADDR
 *        expr(reg)       ->        IS_MEM
 */
{
        char *ptr, *index();

        op->type = UNKNOWN;
        if ( *last( str) == RIGHT) {
                ptr = index( str, LEFT);
                *last( str) = ' ';
                *ptr = ' ';
                if ( is_reg( ptr+1, op)) {
                        op->type = IS_MEM;
                        op->expr = ( *str == ' ' ? "0" : str);
                }
                else {
                        set_label( ptr+1, op);
                        op->type = IS_ADDR;
                }
        }
        else
                if ( is_reg( str, op))
                        op->type = IS_REG;
                else {
                        if ( contains_label( str))
                                set_label( str, op);
                        else {
                                op->type = IS_DATA;
                                op->expr = str;
                        }
                }
}

/**********************************************************************/

mod_RM( reg, op)
int reg;
struct t_operand *op;
```

```
/* This function helps to decode operands in machine format.
 * Note the $-operators
 */
{
      if ( REG( op))
              R233( 0x3, reg, op->reg);
      else if ( ADDR( op)) {
              R233( 0x0, reg, 0x6);
              @reloc2( %$(op->lab), %$(op->off), ABSOLUTE);
      }
      else if ( strcmp( op->expr, "0") == 0)
              switch( op->reg) {
                case SI : R233( 0x0, reg, 0x4);
                          break;

                case DI : R233( 0x0, reg, 0x5);
                          break;

                case BP : R233( 0x1, reg, 0x6);        /* exception! */
                          @text1( 0);
                          break;

                case BX : R233( 0x0, reg, 0x7);
                          break;

                default : fprint( STDERR, "Wrong index register %d\n",
                                  op->reg);
              }
      else {
              @if ( fit_byte( %$(op->expr)))
                      switch( op->reg) {
                          case SI : R233( 0x1, reg, 0x4);
                                    break;

                        case DI : R233( 0x1, reg, 0x5);
                                  break;

                        case BP : R233( 0x1, reg, 0x6);
                                  break;

                        case BX : R233( 0x1, reg, 0x7);
                                  break;

                        default : fprint( STDERR, "Wrong index register %d\n",
                                          op->reg);
                      }
                      @text1( %$(op->expr));
              @else
                      switch( op->reg) {
                        case SI : R233( 0x2, reg, 0x4);
                                  break;

                        case DI : R233( 0x2, reg, 0x5);
                                  break;
```

```
                        case BP : R233( 0x2, reg, 0x6);
                                  break;

                        case BX : R233( 0x2, reg, 0x7);
                                  break;

                        default : fprint( STDERR, "Wrong index register %d\n",
                                          op->reg);
                      }
                      @text2( %$(op->expr));
              @fi
      }
}
```

4.3. Generating assembly code

It is possible to generate assembly instead of object files (see section 5), in which case there is no need to supply "as_table", "as.h", and "as.c". This option is useful for debugging the EM_table.

5. Building a code expander

This section describes how to generate a code expander in two phases. In phase one, the EM_table is written and assembly code is generated. If the assembly code is an actual language, the EM_table can be tested by assembling and running the generated code. If an ad-hoc assembly language is used by the table writer, it is not possible to test the EM_table, but the code generated is at least in readable form. In the second phase, the as_table is written and object code is generated. After the generated object code is fed into the loader, it can be tested.

5.1. Phase one

The following is a list of instructions to make a code expander that generates assembly instructions.

1: Create a new directory.

2: Create the "EM_table", "mach.h", and "mach.c" files; there is no need for "as_table", "as.h", and "as.c" at this moment.

3: type
`install_ceg -as`
install_ceg will create a Makefile and three directories : ceg, ce, and back. Ceg will contain the program ceg; this program will be used to turn "EM_table" into a set of C source files (in the ce directory), one for each EM-instruction. All these files will be compiled and put in a library called **ce.a**.
The option `-as` means that a **back**-library will be generated (in the directory "back") that supports the generation of assembly language. The library is named "back.a".

4: Link a front end, "ce.a", and "back.a" together resulting in a compiler that generates assembly code.

If the table writer has chosen an actual assembly language, the EM_table can be tested (e.g., by running the compiler on the EM test set). If an error occurs, change the EM_table and type

`update_ceg` **C_instr**

where **C_instr** stands for the name of the erroneous EM-instruction. If the table writer has chosen an ad-hoc assembly language, he can at least read the generated code and look for possible errors. If an error is found, the same procedure as described above can be followed.

5.2. Phase two

The next phase is to generate a **ce** that produces relocatable object code.

1: Remove the "ce", "ceg", and "back" directories.

2: Write the "as_table", "as.h", and "as.c" files.

3: type

```
install_ceg -obj
```

The option `-obj` means that "back.a" will contain a library for generating ACK.OUT(5ACK) object files, see appendix B. If the writer does not want to use the default "back.a", the `-obj` flag must omitted and a "back.a" should be supplied that generates the generates object code in the desired format.

4: Link a front end, "ce.a", and "back.a" together resulting in a compiler that generates object code.

The as_table is ready to be tested. If an error occurs, adapt the table. Then there are two ways to proceed:

1: recompile the whole EM_table,

```
update_ceg ALL
```

2: recompile just the few EM-instructions that contained the error,

`update_ceg` **C_instr**

where **C_instr** is an erroneous EM-instruction. This has to be done for every EM-instruction that contained the erroneous assembly instruction.

6. Acknowledgements

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7. References

References

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Appendix A, the **back**-primitives

This appendix describes the routines available to generate relocatable object code. If the default back.a is used, the object code is in ACK.OUT(5ACK) format. In de default back.a, the names defined here are remapped to more hidden names, to avoid name conflicts with for instance names used in the front-end. This remapping is done in an include-file, "back.h". A user-implemented back.a should do the same thing.

A1. Text and data generation; with ONE_BYTE b; TWO_BYTES w; FOUR_BYTES l; arith n;

text1(b)	:	Put one byte in text-segment.
text2(w)	:	Put word (two bytes) in text-segment, byte-order is defined by BYTES_REVERSED in mach.h.
text4(l)	:	Put long (two words) in text-segment, word-order is defined by WORDS_REVERSED in mach.h.
con1(b)	:	Same for CON-segment.
con2(w)	:	
con4(l)	:	
rom1(b)	:	Same for ROM-segment.
rom2(w)	:	
rom4(l)	:	
gen1(b)	:	Same for the current segment, only to be used in the ‘‘..icon’’, ‘‘..ucon’’, etc. pseudo EM-instructions.
gen2(w)	:	
gen4(l)	:	
bss(n)	:	Put n bytes in bss-segment, value is BSS_INIT.
common(n)	:	If there is a saved label, generate a "common" for it, of size n. Otherwise, it is equivalent to bss(n). (see also the save_label routine).

A2. Relocation; with char *s; arith o; int r;

reloc1(s, o, r)	:	Generates relocation-information for 1 byte in the current segment. s : the string which must be relocated o : the offset in bytes from the string. r : relocation type. It can have the values ABSOLUTE or PC_REL. These two constants are defined in the file ‘‘back.h’’
reloc2(s, o, r)	:	Generates relocation-information for 1 word in the current segment. Byte-order according to BYTES_REVERSED in mach.h.
reloc4(s, o, r)	:	Generates relocation-information for 1 long in the current segment. Word-order according to WORDS_REVERSED in mach.h.

A3. Symbol table interaction; with int seg; char *s;

switch_segment(seg)	:	sets current segment to ‘‘seg’’, and does alignment if necessary. ‘‘seg’’ can be one of the four constants defined in ‘‘back.h’’: SEGTXT, SEGROM, SEGCON, SEGBSS.
symbol_definition(s)	:	Define s in symbol-table.
set_local_visible(s)	:	Record scope-information in symbol table.
set_global_visible(s)	:	Record scope-information in symbol table.

A4. Start/end actions; with char *f;

open_back(f)	:	Directs output to file “f”, if f is the null pointer output must be given on standard output.
close_back()	:	close output stream.
init_back()	:	Only used with user-written back-library, gives the opportunity to initialize.
end_back()	:	Only used with user-written back-library.

A5. Label generation routines; with int n; arith g; char *l; These routines all return a "char *" to a static area, which is overwritten at each call.

extnd_pro(n)	:	Label set at the end of procedure *n*, to generate space for locals.
extnd_start(n)	:	Label set at the beginning of procedure *n*, to jump back to after generating space for locals.
extnd_name(l)	:	Create a name for a procedure named *l*.
extnd_dnam(l)	:	Create a name for an external variable named *l*.
extnd_dlb(g)	:	Create a name for numeric data label *g*.
extnd_ilb(l, n)	:	Create a name for instruction label *l* in procedure *n*.
extnd_hol(n)	:	Create a name for HOL block number *n*.
extnd_part(n)	:	Create a unique label for the C_insertpart mechanism.
extnd_cont(n)	:	Create another unique label for the C_insertpart mechanism.
extnd_main(n)	:	Create yet another unique label for the C_insertpart mechanism.

A6. Some miscellaneous routines, with char *l;

save_label(l)	:	Save label *l*. Unfortunately, in EM, when a label is encountered, it is not yet known in which segment it will end up. The save_label/dump_label mechanism is there to solve this problem.
dump_label()	:	If there is a label saved, force definition for it now.
align_word()	:	Align to a word boundary, if the current segment is not a text segment.

Appendix B, description of ACK-a.out library

The object file produced by **ce** is by default in ACK.OUT(5ACK) format. The object file is made up of one header, followed by four segment headers, followed by text, data, relocation information, symbol table, and the string area. The object file is tuned for the ACK-LED, so there are some special things done just before the object file is dumped. First, four relocation records are added which contain the names of the four segments. Second, all the local relocation is resolved. This is done by the function do_relo(). If there is a record belonging to a local name this address is relocated in the segment to which the record belongs. Besides doing the local relocation, do_relo() changes the ''nami''-field of the local relocation records. This field receives the index of one of the four relocation records belonging to a segment. After the local relocation has been resolved the routine output_back() dumps the ACK object file.

If a different a.out format is wanted, one can choose between three strategies:

1: The most simple one is to use a conversion program, which converts the ACK a.out format to the wanted a.out format. This program exists for all most all machines on which ACK runs. However, not all conversion programs can generate relocation information. The disadvantage is that the compiler will become slower.

2: A better solution is to change the functions output_back(), do_relo(), open_back(), and close_back() in such a way that they produce the wanted a.out format. This strategy saves a lot of I/O.

3: If this still is not satisfactory, the **back**-primitives can be adapted to produce the wanted a.out format.