The Programming Language "*immediate C*"

John E. Wulff, B.E., M. Eng. Sc.

Abstract

immediate C - *iC* for short - is an extension of the language C. It utilizes the syntax of C to give meaning to statements that have no semantic support in C. In addition to standard variables, which are modified by the flow of instructions, *iC* provides so called *'immediate'* variables, whose values are updated, whenever a change of input calls for an immediate change in output. An efficient Data Flow technique implements this strategy.

iC provides programmers with built in operators, whose function is closely modelled on integrated circuits. The name *iC* is a reminder of this fact. Logical *AND*, *OR*, *EXCLUSIVE-OR* and *NOT* as well as D flip-flops, SR flip-flops and many others are implemented in such a way, that their use follows the same design rules, which apply to their hardware counterparts. These rules have led to a well-developed hardware technology, whose effectiveness is demonstrated by the success of today's complex computer hardware. Particularly the concept of clocked functions plays an important role in the language *iC*. It gives the same protection against timing races in *iC* programs, as it provides for hardware IC designs.

Writing programs in the language *iC* has the added quality, that many simple ideas and relationships, which should result in direct actions, can be written down *immediately* in one line. The coding of call back routines and other overhead is not required. It was this thought, which also prompted the name "*immediate C*".

For more information about this program, or for information on how
to contact the author, see Appendix A README or visit
http://je-wulff.de or contact ic@je-wulff.de

Zusammenfassung

immediate C - kurz *iC* - ist eine Erweiterung der Sprache C. Sie basiert auf der Syntax von C und gibt vielen Befehlen Bedeutung, die keine semantische Unterstützung in C haben. Zu den einfachen Variablen, die im normalen Programmfluss verändert werden, kommen in *iC* so genannte *'immediate'* oder *'sofort'* Variablen, dessen Wert sofort verändert wird, wenn eine Eingangsänderung, die sofortige Änderung eines Ausgangs zur Folge hat. Um dies zu erreichen, wird eine effiziente Datenfluss-Technik eingesetzt.

iC stellt Programmierern eingebaute Operatoren zur Verfügung, deren Arbeitsweise die Funktionen von IC-Bausteinen modelliert. Der Name *iC* soll an diese Tatsache erinnern. Logisches *UND*, *ODER*, *EXCLUSIV-ODER* und *NICHT* sowie D flip-flops, SR flip-flops und viele mehr sind so implementiert, dass deren Anwendung den gleichen Entwurfsregeln entspricht, wie die der entsprechenden IC-Bausteine. Diese Regeln haben zu einer ausgereiften Technik geführt, deren Wirksamkeit durch unsere heutige komplexe Computertechnik belegt ist. Besonders das Konzept von getakteten (clocked) Funktionen spielt in der Sprache *iC* eine wichtige Rolle. Damit wird derselbe Schutz gegen Laufzeitprobleme in *iC*-Programmen erreicht, der damit in IC-Schaltkreisen bewirkt wird.

Programme die in *iC* geschrieben werden, haben das zusätzliche Merkmal, dass viele einfache Ideen und Zusammenhänge, die zu direkten Aktionen führen sollen, sofort in einer Zeile niedergeschrieben werden können. Callback-Routinen sind nicht notwendig. Auch dieser Gedanke ist im Namen "*immediate C*" enthalten.

Table of Contents

1 Introduction

immediate C - *iC* for short - is an extension of the language C. It utilizes the syntax of C to give meaning to statements that have no semantic support in C. In addition to standard variables, which are modified by the flow of instructions, *iC* provides so called *'immediate'* variables, whose values are updated, whenever a change of input calls for an immediate change in output. An efficient Data Flow technique implements this strategy.

1.1 Relationship to Object Orientation

immediate C uses the OO-paradigm in its concept. Each *immediate* variable is an independent object, which acts on other *immediate* variables by a number of methods. These methods are expressed in a number of functions and overloaded on to the logical and arithmetic operators. In conventional OO languages like Smalltalk or C++, a method is an action which acts on the object owning the method. Conceptually descriptions of Object Orientation talk of methods being actions or messages sent from one object to another. It is in this sense that *iC immediate* variable objects interact with each other by the use of Data Flow techniques.

1.2 Relationship to Instruction Flow Languages

Traditional High Level Languages such as FORTRAN, Pascal or C are called Instruction Flow Languages, because they express instruction sequences for abstract machines, which are closely modelled on the underlying, instruction driven machine. By being independent of the actual machine, these languages have helped to hide unessential details of the hardware, to make programs portable and to focus the programmer's attention on the problem to be solved. The overwhelming usefulness of these instruction flow languages to express precise algorithms is recognized in *iC*, by including the whole of C or C++ as a subset, for dealing with algorithmic problems in established ways. Learning of the language *iC* should therefore be very easy for C and C++ programmers.

Many of the undesirable characteristics of the underlying hardware are reflected in today's High Level Languages. These characteristics make it difficult to express a large number of everyday problems briefly and clearly. Particularly the manipulation of events is not easy to integrate into programs written in traditional High Level Languages. Yet events play an increasing role in today's interactive, mouse driven programs. Many different functions must be ready to execute as a result of external or user generated events, which occur at unpredictable times. The instruction driven computer only executes a particular instruction, *when the flow of instructions in a program gets around to executing that instruction.* This statement may sound pedantic, but much of the complexity of modern programs is a direct result of this fundamental truism. How does one organize a program, so that it can respond quickly to many and varied external events? *iC* provides answers to this question.

The interrupt mechanism, designed to tackle such problems at a system level, is intractable for the average programmer and is not supported in a general way by most High Level Languages. *iC* harnesses interrupts and hides their complexity.

1.3 Programmable Logic Controllers

The situation is even more critical in systems that deal with a large number of external inputs. In the early 1980's a completely new class of computer was developed to deal with such problems in the environment of factories and machine control. These are the "Programmable Logic Controllers" or "PLC" for short. (SPS or Speicher-Programmierbare Steuerung in German) Conventional PLC's have a standard instruction driven architecture. They differ from conventional computers in two main areas:

- They provide fast bit instructions and data access to individual bits on top of the more conventional instructions to manipulate data words.
- They have a built in operating system, which runs the stored program over and over. Inputs are automatically polled at reasonably short intervals and Boolean and arithmetic expressions making up the stored program are re-evaluated continuously. This is necessary, because outputs and intermediate values in a PLC are assumed to reflect an immediate transformation of the inputs, as carried out by the expressions of the stored program.

This organization of PLC's has two very serious drawbacks, which are direct consequences of the differences mentioned:

- Conventional PLC's require a special CPU, which can never be as cheap as a mass produced microprocessor chip, or they emulate the PLC instruction set, in which case they are slow.

- The cyclic execution of the stored program sets very real limits to the length of possible programs. The longer the program, the longer the cycle time, which is the time interval at which inputs are polled. If this time gets too long, the response of the PLC is no longer acceptable for many applications.

PLC's are facing a crisis on two fronts:

- Traditionally PLC program memories were measured in kilobytes. Today megabytes of memory are available at low cost. This 1000 fold increase in potential program size cannot be utilized with the cyclic execution strategy of conventional PLC's. Even with a 10 fold increase in speed, these machines would be too slow.
- The second crisis is the lack of a High Level Language for PLC's. Most PLC programs are developed with antiquated tools that support semi graphical languages for Boolean logic and assembly programming for numerical subsystems. The international standard IEC-1131 is attempting to fill this vacuum by specifying such a language. Unfortunately this standard simply freezes current programming practice, by incorporating five different languages, four of which are the semi graphical and assembly languages in common use today. For algorithmic programming it introduces a completely new High Level Language called 'Structured Text', which will require a large learning effort by programmers and whose utility in the limited area of PLC's seems doubtful. IEC-1131 makes no attempt to confront the fundamental speed problems facing PLC users.

Because PLC's are completely compute bound, the type of program organization they use is unacceptable for standard computers. Nevertheless many programmers designing event controlled applications on standard computers resort to polling schemes, despite the drawbacks involved. The High Level Languages they use do not give them any simple alternatives.

The language *iC* can be used to program standard computer systems and PLC's in a uniform way. *iC* is fast, because it responds immediately to any changes in input, and does not waste time evaluating expressions, whose input operands have not changed. The extensions which *iC* offers over the algorithmic language C, can also be coded graphically, using current CAD packages for IC design. For factory staff, who require very simple programming methods, the use of *Ladder Diagram (LD)* or *Function Block Diagram (FBD)* in conformity with IEC-1131, using suitable front ends is possible.

1.4 Relationship to Integrated Circuits

iC provides programmers with built in operators, whose function is closely modelled on integrated circuits. The name *iC* is a reminder of this fact. Logical *AND*, *OR*, *EXCLUSIVE-OR* and *NOT* are the basic functions implemented using a very fast data-flow algorithm. The full range of arithmetic operators is also available. These are not normally considered as hardware components, although once they formed the basis of the very important “Analog Computer”. They can be used for implementing control algorithms, fuzzy logic – the possibilities are endless. Also implemented as efficient built in functions are the D flip-flop, SR flip-flop, JK flip-flop, shift register and many other popular integrated circuit types, which are implemented in such a way, that their use in *iC* programs follows the same design rules, which apply to their hardware counterparts. These rules have led to a well-developed hardware technology, whose effectiveness is demonstrated by the success of today's complex computer hardware. Particularly the concept of clocked functions plays an important role in the language *iC*. It gives the same protection against timing races in *iC* programs, as it provides for hardware IC designs.

Another idea taken from integrated circuits is Large-Scale-Integration. User defined Function Blocks emulate LSI circuits and produce complex sub-units with a known functionality and a well defined external interface, which can be re-used without regard to the internals. IC hardware design may not be part of the average programmers repertoire, but there is much literature on the subject. The run-time code is not meant to be just a simulation of IC hardware – the generated code is extremely fast, because of the data-flow techniques used and can provide useful control programs.

1.5 Summary

Writing programs in the language *iC* has the added quality, that many simple ideas and relationships, which should result in direct actions, can be written down *immediately* in one line.

```
if (IX0.0) { printf(”Hello! world\n”); }
```

This is a complete runnable *iC* program. `IX0.0` is an external *immediate* bit input in IEC-1131 notation, which generates an event when it changes state. The coding of call back routines and other overhead is not required. It was this thought, which also prompted the name "*immediate C*".

2 Language description

2.1 Immediate Variables

An *immediate* variable is a data object that has a value, but which also has the ability to transmit any change in its value as an event. This event triggers the re-calculation of all expressions that contain the *immediate* variable. The fundamental assumption is, that **the value of an expression only changes, if one of the variables making up the expression changes**. Thus it is only necessary to re-calculate an expression, if one of the variables making up the expression changes. Conversely, if an expression is re-calculated whenever one of its variables changes, and all unnecessary recalculations of expressions are left out, the value of all expressions will be up to date within a very short time. *Immediate* variables provide the mechanism to make this strategy possible.

2.2 Immediate Types

iC introduces the type modifier **imm** to declare *immediate* variables of the basic data types **int** in C and the basic data type **bit**, which is a new data type in *iC*. Type **bit** declares variables capable of holding the values **0** and **1**. Unless the C or C++ compiler, used to translate the generated code, itself supports bit as a basic data type, the use of type bit is restricted to **imm bit**. The word 'boolean' was avoided deliberately, because it has a different semantic bias in languages where it is used. (Truth of a test rather than single bit objects). Both **imm int** and **imm bit** are value types.

iC also has clocking types **imm clock** and **imm timer**, which can only be used as function parameters. These will be discussed later.

2.2.1 *Immediate* declarations

An *immediate* declaration declares an *immediate* variable to be either of type **imm int**, **imm bit**, **imm clock** or **imm timer**, using syntax similar to declarations in C. Any value type variable not declared before it is used is assumed to be of type **imm bit**. Undeclared clocking type variables inherit the type from the assigning function. Calling the *immcc* compiler with the strict option -S makes declarations mandatory for all **imm** variables – this is highly recommended. All variables in a declaration may be assigned directly.

```
imm int fader, colour;                    // declaration only
imm int brightness = fader * colour;      // decl and assignment
```

2.2.2 extern *immediate* declarations

Just like in C, several *iC* sources may be compiled separately and linked into a single application. When immediate variables declared and assigned in one source are referenced in another source, they must be declared with an **extern** declaration, before they can be used in an expression.

```
extern imm int fader, colour;
extern imm int brightness;
```

2.3 Immediate Expressions

Immediate expressions are arithmetic or bit expressions external to all functions, which contain at least one *immediate* value variable. *Immediate* arithmetic expressions may also contain constant expressions. An *immediate* expression is re-calculated whenever the value of one of the *immediate* variables it contains has changed. If an expression consists only of constants and no *immediate* variables it is a constant expression evaluated once during initialisation.

2.4 Operators in immediate expressions

Most operators available in C may be used with *immediate* variables. The precedence of the operators is the same as in C. Some C operators are not valid for *immediate* expressions, because the semantics are different. These are the increment and decrement operators **++** and **--**, as well as structure and pointer operators **->** **.**(dot) **&**(address of) and *****(pointer dereference). Assignment expressions **+=** etc. are also not allowed. These restrictions do not apply to embedded C code in literal blocks and *immediate if else* or *switch* statements, which will be introduced later.

Array variables and index expressions using **[ ]** are available with the Array extension of the language using the pre-compiler **immac** (called automatically). See section section 3.

2.4.1 Arithmetic and Relational Operators

The binary arithmetic operators **+ - * /**, the modulo operator **%**, as well as unary **-** and **+** operate on numeric values and yield numeric results of type **imm int**. The same applies to the shift operators **<<** and **>>**. If an operand of the wrong type is used with one of these operators, automatic type conversion takes place. Values of type **imm bit** are converted to the **int** values 0 or 1 corresponding to the values of the **bit**. The relational and equality operators **<**, **<=**, **>**, **>=**, **==**, **!=** also have numeric operands, but these operators yield **imm bit** results by default.

2.4.2 Bitwise and Bit Operators

If both operands of the binary operators **&**, **|**, **^** or the single operand of operator **~** are of type **imm int**, these operators carry out bitwise manipulation on their integer operands – just like in C. The result is an **imm int**. *Immediate* arithmetic, relational and bitwise logical expressions with numeric operands may contain constants, as well as *immediate* operands.

If one of the operands of the binary operators **&**, **|**, **^** or the single operand of operator **~** are of type **imm bit**, these operators carry out the bit manipulation operations ***and***, ***or***, ***exclusive-or*** and ***not*** on **imm bit** objects. The result is an **imm bit**. Any operands of type **imm int** are converted to **imm bit**. The numeric value **0** converts to **0** (**false**), any other arithmetic value converts to **1** (**true**). The bit operators are used frequently in *immediate C*, since bit manipulation is very common in event driven systems – more so than in algorithmic programs written in conventional languages like C, which does not even provide a type *bit*. Such logical bit expressions in *immediate C* may not contain any constants or *non-immediate* values. Constants in *immediate* bit expressions do not make much sense. They either do not change a variable (**a & 1**, **b | 0**) or they produce another constant (**c & 0**, **d | 1**, **~1**).

2.4.3 Logical Operators

The logical connectives **&&** and **||** are executed as arithmetic expressions, when one of the operands is of type **imm int**. Evaluation is from left to right, and evaluation stops when the truth or falsehood of the result is known – just like in C. The result is of type **imm bit** by default. The unary complement operator **!**, operating on an **imm int** produces an **imm bit** result.

The operators **&&**, **||** and **!** with only **imm bit** operands are interpreted by the compiler exactly like the logical operators **&**, **|** and **~**. There is little sense converting such bit operands to integers, evaluating the arithmetic expression and then converting back to a bit. Since evaluation of **&&** and **||** in bit expressions is not from left to right as expected, but depends on which operands in the expression change, their use and the use of **!** in expressions where all operands are **imm bit** is deprecated and causes a warning.

2.4.4 Conditional Operators

The operators **? :** implement conditional expressions, which are evaluated as a whole in an arithmetic context. The conditional expression

```
expression_1 ? expression_2 : expression_3
```

is a valid *immediate* arithmetic expression, which is triggered by a change in any *immediate* variable in any of the three sub-expressions. An alternate form of conditional expression, which leaves out the middle expression is allowed by modern C compilers, particularly by **gcc** and is allowed in *iC* (if the C compiler used supports the construct)

```
expression_1 ? : expression_3
```

The following excerpt from 'info gcc' explains the advantages and use of the construct:

> 5.8 Conditionals with Omitted Operands
>
> The middle operand in a conditional expression may be omitted. Then if the first operand is non-zero, its value is the value of the conditional expression.
>
> Therefore, the expression
>
> ```
> x ? : y
> ```
>
> has the value of `x' if that is non-zero; otherwise, the value of `y'.
>
> This example is perfectly equivalent to
>
> ```
> x ? x : y
> ```

In this simple case, the ability to omit the middle operand is not especially useful. When it becomes useful is when the first operand does, or may (if it is a macro argument), contain a side effect. Then repeating the operand in the middle would perform the side effect twice. Omitting the middle operand uses the value already computed without the undesirable effects of recomputing it.

2.5 Function and macro calls

Immediate expressions may contain function calls for several types of functions and macros. All of these look very similar to C function calls. The differences will be discussed in later chapters. These can be:

1. Built in *iC* function calls. The parameter ramps and return values are pre-defined.
2. User defined *iC* function block calls. These must be defined by the user before they are called.
3. C function calls.
4. C pre-processor macro calls.

C function and macros called in immediate expressions may only have **int** parameters (if any) and an **int** return value. They should be declared as follows to evoke an error message if the function name is mistyped or the parameter ramp or return value is wrong:

```
extern int rand();           // C function with no parameters
extern int rand(void);       // alternative syntax
extern int abs(int);         // C function with 1 parameter
extern int min(int, int);    // macro with 2 parameters
```

When 'strict' is active, any C functions or macros, which are called in *immediate* expressions must be declared in the *iC* code. If 'strict' is not active, mistyped function names with any type of parameter ramp look like C function calls and will be compiled as such without error. This error is not discovered until link time. With an **extern** declaration, a clean error message is produced and the extra effort is not great. When a pre-declared C function or macro is called in an immediate expression, a check is made, that the number of parameters is correct. Otherwise an error message is issued.

If declared a second time, the following will evoke a warning if 'strict'

```
extern bit rand();           // wrong return type – converted to int
```

If declared a second time, the following will evoke an error if 'strict'

```
extern int rand;             // not used as a function
extern clock rand();         // absolutely wrong return type
extern timer rand();         // absolutely wrong return type
```

No check is made for C function calls in C fragments controlled by **if else** or **switch** statements or other literal C code, since the compilation is handled by the follow up C compiler. Note: built in *iC* functions and *iC* function blocks can not be called in such C fragments under any circumstances.

2.6 Parentheses

In *immediate C* it is possible to write mixed arithmetic and bit expressions, nested to any depth using the usual precedence rules and parentheses.

Immediate arithmetic expressions are evaluated as a whole C expression, every time one of their component *immediate* variables changes – but only then. To improve execution speed, it is sometimes more efficient to break up very long *immediate* arithmetic expressions with many operands into several sub-expressions – particularly if each sub-expression is triggered by different operands. In this case not all the sub-expressions are executed. On the other hand there is a certain amount of overhead for triggering each new node and execution of a compiled C expression is fast, even if it has many operands.

Immediate bit expressions are compiled into a network of forward looking nodes, one for each different bit operand and execute even more efficiently. There is no need to break up a complex immediate bit expression into sub-expressions – the compiler does this already. *Immediate* bit expressions embedded in an arithmetic expression are compiled into separate sub-expressions and only the type converted arithmetic result is used in the arithmetic expression.

2.7 Immediate statements

Most *immediate* statements are *immediate* declarations or *immediate* assignments terminated by a semicolon. *Immediate* declarations and assignments may be combined.

2.7.1 *Immediate* Assignments

Immediate assignments are assignments of *immediate* expressions to *immediate* variables external to all functions. Value changes to an *immediate* variable are detected in the assignment and this event triggers the re-calculation of follow on expressions. Like in C, an *immediate* assignment is also an *immediate* expression, which means that assignments embedded in expressions are allowed. As noted earlier, *immediate* assignments can be combined with the declarations of *immediate* variables.

2.7.2 Aliases

Immediate arithmetic and bit assignments, in which the right hand expression consists of only a single *immediate* variable are accepted by the *iC* compiler, but produce no code. This type of statement is called an alias. The alias name on the left hand side is simply an alternative name for the *immediate* variable on the right hand side. Any reference to the alias will be substituted by the right hand side variable, whose value is always the correct *immediate* value of the intended assignment. Bit aliases may be either *normal* or *inverting*. The bit *not* operator **~** does not produce any code when used on an **imm bit** operand. All **~x** sub-expressions are implemented as inverting aliases of **x**. Thus the direct assignment of **~x** to another **imm bit** variable is also an (inverting) alias.

```
imm bit a, b;       b = a;    // b is an alias for a   (normal)
imm bit x, nx;      nx = ~x;  // nx is an alias for ~x (inverting)
imm int j, k;       k = j;    // k is an alias for j
imm int two;        two = 2;  // two is an alias for 2
```

2.7.3 The single assignment rule

Immediate assignments must obey the single assignment rule, a rule which applies generally for data flow systems[1]. Any *immediate* variable may only be assigned in **one** *immediate* assignment. The value of an *immediate* variable is the value of the expression, from which it is assigned, at all times. A second assignment to the same *immediate* variable would force different values on that variable, causing a conflict. The *immediate* variable being assigned cannot hold different values simultaneously. The single assignment rule is monitored by the *iC* compiler. An error message is generated if it is broken.

Expressions that occur in C code triggered by *immediate* conditional *if else* or *switch* statements or in C functions in literal blocks may contain *immediate* variables. These expressions are not *immediate* expressions and are not triggered by those variables. When such an expression is executed in the C code, the current value of any *immediate* variable is used.

Immediate variables may even be assigned in C code embedded in *immediate* conditional *if else* or *switch* statements and in literal blocks. Such an assignment is **not** an *immediate* assignment – the value is changed when the C statement is executed. Nevertheless any change in the *immediate* variable assigned in the C code will trigger *immediate* expressions that contain that variable. Several such assignments to the same *immediate* variable may be made inside different sections of C code. Every new assignment changes the variable in accordance with the intended algorithm. *Immediate* variables used in C code must be declared as **immC bit** or **immC int** in an *iC* code section. An *immediate* variable that is assigned in C code may not also be assigned in an *immediate* assignment.

2.8 Immediate control statements

An *immediate* conditional *if else* statement and an *immediate switch* statement are the only control constructs available in *iC*. The syntax of both statement types is similar to their C counterpart, except that braces around the C statements are mandatory. In particular an *else if* is not allowed, since the *if* after the *else* would have been part of the C statement controlled by the *else* part of the whole *immediate if* statement, which would be very confusing.

```
if (imm_bit_expression) { C_statement_1 }
if (imm_bit_expression) { C_statement_1 } else { C_statement_2 }
switch (imm_int_expression) { C_statement }
```

[1] see Werner Kluge: The organization of Reduction, Data Flow, and Control Flow Systems - pp. 317. The MIT Press 1992. [Kluge92]

These are valid *immediate* statements when they occur external to any function and when the controlling expression is an *immediate* expression. The controlling expressions in *immediate* conditional *if else* or *switch* statements are synchronized by a clock. The default clock is **iClock**. Other clocks or timers may be specified as explained in section 5. In all cases any change in the controlling *immediate* expression, synchronized by the controlling clock, triggers execution of the C statements.

2.8.1 *Immediate* conditional statement

immediate conditional statements use the keyword ***if*** and optionally ***else***. The controlling expression for an *immediate* conditional statement is an *immediate* bit expression. If not, it is converted from **int** to **bit** automatically. A **0** to **1** transition or rising edge causes C_statement_1 to be executed. A **1** to **0** transition or falling edge causes C_statement_2 to be executed (if an *else* is coded). The C_statements are embedded C compound statements, **not** *immediate* statements.

```
%{
int a, b, c;                /* C declarations in a literal block */
void reset(void);           /* C function declaration */
%}

imm bit sw1, sw2, sw3;      // immediate declarations

if (sw1 & sw2 | sw3) {      /* imm controlling expression */
  a = 1; b = 12; c = -2;    /* C code executed on rising edge */
} else {
  reset();                  /* C code executed on falling edge */
}
```

2.8.2 *Immediate switch* statement

For the *immediate switch* statement, the controlling expression is an *immediate* int expression. The C_statement is an embedded compound statement, which has the usual form of a C switch statement with case labels. Any change in the controlling expression triggers the switch statement. The value of that expression after the change is applied to the switch and the selected case is executed.

```
%{ enum Fuzzy { OFF, DIM, MEDIUM, BRIGHT }; %}  // literal block
switch (brightness) {        // declared and assigned above
  case OFF:    lightVoltage(0);   break;
  case DIM:    lightVoltage(10);  break;
  case MEDIUM: lightVoltage(18);  break;
  case BRIGHT: lightVoltage(24);  break;
  default:     lightVoltage(24);  break;
}                            // end of immediate switch statement
```

The *immediate* conditional *if else* and *switch* statements open the way to trigger the execution of short C fragments on particular events. These events are either rising or falling edges of bit values or changing arithmetic values. If more than a fragment of C code is involved, it is good practice to code this in a C function, and to call that function in the *immediate* statement. Very long *immediate* statements would make the purpose of those statements unclear. Depending on the time critical nature of the application, C code should not take too long to execute, because during the execution of such C-fragments the processing of other immediate events is held up.

2.9 Literal blocks

Literal blocks are sections of C code enclosed in special braces **%{** and **%}**. They may occur before, between and after any *immediate* statements. Literal blocks are copied verbatim to the front of the generated C output code (without the special braces). Literal blocks are useful to declare any C variables, define macros and to declare and define auxiliary C functions to support the application. Any C-pre-processor statements such as **#include** or **#ifdef** must be written as **%#include** or **%#ifdef** in the literal block. The **%#** must be written without intervening spaces. The **%** is dropped by the *iC* compiler in copying the literal block to the generated C code. This allows C-pre-processor statements for the *iC* sections of code which are resolved before the *iC* compilation.

```
%{
%#include <math.h>          /* special iC-pre-processor syntax */
int x, y, z;                /* declarations in a literal block */
int abs(int);               /* C function declaration */
%}
```

The run-time system will call the function **`iCbegin()`** when an *iC* application is started before any *immediate* processing. This function can be provided by the user in a literal block. If it is not provided, an empty function **`iCbegin()`** returning 0 is provided by the system. User implementations should return 1. One use of **`iCbegin()`** is to initialise **`immC`** variables. It may even contain a fork() call to spawn a child process, which will run in parallel with normal immediate processing. This opens up the way to build mixed applications using conventional multi-process or multi-threaded control strategies in parallel with *immediate* C code, which leaves a lot of CPU time to do other things.

The complementary function **`iCend()`** is called by the run-time system when an *iC* application is terminated externally (*iC* applications never terminate by themselves). **`iCend()`** could be used to free memory allocated with *malloc* or *new*.

```
%{
int iCbegin() { ...; return 1; } /* optional C initialisation */
int iCend()   { ...; return 1; } /* optional C termination */
%}
```

If the code in literal blocks, or code in C blocks controlled by an *immediate if else* or *switch*, is specifically C++ code, then the generated code must be compiled by a C++ compiler. The Code generated from the *iC* statements is pure C code.

2.10 Comments

C style comments **`/* ... */`** can be used anywhere between tokens of *iC* programs. C++ style comments may be used at the end of *iC* lines. **`// ...`**

Some older C compilers do not support C++ comments, so their use in literal blocks and C statement blocks controlled by *if else* or *switch* may lead to portability problems.

2.11 Scope of immediate statements

Immediate variables are global or static and must be declared external to all functions like other global variables in C. Moreover all *immediate* statements must also be placed external to functions. A statement in a function is only executed (made active) during the execution of that function. *Immediate* statements are active at all times.

Consecutive *immediate* statements are **not** executed in sequence. Each *immediate* statement is independent of all other *immediate* statements. They can be placed in any order, without influencing the behaviour of the program. This is analogous to the placement of global variables and functions in C.

Immediate assignments are often combined with their declarations and look like the initialization expressions of ordinary global C variables. In C, this initialization takes place before the function *main()* is started. In *iC*, *immediate* statements simply stay active until the program is stopped. For most of the time the process running the *iC* program waits in a select() call, which wakes up whenever an external input or internal timer changes. Because the processing required to react to such an input is in the order of microseconds, this strategy ensures that the CPU loading of an *iC* process is minimal. This can be observed easily with tools like *xosview* under Linux. Times measured with a modern 1.8 GHz processor were > 100 us, which is mostly overhead to get the input process scheduled. The time to even execute a chain of 10 consecutive events is of the order of 10 us. This corresponds to a 0.1% loading for a process including a 100 ms timer, of which 0.01% is actually used by the *immediate* statements.

```
/* VERY SIMPLE WASHING MACHINE PROGRAM */
imm bit on;                  // switch to turn system on/off
imm bit waterLo;             // water level switch
imm bit tempLo;              // thermostat, turns off when hot
imm bit fill = on & waterLo; // fill with water until filled
imm bit heat = on & ~waterLo & tempLo; // heat water when filled
```

2.12 Intrinsic limitations of immediate statements

Arrays of *immediate* variables have been realized and will be covered in the next chapter. Structures containing *immediate* variables have not been realized in the current release, although they are possible and may be implemented in a future release. Pointers to *immediate* variables in *immediate* expressions are semantically indeterminate. They are therefore not implemented. This is also pointed out in one of the recommendations in the IEC-1131 standard, which justifies the language 'Structured Text' instead of C on the grounds, that a pointer in a machine control program has no meaning and could cause disaster. The same limitation has been recognized in the language Java, which only recognizes references as constant pointers.

Immediate assignments, in which the left hand side variable appears in the right hand side expression are of very doubtful utility. Such a statement expresses a very tight feedback loop, which will either lock up, or generate a high speed oscillator. For this reason a warning message is generated by the *iC* compiler.

```
imm bit a, b;
a = a & b;                    // a locks up when b becomes 0
b = ~b | a;                   // b oscillates when a is 0
imm int j;
j = j + 1;                    // j never catches up with itself
```

For the above reason the C assignment operators **+=**, **-=** etc. as well as **++** and **--** cannot be used in *immediate* statements. Feedback over several statements is allowed, but oscillations are controlled so that the system does not become compute bound. If oscillations do occur, a runtime warning is produced since they are probably not intended.

Like in any programming language, it is possible to write incorrect *iC* programs. It is the job of the programmer, to understand the model on which the execution of the *iC* language constructs is based, and to create programs that use these constructs correctly. *iC* is modelled on hardware building blocks, which provides an easy starting point.

The following was probably intended by the last statement above:

```
imm bit gate, p;
imm int j;                    // j counts every rising edge
if (gate & p) { j++; }        // of p, while gate is hi
```

In this example, `gate & p` is an *immediate* expression that triggers execution of the *non-immediate C* statement `j++;` Assignment operators **+=**, **-=** etc. as well as **++** and **--** with *immediate* variables are allowed in embedded C statements. The above construct is one way to implement a counters in *iC*. A better way is shown in section 4.9.

2.13 Pragmas

Pragmas affect the compilation phase of an *iC* program. Pragmas are introduced by the keywords **use** and **no**.

use	turns a pragma option on
no	turns it off

Currently two pragmas are implemented in *immediate* C: **alias** and **strict**.

```
use alias;            // equivalent to -A command line option
no alias;             // turn alias option off

use strict;           // equivalent to -S command line option
no strict;            // turn strict option off
```

1. The **alias** pragma or -A command line option forces the compiler to generate a node for each alias in the generated C-code (default is to generate no node). This is needed in two circumstances:

   - It is required, if an *iC* source refers to an alias in another *iC* source by an **extern** reference. Since all references to aliases are normally removed from the compiled code, the C-object modules, which are generated from such code could not be linked. With the **use alias** option, the code can be linked and the remaining aliases are resolved at start up.

   - The **use alias** option is also useful for debugging. Only when it is set, are alias names displayed as active words by **iClive**.

2. The **strict** pragma or -S command line option forces the compiler to expect a declaration of all *immediate* variables, before assignment. The default with **no strict**, is to generate an **imm bit** node for an assignment to an undeclared name. Similarly an assignment to an undeclared name from a CLOCK() or TIMER() function call results in a default **imm clock** or **imm timer** variable. Such laxness is OK for small single source projects, but can lead to problems with larger projects. I had a case in a large project, where I had declared a number of **imm int** variables and mistyped one of them, so the correct name was not declared. This name was then assigned - but converted to **imm bit** and then back to **imm int** when used, leading to incorrect arithmetic.

   As noted earlier, C functions and macros should be declared extern with their correct parameter ramp and return value. When "strict" is active, error messages are output if an undeclared C function or macro is called in an *immediate C* expression.

Several options (currently only two) may be set or reset together in one pragma call:

```
use alias strict;   // equivalent to -AS command line option
no strict alias;    // turn both options off
```

It is recommended to write

```
use alias strict;
```

as the first line of all production *iC* programs - the space overhead for extra alias nodes is insignificant and debugging becomes much easier. Particularly the **strict** option is highly recommended anyway and results in no binary overhead. (Grateful acknowledgements to the designers of PERL).

The scope of these pragmas is a file. If a pragma is enabled in one file it carries over to an included *iC* header file. If on the other hand a pragma is changed in a header file, it reverts to its previous value in the *iC* file after the #include statement, which includes the header file. This makes sure that sloppy *iC* programs, which include a header file, which uses "**strict**" syntax, will not report errors, because they do not follow the "**strict**" syntax. This scope feature can only be used successfully with the **use strict** pragma, since **use alias** only comes into effect during C code generation – at this point the complete source has been parsed. This means **use alias** should definitely be used once in *iC* programs, which consists of several parts with extern references between them. Other single source *iC* programs can **use alias** , which produces slightly larger code, but which can be debugged without recompiling with the -A flag.

3 Arrays

Arrays in conventional instruction flow languages are a named collection (often of fixed length) of similar variables, which are accessed by an index expression, eg a[5]. Each such entity is an individual object, but in instruction flow languages the index is often a variable, which is manipulated in a loop and references to the individual indexed entities occur sequentially, as in the following C example:

```
for (n = 0; n < 4; n++) {
     a[n] = b[n] * c[n];
}
```

3.1 Immediate Arrays

In data flow languages like *immediate C* loops at run-time are meaningless. Each *immediate* variable is an entity, which is controlled by one assignment statement. The variable changes, when a variable in the expression of the controlling statement changes and not when some loop runs. It is well to remember, that *immediate* variables and their controlling expressions are more like IC building blocks connected in a static network. In that sense *immediate* Arrays are like hardware registers.

Arrays may be defined in *immediate C*, but each entity acts individually at run-time, which means that an individual *immediate* object must be generated for each *immediate* array member.

3.2 Use of immediate Arrays

Arrays in conventional languages as well as in *immediate C* give programmers extra capabilities to express themselves. These fall into two distinct categories:

1. Arrays allow the writing of repeated similar statements as one statement – this saves a lot of writing, but could also be done without arrays.
2. Additionally arrays allow the parametrisation of the array length, both within the program and in the command line of the program, which is probably more important. For *immediate C*, this makes possible the writing of control programs in which the number of control elements or groups is variable and the actual number is not bound until compile time. This would not be possible without arrays in the language.

   NOTE: the definition of dynamic arrays, whose sizes change at run-time is meaningless and not possible in *immediate C*.

An example of the usefulness of arrays in the language would be an *iC* program controlling lifts in a building. The number of floors varies from building to building – so do the number of parallel lifts, which may be required. With arrays, a single *iC* program can be written, which can be compiled for a different number of floors and a different number of parallel lifts as follows:

```
immac -P FLOORS=12 -P LIFTS=2 liftControl.ica
```

3.3 Implementation of immediate Arrays

Since each immediate array member is an individual immediate object at run time, it is important for debugging with **iClive** to be able to have a listing showing each individual array member – not just its collective form, eg a[n]. To achieve this, an *iC* program containing arrays is translated by the pre-processor **immac** to *iC* code without arrays. This is a simple text operation in which macros are expanded, loops are unrolled and index expressions are evaluated.

The *iC* language with arrays has three additional language extensions:

1. C-style 'FOR loops', which define a loop variable and a range.
2. Index expressions in square brackets, which allow the definition of array variables – usually in a loop.
3. Macro definitions, which are processed directly by **immac** - can be defined in two ways:
   - in C-pre-processor style with **%define** instead of **#define**, eg
     %define FLOORS 12
   - in the command line, just like for a C compiler, eg
     -P FLOORS=12

Macros will mostly be used inside the square brackets of an array variable or in the control line of a FOR loop, but they can be used anywhere in the *iC* code or in the definition of another **%define** macro – macros may be nested. The above implies, that the **immac** pre-compiler could be used as a macro pre-processor for *iC* programs without any arrays at all.

iC programs containing the above three extensions are called *iCa* programs and should be written in a file with the extension .ica – the **immac** pre-compiler translates an *iCa* program to an *iC* program with the extension .ic in which macros and 'FOR loops' are expanded and *immediate* array instances are converted to simple *immediate* variables. The following *iCa* snippet in file lift.ica

```
%define FLOORS 4

FOR (n = 0; n < FLOORS; n++) {
    imm bit a[n] = b[n] & c[n];
}
```

expands to the following *iC* file lift.ic when compiled by **immac**:

```
imm bit a0 = b0 & c0;
imm bit a1 = b1 & c1;
imm bit a2 = b2 & c2;
imm bit a3 = b3 & c3;
```

The 'FOR loop' is executed at compile time and generates repeated copies of the statement(s) in the compound statement controlled by the loop. This only makes sense, if there are elements in the loop statement(s), which are modified by index operations using the control variable of the 'FOR statement' – in the above example that is the variable **n**.

The translation of indices in square brackets is carried out in two steps:

1. The expression in square brackets is evaluated as an integer expression.
2. The numerical value produced replaces the square brackets and the expression it contains.

In the above example the index expressions are simply the variable **n**. But the index expressions can be more complex. A feature of *iCa* indexing may seem strange at first, but it turns out to be very useful; the square bracketed index expression may be placed anywhere in a word, not only at the end of a word. It may even be placed on its own – in that case the expression is evaluated and becomes a suitably modified integer constant in an *iC* statement. The following example shows both:

```
FOR (n = 0; n < 10; n++) {
    QB[n] = IB[n+1] * [n+2];
    QX[n/8].[n%8] = IX[n/8].[n%8] & IX[10+(n/8)].[n%8];  // out: [n]
}
```

expands to:

```
QB0 = IB1 * 2;
QX0.0 = IX0.0 & IX10.0; // out: 0
QB1 = IB2 * 3;
QX0.1 = IX0.1 & IX10.1; // out: 1
QB2 = IB3 * 4;
QX0.2 = IX0.2 & IX10.2; // out: 2
QB3 = IB4 * 5;
QX0.3 = IX0.3 & IX10.3; // out: 3
QB4 = IB5 * 6;
QX0.4 = IX0.4 & IX10.4; // out: 4
QB5 = IB6 * 7;
QX0.5 = IX0.5 & IX10.5; // out: 5
QB6 = IB7 * 8;
QX0.6 = IX0.6 & IX10.6; // out: 6
QB7 = IB8 * 9;
QX0.7 = IX0.7 & IX10.7; // out: 7
QB8 = IB9 * 10;
QX1.0 = IX1.0 & IX11.0; // out: 8
QB9 = IB10 * 11;
QX1.1 = IX1.1 & IX11.1; // out: 9
```

As shown above, index expressions may even be used in comments. This can be useful, because the expanded *iC* text must later be used for debugging with iClive – the original text with 'FOR loops' and index expressions is not meaningful for following the values of actual nodes at run-time. The above example already gives a hint of how much writing can be saved. The way I/O bit variables following the IEC-1131 standard are expanded is particularly useful.

The *iCa* extensions to the *iC* language can be embedded as additional lines in regular *iC* code. A FOR statement and a %define macro definition may **not** be embedded in the middle of a line of *iC* code – not even between *iC* statements, which have been written in one line. This limitation is similar to the limitations imposed by the C pre-processor **cpp** on the C language.

3.3.1 FOR loops

'FOR loops' follow the syntax of C 'for statements' with the difference, that the controlled *iC* statements **must** be enclosed in braces (which is also required for *immediate* **switch** and **if else** statements):

```
FOR (expr1; expr2; expr3) {
  iC statement(s), which are repeated under control of the loop
  or nested 'FOR loops'
}
```

Other restrictions are:

1. The controlling FOR (;;) must be written in a single line.
2. The opening brace may follow the FOR (;;) on that line or must be written by itself on the next line.
3. The closing brace must follow any *iC* statement(s) on a line by itself.
4. The 'FOR statement' line and the lines containing braces controlled by the 'FOR statement' may finish with a C or C++ comment (a C comment must finish on that line). There may be no leading or embedded comment(s).
5. A 'FOR statement' may only use one control variable, which is an **int** by default:

   FOR (n = 0; n < 10; n++**) or FOR (int** n = 0; n < 10; n++**)**

   The control variable is the first 'word' of expr1, which is not '**int**' followed by '='. The word '**int**' in the second form is optional and can be written to remind programmers, that the control variable is an integer. The control variable may not be declared anywhere else.
6. Other atoms in the three expressions must be either constant expressions or expressions which contain control variables of the current and of outer 'FOR loops'. All expressions may contain macros, which must expand to integer constants or expressions containing valid loop control variables. Under no circumstances may *immediate* variables be used in these expressions.
7. The names of control variables must be different from any *immediate* variable.
8. The scope of the control variable of a 'FOR loop' begins when the control variable is initialised in the 'FOR statement' and ends with the final matching brace. The control variable is not valid outside of this scope.

Since **immac** is implemented as a Perl script, an alternate Perl type of 'FOR loop' may be used, although its use is deprecated. For completeness it is described here.

```
FOR n (<Perl type list>) {
  iC statement(s), which are repeated under control of the loop
  or nested 'FOR loops'
}
```

Similar restrictions to those above apply. The variable after the 'FOR' is the loop control variable. It may optionally be preceded by the word 'int'. The control variable is given each value of the 'Perl list' for each iteration of the loop. Some powerful manipulations are possible with this form.

```
FOR int n (0 .. 3) {
     a[n],\
}
```

produces

```
a0, a1, a2, a3,
```

whereas the following loop

```
call(\
FOR n ("abc", "def", "ghi", "jkl") { // list of strings
    [n],\
}\
 );
```

produces

```
call( abc, def, ghi, jkl, );
```

As shown in the two examples above, lines terminated by a back-slash (\) are output without starting a new line – this make it possible to generate lists in a single line. This applies both outside and inside 'FOR loops'. The end of the 'FOR loop' will terminate such a generated list, unless the final brace of the 'FOR loop' is also followed by a back-slash (\) as shown in the generated function block call statement in the last example above. The last parameter in that generated call statement is followed by a comma, which is allowed in *iC* for parameter lists.

Comma separated lists in normal and extern declarations must be terminated by a semi colon. They may not have a comma followed by a semi colon '**,;**' at the end. To achieve this, a special characteristic of *iCa* index expressions is used (see next paragraph). The value in square brackets may be strings as well as numbers, since they are actually generated by Perl code. To generate a variable length – single line – declaration, use the following:

```
%define MAX    5   // iCa macro explained in section 3.4

imm bit\
FOR (n = 0; n <= MAX; n++) {
    a[n] [n < MAX ? "," : ";"]\
}
```

produces

```
imm bit a0, a1, a2, a3, a4, a5;
```

Each execution of the second conditional index expression `[n < MAX ? "," : ";"]` in the loop for `n < 5` produces a single comma, which is appended – the last execution of the index expression produces a semi colon. For this to work, the first string must contain a comma – the second string can be any value – even the empty string `""`.

The 'FOR statement' line of both types of 'FOR loop' and the lines containing the associated braces are not copied to the target except as comment lines, if the **-a** option is active for the **immac** compiler.

3.3.2 Index expressions

Index expressions are expressions in square brackets usually involving integer constants and loop control variables. Unlike in other languages these 'index' expressions can be placed anywhere in the *iC* code – not just as an index of an array variable. *immediate* array variables cannot even be declared directly – they come into existence as simple immediate variables by evaluating the index expression and replacing the square brackets by the numeric or string result of that evaluation. The underlying simple *immediate* variables must of course be declared (unless `not strict`) – this is best done as follows:

```
FOR (n = 0; n < 10; n++) {
  imm bit a[n];
}
```

Normally the square brackets are placed after a name, which then makes the array variables look like those in C. But there are special cases where the square bracketed index expression is placed somewhere else, as we saw in the earlier examples (computing IEC-1131 I/O variable names).

The semantics of index expressions is, that the expression in square brackets is evaluated during compilation and the numerical or string result replaces the square brackets and the expression they enclose. When the index expression is a simple array reference, this produces a name followed by a number.

Normally index expressions occur in *iC* code in a 'FOR loop'. I deliberately say *iC* code and not *iC* statements, because 'FOR loops' are used not only to generate lists of statements, but also lists of parameters – both for the definition and the call of function blocks, whose parameter lists can be varied at compile time. Another use is varying constant parameters. Inside a 'FOR loop' or a nest of 'FOR loops', the *iC* code usually use the 'FOR loop' control variable(s) in the index expression(s) to make each repeated *iC* code line different.

For index expressions in *immediate C* code outside of a 'FOR loop', the expression must be a constant expression – no variables are allowed (remember no 'FOR loop' control variables are in scope anyway). Nevertheless an *iC* variable, which must be used as an indexed array variable inside a 'FOR loop' looks better if it follows the same syntax outside of the loop. The variable **a[1]** could of course be written as **a1** – this is the same immediate variable. But inside a loop it must be written as **a[n]** and only the varying value of **n** will produce **a0 a1** etc.

Index expressions in embedded C code – either in a literal block or in a compound C statement contolled by an *immediate* **if else** or **switch** statement may have index expressions, but they are part of the C code and are not changed except index expressions, which contain an in-scope FOR loop control variable. This means that the translation of constant index expressions – as described in the previous paragraph - are not carried out in embedded C code. In the rare instances where such a translation is needed, it must be done manually – write **a1** instead of **a[1]**.

A special case in embedded C code occurs, if a numerical value generated by the control variable of a FOR loop must be placed inside the square brackets of a C array reference. This can be done by simply embedding the iCa index expression in the C index expression – eg:

```
if (IX0.0) {
  int carray[3];          // start of embedded C code
  FOR (n = 0; n < 3; n++) {
     carray[[n]] = icarray[n];
  }
}
```

produces

```
if (IX0.0) {
  int carray[3];          // start of embedded C code
  carray[0] = icarray0;
  carray[1] = icarray1;
  carray[2] = icarray2;
}
```

As can be seen in the above example, *iCa* 'For loops' may be embedded in C code – this is the reason why the keyword '**FOR**' was chosen instead of '**for**' – the C code may also contain C for statements.

3.3.3 immediate Array syntax

To sum up, immediate arrays are not declared as such – variable names are used with index expressions in square brackets. The programmer must be aware that this generates simple immediate variables starting with the array name followed by a number. Such generated variable names cannot be used anywhere else – this would show up as a multiple declaration during *iC* compilation. If we use a one-dimensional array in an *iCa* program – eg **sa**, any array reference will simply have a number appended to the array name in the generated *iC* code.

```
i = 2,          sa[i]   produces sa2
i = 22,         sa[i+1] produces sa23
```

A special case are multi-dimensional arrays. If we use the standard C syntax to write a multiple array reference, eg **ma[i][j]**, and the **immac** pre-processor did not take special action, we would get the following compile resolution for the following pairs of index values:

```
i = 2,  j = 34   ma[i][j] would produce ma234 // NOT output
i = 23, j = 4    ma[i][j] would produce ma234 // NOT output
```

This would be unsatisfactory, because it is ambiguous – therefore **immac** inserts a letter **x** between adjacent index expressions, producing the following output instead:

```
i = 2,  j = 34   ma[i][j] produces ma2x34
i = 23, j = 4    ma[i][j] produces ma23x4
```

This is no longer ambiguous. Any multiple index is separated by an **x**, which is easily recognised in the generated *iC* code as a member of a multiple-dimensional array – even the numerical index values can be recognised easily in the generated names.

Both in C and by analogy in *immediate C* with arrays (*iCa*), array names and the index expressions in square brackets (and of course the expressions in the square brackets) may be separated by spaces and tab's – as follows:

```
i = 2,  j = 34    ma   [ i ]  [ j ]   still produces ma2x34
i = 23, j = 4     ma   [ i ]  [ j ]   still produces ma23x4
```

One caveat applies for **immac**: *such an array name with all its subsequent square bracketed index expressions must be in the same line.* (In C any sort of white space is allowed).

Another case where **immac** inserts an extra character are array names which finish with a numeral. This could also lead to ambiguity if special action were not taken:

```
i = 2,            sa9  [ i ]          produces sa9y2
i = 22,           sa9  [ i+1 ]        produces sa9y23
```

Although the way **immac** handles array names, which finish with a numeral avoids ambiguity, such names should be avoided, because in the generated *iC* code they look too much like expanded array names with an extra index, which could easily lead to clashes. To avoid this clash a **y** is inserted in this case.

String index expressions in square brackets, which contain a string value in parentheses, eg

```
[n < MAX ? "," : ";"]
```

are not separated from an adjacent index expression by **x** or **y**.

In every case, the names generated from single- and multi-dimensional array references are well formed *iC* variables, which show their name and index value(s). The main thing to remember with array references is, that every array reference translates to a simple *iC* variable name, which shows up in the generated *iC* code, which will normally be a lot longer than the *iCa* code, but which must be used for live debugging with **iClive**. The mental translation between indexed array references and the resolved *iC* names is so simple, that it should not cause any problems to the user.

3.4 immac Macro facility

The pre-compiler **immac** provides a light weight macro facility very similar to that provided by the C pre-processor **cpp**. Only simple word macros may be defined, but not macro's with parameters. The keyword to introduce an **immac** macro definition is **%define** not **#define** – that is reserved for **cpp**, which can also be used in conjunction with the full *iC* compiler **immcc**.

```
%define LENGTH 4
```

The same macro term **LENGTH** could also be pre-defined in the command line with the **-P** option:

```
immac -P LENGTH=8
```

Unlike **cpp**, the definition in the command line has precedence over the definition with a **%define** line in the program. This allows *iCa* programs to define default values for macro terms, which can be re-defined in the command line. Macro definitions can be any sort of text, which may also include previously defined macros. For replacement as index values, they should of course reduce to numeric values.

```
%define WIDTH  (5+1)                  /* C comment */
%define AREA   (LENGTH * WIDTH)       // C++ comment
```

As shown above **%define** lines may be terminated with a C or C++ comment. As with 'FOR loop' control lines, a C comment must finish on the **%define** line. Also the **%define** lines are not copied to the target except as comment lines, if the **-a** option is active for the **immac** compiler.

Macro replacements may be made in all parts of the *iCa* code. They are of course particularly useful to parametrise the termination of a 'FOR loop' and hence the number of blocks of *iC* code, which is generated by the 'FOR loop'.

4 Built-in Functions

iC has a number of built in functions, which are so central to the operation of the system, that they have been made a part of the language. They are implemented as efficient building blocks in the supporting run time package. Functions, which could not be created from simpler *iC* statements are generated by the compiler – others are defined internally as built-in Function Blocks. All except the LATCH and the FORCE functions are 'clocked', which is analogous to similar functionality in hardware IC's.

4.1 Unclocked flip-flop or LATCH

The unclocked R-S flip-flop is the LATCH function with the following calling sequence:

```
LATCH(set, reset)
```

The following truth table describes the LATCH function:

set	reset	LATCH(set,reset) Q
0	0	Q
1	0	1
0	1	0
1	1	Q [2]

The LATCH function is particularly fast and efficient, using only a single gate node. It is of course possible to program a latch function with a pair of cross coupled OR gates. In *iC* this looks as follows:

```
imm bit set, reset, Q, Qbar;
Q    = set   | ~Qbar;
Qbar = reset | ~Q; 3
```

The disadvantage of this implementation is the fact that its function as a latch is hidden, that two gates are used and that Q and Qbar are both 1, when set and reset are 1 (which means that Qbar should never be used). LATCH clearly shows its function.

4.2 FORCE function

Closely related to the LATCH function is the FORCE function with the following calling sequence and truth table:

```
FORCE(arg1, on, off)
```

arg1	on	off	FORCE(arg1,on,off)
0	0	0	0
1	0	0	1
X	1	0	1
X	0	1	0
0	1	1	0
1	1	1	1

The FORCE function passes the value of arg1 to the output if both on and off are 0 (or both are 1). If only on is 1 then the output is forced to 1, independent of the value of arg1. Conversely if only off is 1 then the output is forced to 0. This function is useful for testing.

[2] Note the memory behaviour of a LATCH when both **set** and **reset** is 1

[3] Note for PLC programmers: the order of the **set** and **reset** statement has no influence on the output of flip-flops and latches as it does in sequentially executed PLC programs - even in the case of this latch example using two gates.

Note for deep thinkers: the following expression generates a LATCH function from a FORCE function. This is how a LATCH is generated by the *iC* compiler from the more fundamental FORCE function - using feedback of its own output to hold that value at its input, unless the 'on' or 'off' inputs force the output to a different value.

```
(temp001 = FORCE(temp001, set, reset))
```

4.3 Clocked D flip-flop

The simplest clocked flip-flop is the D flip-flop or delay memory element, a function having a single input, a clock input and an output equal to the input in the previous clock period.

```
D(expr, c)   or   D(expr)    /* default iClock used as clock */
```

The following truth table describes the D flip-flop:

expr D^n	D(expr,c) Q^{n+1}
0	0
1	1

The D flip-flop has become the most commonly used clocked flip-flop in hardware design. Its application is called for, when several logic expressions must produce synchronized outputs, so that any further logic done with these outputs does not suffer from timing races. A typical example is the implementation of a state machine. The D flip-flop is also a 1 bit memory element, which can store information from one clock period to the next. The D flip-flop is called for in any design where feedback is involved. The use of the clocked D flip-flop in *iC* will probably fall into a similar pattern.

Examples of statements using D flip-flops is the generation of a pulse on the rising edge of an input and of a pulse on a change of input.

```
imm bit    input;
imm bit    rise   = input & ~D(input);
imm bit    change = input ^  D(input);
```

The output 'rise' goes hi when 'input' goes hi and goes lo again when the output of the inverted D flip-flop goes lo after the next (implicit) clock pulse. The second example uses the exclusive-or operator ^ to generate a pulse on both the rising and falling edge of the input.

4.4 Clocked SR flip-flop

The memory element that is represented in most PLC instruction sets is the R-S flip-flop. This flip-flop has two inputs. The rising edge of the set input puts the flip-flop in the "one" state and the rising edge of the reset input puts the flip-flop in the "zero" state. Many books on switching theory describe a simple unclocked latch memory element by the name R-S flip-flop. Following the usage in IEC-1131, and because the set parameter precedes the reset parameter in the calling sequence, the clocked Set-Reset flip-flop was named SR flip-flop in *iC*:

```
SR(set, reset, c)
```

The following truth table describes the SR flip-flop:

set S^n	reset R^n	SR(set,reset,c) Q^{n+1}
0	0	Q^n
0/1	X	1
X	0/1	0
1	1	Q^n

The SR flip-flop implemented in *iC* differs marginally from the classical R-S flip-flop described in the literature, which has the disadvantage that Qn+1 is undefined for S and R both "one". The design rules stated that S and R must never be "one" together. Since this would cause unwarranted confusion the implementation with the above truth table was chosen, which gives identical results with designs following the rules of the classical R-S flip-flop. If the rule of both inputs "one" is ignored, the results are still easy to interpret. For the above reasons clocked R-S flip-flops are rare as integrated circuits.

4.5 Clocked SRX flip-flop

In practice the simple clocked SR flip-flop can be difficult to control under the following conditions:

A `0/1` set transition has occurred which sets the flip-flop and some time later a `0/1` reset transition occurs which resets it, while set is still a `1`. Even if reset goes back to `0`, the set input is not active again until it goes back to `0` and then to `1` again. This works well in many situations, but can be counter intuitive for which reason the SRX flip-flop or the JK flip-flop can be used more effectively.

`SRX(set, reset, c)` equivalent to `SR(set & ~reset, reset & ~set, c)`

The following truth table describes the SRX flip-flop:

set	reset	SRX(set,reset,c)
S^n	R^n	Q^{n+1}
0	0	Q^n
0/1	0	1
0	0/1	0
1	1	Q^n
1\0	1	0
1	1\0	1

When both set and reset are `1`, then both internal S and R inputs are `0`. If there is a `1\0` transition on either `set` or `reset`, then the alternate input has a `0/1` transition, which sets or resets Q.

4.6 Clocked JK flip-flop

Instead JK flip-flops were made, which toggled their output on every clock pulse, when J and K are both "one". In recent years even these have not been listed in the IC data books. A JK flip-flop has been implemented in *iC*. :

`JK(set, reset, c) equivalent to  SR(set & ~Q, reset & Q, c)`

The following truth table describes the JK flip-flop:

set	reset	JK(set,reset,c)
J^n	K^n	Q^{n+1}
0	0	Q^n
1	0	1
0	1	0
1	1	$\sim Q^n$

4.7 D flip-flop with Set and Reset

D flip-flops may have an optional reset input. Another option is to have both a set and reset input as well as the D input. The names of these variants indicate which parameters are required:

```
DR(expr, reset, c)
DSR(expr, set, reset, c)
```

For all built in functions, each parameter may have its own clock parameter. If a clock parameter is supplied it applies to all parameters on its left, which do not have their own clock. If no clock parameter is specified, the built in `iClock` is used.

4.8 Mono-Flop with optional Reset

The Mono-Flop, or SRT() function is a modified SR flip-flop, in which the output is internally connected back to a reset input. This internal reset is usually clocked by a TIMER, which is controlled by a delay parameter. The delay parameter may have a fixed or variable numeric value. The SRT output is reset, when the number of "TIMER" ticks corresponding to the value of "delay", when the SRT was set, has occurred. An additional optional reset parameter can reset the SRT mono-flop prematurely.

```
SRT(set, timer, delay)
SRT(set, reset, timer, delay)
```

Instead of clocking with a delay TIMER, any clock may be used. The SRT mono-flop is then reset on the next clock pulse after it has been set. When no clock is specified `iClock` is used, which produces a thin pulse, one clock period wide.

4.9 Sample and Hold

This function is a direct analogy of the clocked D flip-flop for arithmetic values. The arithmetic output equals the arithmetic input in the previous clock period.

```
SH(arithmeticExpr, c)
```

The sample and hold function can be used to sample fast changing arithmetic inputs at a constant clock rate. Other uses are the implementation of many useful constructs such as state machines, counters and shift registers, to name a few.

```
imm int count = SH(count + 1, c);    // count clock c pulses
// shift register with b as input in the least significant bit.
imm bit b;                           // b assigned somewhere else
imm int shift = SH((shift << 1) + b, c);
```

4.10 Sample and Hold with Set and Reset

The Sample and Hold function also comes with either reset or set and reset inputs. When the reset input is clocked, the output is set to all 0's. By analogy when the set input is clocked the output is set to all 1's. The inputs `set` and `reset` are **`imm bit`** expressions; whereas the main input `arithmeticExpr` and the output are **`imm int`**.

```
SHR(arithmeticExpr, reset, c)
SHSR(arithmeticExpr, set, reset, c)
```

4.11 Edge detectors

It is often useful to generate a pulse on the rising edge of a logic signal or on a change of value. These pulses should turn off at the next clock. In connection with the D flip-flop, expressions were shown which generate such pulses. Since these operations are quite important, more efficient functions RISE(expr,c), FALL(expr, c) and CHANGE(expr,c) are implemented in *iC*. The following statements achieve the same results:

```
imm bit input;
imm bit rise   = RISE(input, c);      // pulse on rising edge
imm bit fall   = FALL(input, c);      // pulse on falling edge
imm bit change = CHANGE(input, c);    // pulse on both edges
```

The CHANGE function is also implemented for arithmetic expressions (type **`int`**). The output is nevertheless of type **`bit`**.

```
imm int value;
imm bit arithmeticChange = CHANGE(value, c);
```

The **`bit`** variable `arithmeticChange` pulses every time `value` changes, qualified by the clock `c`. The clock limits the rate at which changes are recognized. This is often useful with numeric values, which may change at a high rate, and a slower sampling rate is called for.

The pulse outputs of all edge detectors are just long enough, so that they catch the next clock pulse after the edge, but only that one clock pulse - not more. When the output of an edge detector is used directly or indirectly as input of another clocked function with the same clock, correct synchronization is achieved.

NOTE: there is a significant difference between the output of the RISE function and the output of the SRT mono-flop. The output of the RISE function turns on with the rising input signal and turns off again on the next clock. The output of the mono-flop turns on with the next clock after the set signal and turns off with the next clock after that, which is one clock pulse later, assuming the same clock is used for set and internal reset. When the two clocks are different, which is usual for SRT mono-flops, the case is different again.

5 Clock Signals

There are two types of Clock signal, '**clock**' and '**timer**'. It is important to realize that Clock signals are not of the same type as logic or numeric signals of type '**bit**' or '**int**'. Clock signals are declared as follows:

```
imm clock myClock;
imm timer myTimer;
```

Under no circumstances may clocks be interconnected with logic or numeric signals. Any attempt to do so generates an error message. Clock signals in *iC* are best thought of as timeless pulses, whose occurrence marks the separation of one clock period from the next along the time axis. All clocked functions in *iC* follow the *Master-Slave* principle. The *Master* element in a D flip-flop follows the input. The output of this *Master* gate is transferred to the *Slave* element during the active phase of the next clock pulse. The output of the *Slave* element is the output of the D flip-flop. All *Master-Slave* transfers during one particular clock pulse are completed before more combinatorial logic or arithmetic expressions are executed. This insures that the outputs of all functions, which are synchronized by the same clock, change simultaneously as far as the logic is concerned.

Clock signals can come from four different sources:

1. The built-in **iClock**, which is signal type **imm clock**
2. The CLOCK function, which generates type **imm clock**
3. The TIMER function, which generates type **imm timer**
4. The TIMER1 function, which also generates type **imm timer**

5.1 Built-in immediate clock

There is a built-in *immediate* clock with the name **iClock**. This clock runs at the highest system rate. **iClock** is used as the default clock, when no other clock is specified. It may also be specified by the name **iClock** when no default clock is allowed by the syntax of a function call.

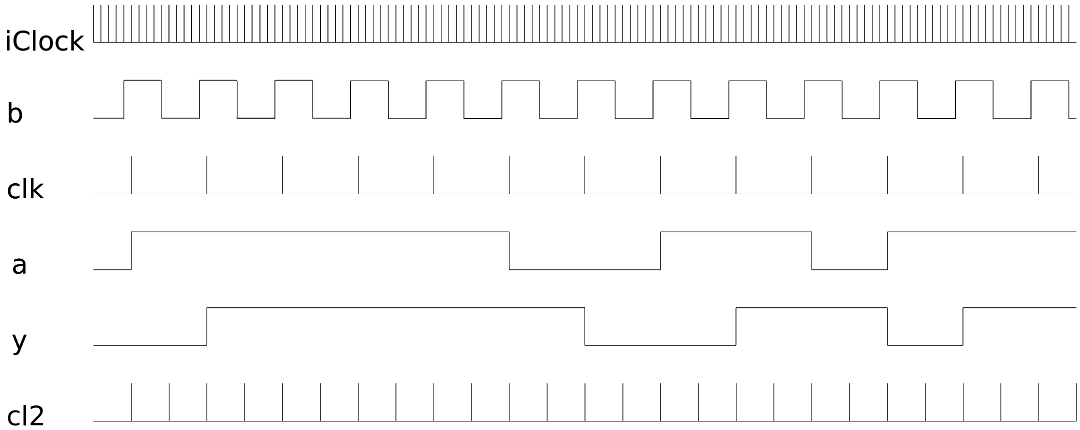
```
x = SR(a, b);       // Set and Reset clocked by built-in iClock

y = SR(a, iClock, b, myClock);     // clock for the Set argument
                                   // must be named if different
                                   // from the Reset clock
```

5.2 CLOCK function

The second source of clock signals is the CLOCK function, which has one or two logic inputs and an optional clock input. The CLOCK function produces an output **clock** pulse during the active phase of the input clock, which follows a 0 to 1 transition of one of the logic inputs. If no clock input is specified, **iClock** is used. All CLOCK outputs are synchronous with their input clock.

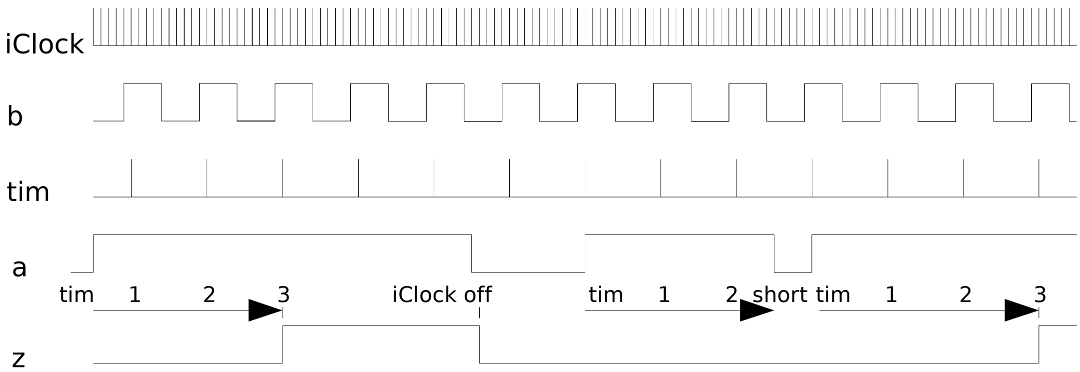
```
imm clock clk = CLOCK(b);    // 'clk' on the rising edge of b
                             // clocked by next 'iClock'(default)
imm bit   y   = D(a, clk);   // D flip-flop clocked by 'clk'
imm clock cl2 = CLOCK(b,~b); // clock on rising and falling edge
                             // of b, clocked by 'iClock'
```



5.3TIMER function

The third source of clock signals is the TIMER function, which also has one or two logic inputs and an optional clock input. The output generated by the TIMER function are of signal type **imm timer** and are generated in precisely the same way and at the same time as **clock** pulses from a CLOCK function with the same inputs. **timer** pulses differ from **clock** pulses in the way they are used. Input parameters of type **timer** are followed by an optional delay parameter, which may be a constant value or an arithmetic expression (if missing a value of 1 is used). The current value of the delay expression is read on the rising edge of the associated logic input, and the result n is used to count **timer** pulses. The output is clocked by the n'th **timer** pulse after the rising input. If the delay value n is 0 - or on the falling edge of the logic input - the output is clocked immediately by **iClock**. For a CLOCK generated **clock**, the output is clocked by the first **clock** pulse after the rising or falling input. A D flip-flop clocked with a **timer** produces a function with turn on delay. If the logic input to such a delay element turns off before the delay time is up, the output never turns on. This is a very useful function to implement time-outs, which are notoriously difficult to implement by conventional means.

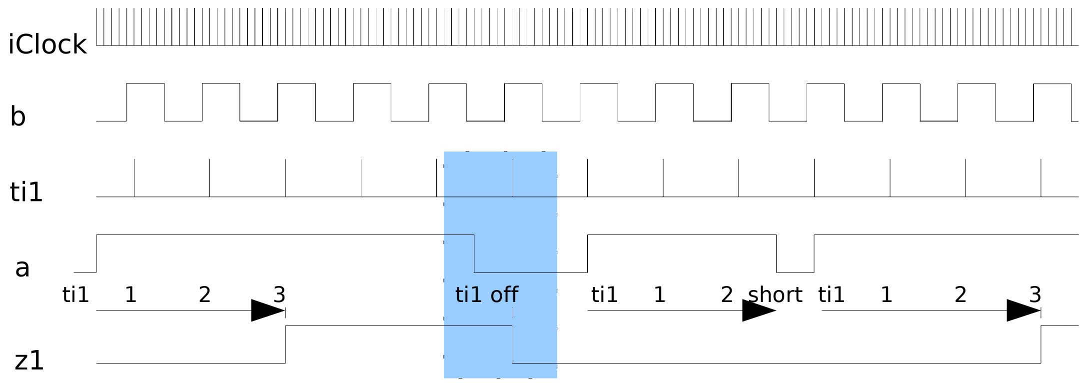
```
imm timer tim = TIMER(b);    // 'tim' on the rising edge of b
                             // clocked by next 'iClock'(default)
imm bit   z   = D(a, tim, 3);// D flip-flop clocked by 'tim',
                   // turn on delayed by 3 'tim' pulses,
                   // immediate turn off clocked by 'iClock'
```



5.4 TIMER1 function

The fourth source of clock signals is the TIMER1 function, which is very similar to the normal TIMER function. The signal type generated is **imm timer** – the same as the type generated by a normal TIMER. The only difference is the way in which a 0 delay and the falling logic input is handled, when a **timer**, generated by the TIMER1 function controls a clocked function. A 0 delay is handled like a delay of 1 – turn on is at the next **timer** pulse. On the falling edge of the logic input the output is clocked on the next **timer** pulse, rather than by the next **iClock**, which is the case for TIMER generated **timer** signals. A TIMER1 generated **timer**, used with a delay of 1 (or 0), functions identically to a CLOCK generated **clock** signal, except there is a small, but significant amount of overhead in handling **timer** signals. For this reason CLOCK functions are to be preferred – their use is very fast. The following diagram shows the different turn-off handling for a TIMER1 generated **timer** (in the shaded area):

```
imm timer ti1 = TIMER1(b);   // ‘ti1‘ on the rising edge of b
                             // clocked by next ‘iClock’(default)
imm bit   z1  = D(a, ti1, 3);// D flip-flop clocked by ‘ti1‘,
                       // turn on delayed by 3 ‘ti1‘ pulses,
                       // turn off clocked by next ‘ti1‘
```



CLOCK, TIMER and TIMER1 functions have optional clock inputs, which may come from other CLOCK or TIMER functions. The cascading of these functions allows the realization of many useful applications.

6 Inputs and Outputs

6.1 Built-in Inputs

There are a number of inputs, which have such universal significance, that they are implemented in the run time system.

6.1.1 iClock

There is a built-in *immediate* clock with the name `iClock`. This clock runs at the highest system rate. The name `iClock` is built-in and may be used as defined above in 5.1.

Because secondary clocks either use `iClock` by default, or another clock that is eventually clocked by `iClock`, all clocks (and timers) are synchronous with `iClock`. The execution of *immediate* logic is triggered by some input, which causes evaluation of follow up statements, until no more changes occur. `iClock` generates a clock pulse after every such burst of activity in the logic. `iClock` has the same significance for *immediate* logic as the end of the program cycle in a conventional PLC. The main difference is, that for a conventional PLC all statements are executed for each program cycle. For *immediate* logic only the changes triggered by one or at most a few simultaneous inputs are executed for each program cycle. This typically takes a few microseconds at most for a modern processor. There are support tools which can measure and display this time in microseconds.

6.1.2 End of Initialization

The rising edge of `TX0.0` is guaranteed to be the first input to the system and can be used for initializing user constructs. It is high for the remainder of the program (forever as far as applications are concerned)

```
TX0.0     EOI, off during initialization, then always on
```

6.1.3 Timing inputs

To allow programs to work with real time, the following timing inputs have been provided:

```
TX0.1     100 microseconds    // requires a 10 kHz Kernel
TX0.2     1 millisecond       // requires a 1 kHz Kernel
TX0.3     10 milliseconds     // standard 100 Hz Linux Kernel
TX0.4     100 milliseconds    // for the remaining timers
TX0.5     1 second
TX0.6     10 seconds
TX0.7     60 seconds or 1 minute
```

These inputs can be used to generate clocks, which are synchronous with real time. For example:

```
imm clock clk100m = CLOCK(TX0.4);      // every 100 milliseconds
```

6.2 External Inputs and Outputs

Inputs and Outputs are named according to the standard IEC-1131. Inputs start with the letter I, outputs with the letter Q. These are followed by a second letter which defines the type of the input or output. X defines a bit I/O, B a byte I/O, W a 16 bit word I/O and L a 32 bit long word I/O variable. The 2 capital letters are followed by a number, which defines the address index of the variable in the I/O field. For bit I/O variables a full stop and a number in the range 0 to 7, marking the bit address of the variable in the addressed I/O byte, follow this. The maximum address index that can be used depends on the implementation of the driver and the underlying hardware. Addresses in the I/O field may be used for bit, byte, word or long word I/O. If all of these are in the same physical address space, care must be taken not to overlap different types of I/O. In this case 16 and 32 bit word I/O's the byte addresses used must be on a 16 bit word or a 32 bit long word boundary respectively. The *iC* compiler can generate warnings if I/O fields overlap. In the default case, each size variable is assumed to be in its own address space and the address of each variable is simply in index into each address space.

6.2.1 Digital inputs

```
IX0.0     bit 0 of input byte 0 - pre-declared as imm bit
IX0.1     bit 1 of input byte 0
IX0.2     bit 2 of input byte 0
IX0.3     bit 3 of input byte 0
IX0.4     bit 4 of input byte 0
IX0.5     bit 5 of input byte 0
IX0.6     bit 6 of input byte 0
IX0.7     bit 7 of input byte 0

IX1.0     bit 0 of input byte 1
IX1.1     bit 1 of input byte 1
IX1.2     bit 2 of input byte 1
IX1.3     bit 3 of input byte 1
IX1.4     bit 4 of input byte 1
IX1.5     bit 5 of input byte 1
IX1.6     bit 6 of input byte 1
IX1.7     bit 7 of input byte 1
...
```

6.2.2 Digital outputs

```
QX0.0     bit 0 of output byte 0 - pre-declared as imm bit
QX0.1     bit 1 of output byte 0
QX0.2     bit 2 of output byte 0
QX0.3     bit 3 of output byte 0
QX0.4     bit 4 of output byte 0
QX0.5     bit 5 of output byte 0
QX0.6     bit 6 of output byte 0
QX0.7     bit 7 of output byte 0

QX1.0     bit 0 of output byte 1
QX1.1     bit 1 of output byte 1
QX1.2     bit 2 of output byte 1
QX1.3     bit 3 of output byte 1
QX1.4     bit 4 of output byte 1
QX1.5     bit 5 of output byte 1
QX1.6     bit 6 of output byte 1
QX1.7     bit 7 of output byte 1
...
```

6.2.3 Analog inputs

```
IB2       input byte 2 - pre-declared as imm int (8 bit input)
IB3       input byte 3
IB4       input byte 4
IB5       input byte 5

IW6       input word 6                       (16 bit input)
IW8       input word 8
IW10      input word 10
IW12      input word 12
IW14      input word 14

IL16      input long 16                      (32 bit input)
IL20      input long 20
IL24      input long 24
IL28      input long 28
...
```

6.2.4 Analog outputs

```
QB2      output byte 2 - pre-declared as imm int (8 bit output)
QB3      output byte 3
QB4      output byte 4
QB5      output byte 5

QW6      output word 6                        (16 bit output)
QW8      output word 8
QW10     output word 10
QW12     output word 12
QW14     output word 14

QL16     output long 16                       (32 bit output)
QL20     output long 20
QL24     output long 24
QL28     output long 28
...
```

The IEC-1131 names above define the physical addresses of inputs and outputs in the I/O field. For more readable applications it is highly recommended, that alternate descriptive names are defined for IEC-1131 inputs and outputs. This would normally be done in a table of alias assignments at the start of an *iC* program. One advantage of this scheme is, that if an input or output is physically moved to another I/O pin, only 1 statement in the source needs to be changed.

```
imm bit   waterLo, motorOn, heaterOn;
imm int   waterTemp, motorSpeed;

waterLo   = IX1.3;          // these statements define aliases
waterTemp = IB2;            // which produce no run-time overhead

QX10.2    = motorOn;        // here the IEC-1131 names are the
QX10.3    = heaterOn;       // aliases, which is appropriate
QW8       = motorSpeed;     // for outputs
```

IEC-1131 I/O variable names are pre-declared as immediate variables in *iC* program code, but they are not defined in embedded C code. Only variables declared with an **imm bit, imm int, immC bit** or **immC int** statement are defined in C code. If I/O variables must be accessed in C code the declared names must be used. This is another reason for defining descriptive aliases for I/O variables early in the program design phase.

7 User defined *immediate* Function Blocks

User defined *immediate* functions are commonly called function blocks in the PLC world, because they act more like functional blocks or templates rather than functions in the instruction flow sense, where a function evaluates a sequence of instructions whenever it is called. An *immediate* Function Block is a separate *immediate* subsystem with *immediate* parameters which are its inputs and outputs from other section of the *immediate* system, optional internal *immediate* variables, which must be declared inside the Function Block and an optional *immediate* return value, which may be used like any other immediate value – in an expression – assigned to an immediate variable or used as an input parameter in a built in function or function block call. Only standard IEC-1131 I/O variables may be used in a Function Block without being declared, although they may only be used as inputs, since any assignment to an I/O variable such as QX0.0 inside a Function Block would lead to a multiple assignment, once the Function Block is used more than once. Another way to look at an immediate Function Block is like a higher level integrated circuit, which has connections into the system and provides a certain complex function with many internal components and connections.

7.1 *immediate Function Block Definition*

An *immediate* Function Block must be defined before it is used. Since the definition of a Function Block does not itself generate any C-Code on compilation it can be and usually is defined with its code body in a header file, if multiple source files are used for a project. For small projects with a single source file Function Blocks can be defined at the start of the source file.

immediate Function Blocks definitions are very similar to C-functions, although there are significant differences in detail. The definition of an immediate Function Block consists of a return value type, a Function Block name, a comma separated parameter list in parentheses and a function body in curly braces, e.g.

```
imm bit fall(bit f, clock c) { this = RISE(~f, c); }
```

The return value may be one of 5 types:

```
imm void  // which means no value is returned
imm bit
imm int
imm clock
imm timer
```

The **imm** modifier is mandatory for the return type – it identifies an immediate Function Block Definition syntactically. The Function Block name can be any valid name starting with a letter followed by any number of alphanumeric characters or underscores. A leading underscore is possible, but should be avoided. The name must be distinct from all other immediate variable names in a project.

The individual formal parameters in the parameter list must be of the following 4 types:

```
imm bit   // or simply      bit
imm int   // or simply      int
imm clock // or simply      clock
imm timer // or simply      timer
```

The **imm** modifier is optional for parameters in the parameter list. The variable declared is nevertheless immediate. Parameters may be either input value parameters, in which case only their type is written in the list or the parameter may be an immediate output to which a value from the Function Block is to be assigned. In this case the type of the parameter must be preceded by the keyword **assign**.

The body of a Function Block is one or more immediate statements defining the functionality of the block encoded in curly braces. Immediate variables internal to the function must be declared before use in the Function Block. Parameter names and internal variable names are in a separate name space for each function, which is also separate form the global name space. If a Function Block is not **imm void** the body must contain a *return* statement. The semantics of the *return* statement is the assignment to the variable to which the Function Block is assigned, when it is called. This variable, which is identified by the keyword **this**, may be used in other expressions inside the Function Block. The preferred way to write the *return* statements is:

```
this = some + immediate + expression;    // preferred return syntax
```

The usual C-syntax may also be used, but does not make the action as clear:

```
return some + immediate + expression;     // deprecated earlier syntax
```

The *return* statement need not be the last statement in the Function Block definition – its position does not influence when it is executed – that is controlled purely by changes in the values of the variables making up the *return* statement – something which holds for all *immediate* statements. This situation is more clearly expressed by the assignment to **this**. An **imm void** Function Block has no **this** variable, may not contain a *return* statement and may not be assigned when called.

Each **assign** parameter must be on the left side of an assignment statement in the Function Block. The values of **assign** parameters may be used inside the Function Block. Each variable declared inside the Function Block must also be assigned in the Function Block. Variables declared **extern** outside or inside the Function Block may not be assigned to inside the Function Block. As is the case with I-O variables (which are implicitly extern) **extern** variables may only be used as values inside the Function Block. They may not be declared again as local inside the Function Block. Variables declared **extern** in a function may be declared after the definition of the Function Block in the *iC* code following the definition, to declare that the variable will be assigned in this module. A variable with the same name as an extern variable may be declared locally in another Function Block, but it is a different formal variable local to that Function Block.

All *immediate* statement types – assignments, *if else*, *switch*, Built in Functions and other user defined Function Block calls may be used in Function Block definitions. Function Blocks may be nested to any depth as long as Function Blocks are used, which have been previously defined. This implies that Function Blocks cannot be called recursively, either directly or indirectly. Function Blocks may be very simple one line definitions or complex systems with hundreds of parameters. Several examples follow:

The SRX flip-flop is built into the compiler, but defined in just this way during initialisation of the compiler. In the latest version of the compiler, all but the most primitive built ins, are defined as Function Blocks.

```
/* SRX flip-flop defined as a function block */

imm bit srx(imm bit set, imm clock scl,
            imm bit res, imm clock rcl)
{
        this = SR(set & ~res, scl, ~set & res, rcl;
}
```

The CountClk function adds '`increment`' to '`this`' for every occurrence of '`clk`':

```
imm int CountClk(imm clock clk, imm int increment)
{
        this = SH(this + increment, clk);
}
```

The CountBit function adds '`increment`' to '`this`' for every rising edge of '`step`':

```
imm int CountBit(imm bit step, imm int increment)
{
        this = CountClk(CLOCK(step), increment); // nested call
}
```

The SelectClk function selects either a 100 ms or a 1 second clock with variable '`second`':

```
imm clock SelectClk(imm bit second)
{
        this = CLOCK(TX0.4 & ~second |         // 100 ms
                     TX0.5 &  second );        // 1 second
}
```

The following function block ADConvert assigns the conversion of `int val` to 8 `assign bit` variables `b0` to `b7` passed as parameters (`imm` is implied for value and assign parameters).

```
/* Analog to digital conversion of a byte value */
imm void ADConvert(int val,            // input parameter
                   assign bit b0,      // output parameters
                   assign bit b1,
                   assign bit b2,
                   assign bit b3,
                   assign bit b4,
                   assign bit b5,
                   assign bit b6,
                   assign bit b7,
         )
{
         b0 = val & (1 << 0);          // assignments to outputs
         b1 = val & (1 << 1);
         b2 = val & (1 << 2);
         b3 = val & (1 << 3);
         b4 = val & (1 << 4);
         b5 = val & (1 << 5);
         b6 = val & (1 << 6);
         b7 = val & (1 << 7);
}
```

Note: the parameter list may have a trailing comma before the closing parentheses. This is generally the case for comma separated lists in *iC* and makes it easier to edit the lists and copy parameters when written vertically, which is useful for large parameter lists.

The *iC* compiler builds a template of the Function Block, replacing each parameter and internally declared variable by the name of the Function Block followed by a '@' and the formal parameter or declared variable name. This strategy ensures a private name space for each Function Block. When called, the template is copied, with each formal parameter replaced by its real parameter and internally declared variables replaced by the formal name with the '@' replaced by an underscore '_' and followed by an underscore and an instance number. The instance number scheme ensures that there is no clash of compiler generated variable names (even for separately compiled modules).

7.2 immediate Function Block Call

An immediate Function Block is called in a similar fashion to a C-function, again with some significant differences. In practice immediate Function Blocks are not called. When the compiler encounters a Function Block call, the pre-compiled Function Block, which is like a template, is copied, with all parameters replacing the formal parameters in the template. The resulting network of nodes will then be used at run-time like the network of nodes produced from all other immediate statements.

If an **imm void** function is encountered it looks like a subroutine call:

```
ADConvert(IB1,
                   QX0.0, QX0.1, QX0.2, QX0.3,
                   QX0.4, QX0.5, QX0.6, QX0.7,
              );
```

This statement will assign bits 0 to 7 of `IB1` to `QX0.0` to `QX0.7` whenever `IB1` changes.

A Function Block with a return value must either be assigned to a suitable variable or else it must be used as a value of a suitable type in an expression or in a parameter list. An **imm bit** Function Block may be used as an **imm int** value and vice versa – appropriate conversion takes place. **imm clock** and **imm timer** Function Blocks can either be assigned to correctly declared **clock** or **timer** variables or else used as a **clock** or **timer** value in a parameter list.

```
/* count every rise of IX1.0 */
imm int count = CountBit(IX1.0, 1);

/* selects 1 sec when IX1.7 is on else 100 ms */
imm clock clk = SelectClk(IX1.7);
```

Real parameters of type **imm int** and **imm bit** may be mismatched with their formal parameter types – value and assign parameters in the call will be forced to their formal type. **assign** parameters of type **imm clock** and **imm timer** must match – so must a value parameter of type **imm timer**. The handling if formal **imm clock** parameters is more complex, allowing the use of default clocks.

Positions for formal **`imm clock`** parameters are handled as follows:

1. the position may be filled by a real **`imm clock`** parameter.
2. the position may be filled by a real **`imm timer`** parameter followed by an optional **`imm int`** delay (if delay is left out it will be set to 1).
3. the position may be left out altogether, in which case the next clock or timer parameter on the right will be replicated for the position. If there is no real clock parameter following on the right, **`iClock`** will be used.

Real **`timer`** parameters for formal **`timer`** parameters cannot be extended by a delay – the delay used is determined in the Function Block with delay(s) associated with the use of the formal **`timer`** parameter in the code of the Function Block.

The following calls of the user defined srx() Function Block (which is identical to the built in SRX) with two formal clock parameters – one each for set and reset.

```
imm clock c = CLOCK(IX1.1), clk = CLOCK(IX1.2);
imm timer t = TIMER(IX1.3);
imm bit s, r;
imm bit m1 = srx(s, clk, r, c);        // uses individual clocks
imm bit m2 = srx(s, t, 3, r, t, 5);    // individual timer delays
imm bit m3 = srx(s, r, clk);           // one clock for s and r
imm bit m4 = srx(s, r, t, 5);          // one timer for s and r
imm bit m5 = srx(s, clk, r);           // default iClock for r
imm bit m6 = srx(s, iClock, r, c);     // must specify iClock here
imm bit m7 = srx(s, r);                // default iClock for both
```

The following example is a controller for a full scale application which required all the space and speed resources of a PLC in the mid 80's. This project for a parcel sorting system for the Australian Railways prompted the author to look at alternate event driven systems for machine control.

The program is meant to control 4 high speed belts moving at 5 metres/second generating independent strobe pulses for every 15 mm movement of the belt. That means a strobe pulse every 3 ms. Each belt is equipped with 32 destination gates spaced 12 strobe pulse apart and open for 7 strobe pulses (in practice this must be 72 strobe pulses or more).

The implementation consists of several function blocks:

> **feeder()** controls the insertion of the destination code onto the initial feeder segment of the belt.
> **segment()** controls one of the 32 identical segments of the belt.
> **belt()** is a Function Block for one belt, calling feeder() once and segment() 32 times. Finally belt() is called 4 times – once for each belt.
> **tick()** is an auxiliary Function Block generating strobe pulses for the simulation. Note the way tick() is called in the strobe parameter position of belt().

The compiled *iC* program consists of 1,944 Gate nodes, 8,642 links and 10 C functions consisting of 1 line of C code each.

```
/*******************************************************************
 *
 *      Parcel sorter for long belts
 *      Author: J.E. Wulff
 *      Source: Test8/sorti.ic
 *
 *******************************************************************/
/*******************************************************************
 *
 *      Feeder segment
 *
 *******************************************************************/

imm bit feeder(                 /* feeds code into feeder segment */
        imm bit transfer,       /* photo cell to transfer code */
 assign imm int carryOut,       /* shift bit (as int) for the following segment */
        imm int code,           /* destination code - 0 to 31 */
        imm int length,         /* sets the length of the segment */
        imm int width,          /* width of lock frame 6 + 6 for 0x7f */
        imm clock c,            /* stepping clock for the belt */
    )
{
    extern imm bit reset;       /* general re-initialisation */
    imm bit pip   = RISE(transfer & ~this & ~reset, c);
    imm int shift = SHR((shift << 1) + (pip * (0x41 + (code << 1))), c, reset);
    imm int mask  = 0x41 << width;
    carryOut = (shift >> length) & 0x00000001;
    this = SRX(pip,             /* unlock after width steps */
               (shift & mask) == mask | reset, c);
}
/*******************************************************************
 *
 *      Segment
 *
 *      Each segment controls one gate and may be up to 32 steps long
 *
 *******************************************************************/

imm bit segment(                /* returns gate control output */
        imm int carryIn,        /* shift bit (as int) from the previous segment */
 assign imm int carryOut,       /* shift bit (as int) for the following segment */
        imm int code,           /* code identifying this segment */
        imm int length,         /* segment length */
        imm int width,          /* width of the gate */
        imm clock c,            /* stepping clock for the belt */
    )
{
    extern imm bit reset;       /* general re-initialisation */
    imm int shift = SHR((shift << 1) + carryIn, c, reset);
    imm int mask  = 0x41 << width;
    carryOut = (shift >> length) & 0x00000001;
    this = SRX((shift & 0x7f) == 0x41 + (code << 1),
               (shift & mask) == mask | reset, c);
}
/*******************************************************************
 *
 *      Belt
 *
 *      Each belt has 32 gates
 *
 *******************************************************************/

imm int belt(
        assign  imm bit lock,           /* lock indicator */
        assign  imm bit gate00,
        assign  imm bit gate01,
        assign  imm bit gate02,
        assign  imm bit gate03,
        assign  imm bit gate04,
        assign  imm bit gate05,
        assign  imm bit gate06,
        assign  imm bit gate07,
        assign  imm bit gate08,
        assign  imm bit gate09,
        assign  imm bit gate10,
        assign  imm bit gate11,
        assign  imm bit gate12,
        assign  imm bit gate13,
```

```
        assign  imm bit gate14,
        assign  imm bit gate15,
        assign  imm bit gate16,
        assign  imm bit gate17,
        assign  imm bit gate18,
        assign  imm bit gate19,
        assign  imm bit gate20,
        assign  imm bit gate21,
        assign  imm bit gate22,
        assign  imm bit gate23,
        assign  imm bit gate24,
        assign  imm bit gate25,
        assign  imm bit gate26,
        assign  imm bit gate27,
        assign  imm bit gate28,
        assign  imm bit gate29,
        assign  imm bit gate30,
        assign  imm bit gate31,
                imm int code,            /* gate code 0 to 31 for parcel destination */
                imm bit p_cell,          /* photo cell monitoring parcel onto belt */
                imm bit strobe,          /* strobe pulse from belt movement */
    )
{
    imm int carfd;                       /* carry bits */
    imm int car00, car01, car02, car03, car04, car05, car06, car07;
    imm int car08, car09, car10, car11, car12, car13, car14, car15;
    imm int car16, car17, car18, car19, car20, car21, car22, car23;
    imm int car24, car25, car26, car27, car28, car29, car30, car31;

    imm clock clk = CLOCK(strobe);

    lock   = feeder(p_cell, carfd, code, 12, 11, clk);
    gate00 = segment(carfd, car00,    0, 12,  7, clk);
    gate01 = segment(car00, car01,    1, 12,  7, clk);
    gate02 = segment(car01, car02,    2, 12,  7, clk);
    gate03 = segment(car02, car03,    3, 12,  7, clk);
    gate04 = segment(car03, car04,    4, 12,  7, clk);
    gate05 = segment(car04, car05,    5, 12,  7, clk);
    gate06 = segment(car05, car06,    6, 12,  7, clk);
    gate07 = segment(car06, car07,    7, 12,  7, clk);
    gate08 = segment(car07, car08,    8, 12,  7, clk);
    gate09 = segment(car08, car09,    9, 12,  7, clk);
    gate10 = segment(car09, car10,   10, 12,  7, clk);
    gate11 = segment(car10, car11,   11, 12,  7, clk);
    gate12 = segment(car11, car12,   12, 12,  7, clk);
    gate13 = segment(car12, car13,   13, 12,  7, clk);
    gate14 = segment(car13, car14,   14, 12,  7, clk);
    gate15 = segment(car14, car15,   15, 12,  7, clk);
    gate16 = segment(car15, car16,   16, 12,  7, clk);
    gate17 = segment(car16, car17,   17, 12,  7, clk);
    gate18 = segment(car17, car18,   18, 12,  7, clk);
    gate19 = segment(car18, car19,   19, 12,  7, clk);
    gate20 = segment(car19, car20,   20, 12,  7, clk);
    gate21 = segment(car20, car21,   21, 12,  7, clk);
    gate22 = segment(car21, car22,   22, 12,  7, clk);
    gate23 = segment(car22, car23,   23, 12,  7, clk);
    gate24 = segment(car23, car24,   24, 12,  7, clk);
    gate25 = segment(car24, car25,   25, 12,  7, clk);
    gate26 = segment(car25, car26,   26, 12,  7, clk);
    gate27 = segment(car26, car27,   27, 12,  7, clk);
    gate28 = segment(car27, car28,   28, 12,  7, clk);
    gate29 = segment(car28, car29,   29, 12,  7, clk);
    gate30 = segment(car29, car30,   30, 12,  7, clk);
    gate31 = segment(car30, car31,   31, 12,  7, clk);
    this = car31;                        /* allows concatenation of belts */
}
/*******************************************************************
 *
 *      Generate tick
 *      input fast1 or fast2 cause 50 ms ticks
 *      else tick for every change of manual input
 *
 *******************************************************************/

imm bit tick(bit manual, bit fast1, bit fast2) {
    imm bit fast = fast1 | fast2;
    this = CHANGE(manual & ~fast | TX0.4 & fast);
}
```

```
/******************************************************************
 *
 *      4 belts
 *
 *      Each belt has 32 gates
 *
 *****************************************************************/

imm bit reset = IX0.7;   /* general re-initialisation */

QX8.0 = belt(
    QX8.1,               /* lock indicator */
    QX0.0, QX0.1, QX0.2, QX0.3, QX0.4, QX0.5, QX0.6, QX0.7,
    QX1.0, QX1.1, QX1.2, QX1.3, QX1.4, QX1.5, QX1.6, QX1.7,
    QX2.0, QX2.1, QX2.2, QX2.3, QX2.4, QX2.5, QX2.6, QX2.7,
    QX3.0, QX3.1, QX3.2, QX3.3, QX3.4, QX3.5, QX3.6, QX3.7,
    IB3,                 /* gate code 0 to 31 for parcel destination */
    IX0.1,               /* photo cell monitoring parcel onto belt */
    tick(IX0.0, IX0.6, IX0.5), /* strobe pulse from belt movement */
);

QX8.2 = belt(
    QX8.3,               /* lock indicator */
    QX4.0, QX4.1, QX4.2, QX4.3, QX4.4, QX4.5, QX4.6, QX4.7,
    QX5.0, QX5.1, QX5.2, QX5.3, QX5.4, QX5.5, QX5.6, QX5.7,
    QX6.0, QX6.1, QX6.2, QX6.3, QX6.4, QX6.5, QX6.6, QX6.7,
    QX7.0, QX7.1, QX7.2, QX7.3, QX7.4, QX7.5, QX7.6, QX7.7,
    IB7,                 /* gate code 0 to 31 for parcel destination */
    IX4.1,               /* photo cell monitoring parcel onto belt */
    tick(IX4.0, IX4.6, IX0.5), /* strobe pulse from belt movement */
);

QX8.4 = belt(
    QX8.5,               /* lock indicator */
    QX10.0, QX10.1, QX10.2, QX10.3, QX10.4, QX10.5, QX10.6, QX10.7,
    QX11.0, QX11.1, QX11.2, QX11.3, QX11.4, QX11.5, QX11.6, QX11.7,
    QX12.0, QX12.1, QX12.2, QX12.3, QX12.4, QX12.5, QX12.6, QX12.7,
    QX13.0, QX13.1, QX13.2, QX13.3, QX13.4, QX13.5, QX13.6, QX13.7,
    IB13,                /* gate code 0 to 31 for parcel destination */
    IX10.1,              /* photo cell monitoring parcel onto belt */
    tick(IX10.0, IX10.6, IX0.5), /* strobe pulse from belt movement */
);

QX8.6 = belt(
    QX8.7,               /* lock indicator */
    QX14.0, QX14.1, QX14.2, QX14.3, QX14.4, QX14.5, QX14.6, QX14.7,
    QX15.0, QX15.1, QX15.2, QX15.3, QX15.4, QX15.5, QX15.6, QX15.7,
    QX16.0, QX16.1, QX16.2, QX16.3, QX16.4, QX16.5, QX16.6, QX16.7,
    QX17.0, QX17.1, QX17.2, QX17.3, QX17.4, QX17.5, QX17.6, QX17.7,
    IB17,                /* gate code 0 to 31 for parcel destination */
    IX14.1,              /* photo cell monitoring parcel onto belt */
    tick(IX14.0, IX14.6, IX0.5), /* strobe pulse from belt movement */
);
```

The following are the 10 generated C code fragments. The macro `iC_MV()` accesses an indexed value on the generated link array. One can see from this that even for **`int`** nodes the execution time for one event is going to be no more than a few microseconds.

```
000     (1)     return iC_MV(1)?iC_MV(2):iC_MV(3);
026     (3)     return (iC_MV(1)<<1)+(iC_MV(2)*(0x41+(iC_MV(3)<<1)));
027     (4)     return 0x41<<iC_MV(1);
028     (5)     return (iC_MV(1)>>iC_MV(2))&1;
030     (6)     return (iC_MV(1)&iC_MV(2))==iC_MV(2);
051     (7)     return (iC_MV(1)<<1)+iC_MV(2);
052     (8)     return 0x41<<iC_MV(1);
053     (9)     return (iC_MV(1)>>iC_MV(2))&1;
055     (10)    return (iC_MV(1)&iC_MV(2))==iC_MV(2);
055     (11)    return (iC_MV(1)&0x7f)==0x41+(iC_MV(2)<<1);
```

8 The *iC* run-time model

The *iC* compiler ***immcc*** parses the statements of an iC source, e.g. **`example.ic`** and produces a C file **`example.c`** and optionally a listing file **`example.lst`**. The C file is compiled by a C compiler to produce **`example.o`** (**`example.obj`** under Windows), which is linked with the *iC* runtime library ***libict.a*** to produce an executable **`example`** (**`example.exe`** under Windows).

```
********************* SOURCE example.ic *********************

imm bit a = IX0.0 & ~IX0.1 | ~IX0.0 & IX0.1;
QX0.0 = a;
imm bit b = IX0.2 ^ IX0.3;
imm bit d = ~IX0.2 & ~IX0.3;
imm bit mem = LATCH(b, d);
QX0.1 = mem;
```

```
********************* LISTING example.lst *******************

001   imm bit a =  IX0.0 & ~IX0.1 | ~IX0.0 &  IX0.1;

      a_1        ---|  a
      a_2        ---|

      IX0.0      ---&  a_1
      IX0.1    ~ ---&

      IX0.0    ~ ---&  a_2
      IX0.1      ---&

002   QX0.0 = a;

      a          ---|  QX0.0 X

003   imm bit b =  IX0.2 ^  IX0.3;

      IX0.2      ---^  b
      IX0.3      ---^

004   imm bit d = ~IX0.2 & ~IX0.3;

      IX0.2    ~ ---&  d
      IX0.3    ~ ---&

005   imm bit mem = LATCH(b, d);

      mem        ---%  mem
      b          ---%
      d        ~ ---%         *

006   QX0.1 = mem;

      mem        ---|  QX0.1 X
```

```
******* NET TOPOLOGY    *******

IX0.0   <    ~a_2&    a_1&
IX0.1   <     a_2&   ~a_1&
IX0.2   <     b^     ~d&
IX0.3   <     b^     ~d&
QX0.0   |  X
QX0.1   |  X
a       |     QX0.0|
a_1     &     a|
a_2     &     a|
b       ^     mem%
d       &    ~mem%  *
mem     %     mem%    QX0.1|
```

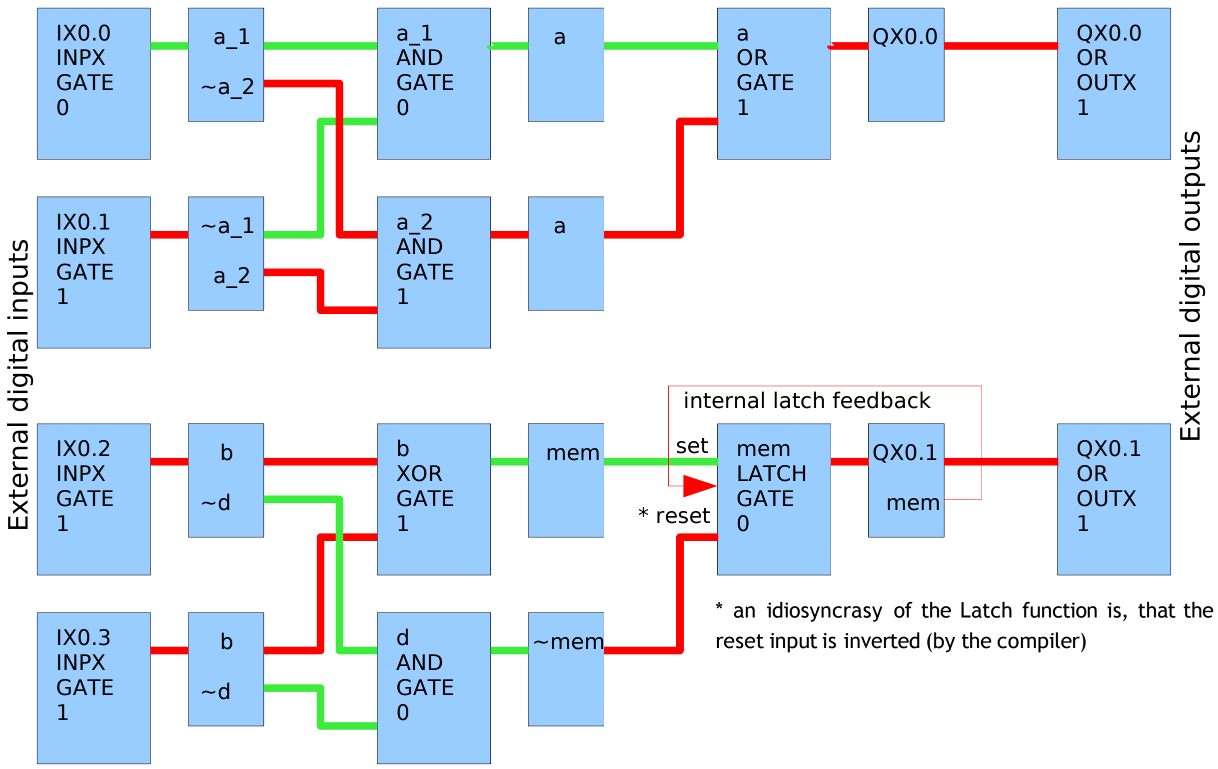


Fig. 1 Graph representation of the iC program ***example.ic***

```
//******************** C OUTPUT CODE example.c ********************

static Gate *     l_[];
/*****************************************************************
 *     Gate list
 *****************************************************************/
Gate IX0_0    = { 1,  INPX,  GATE, 0, "IX0.0", 0, 0,       0     };
Gate IX0_1    = { 1,  INPX,  GATE, 0, "IX0.1", 0, 0,       &IX0_0 };
Gate IX0_2    = { 1,  INPX,  GATE, 0, "IX0.2", 0, 0,       &IX0_1 };
Gate IX0_3    = { 1,  INPX,  GATE, 0, "IX0.3", 0, 0,       &IX0_2 };
Gate QX0_0    = { 1,  OR,    OUTX, 0, "QX0.0", 0, &l_[0],  &IX0_3 };
Gate QX0_1    = { 1,  OR,    OUTX, 0, "QX0.1", 0, &l_[3],  &QX0_0 };
Gate a        = { 1,  OR,    GATE, 0, "a",     0, &l_[6],  &QX0_1 };
Gate a_1      = { 1,  AND,   GATE, 0, "a_1",   0, &l_[10], &a     };
Gate a_2      = { 1,  AND,   GATE, 0, "a_2",   0, &l_[14], &a_1   };
Gate b        = { 1,  XOR,   GATE, 0, "b",     0, &l_[18], &a_2   };
Gate d        = { 1,  AND,   GATE, 0, "d",     0, &l_[22], &b     };
Gate mem      = { 1,  LATCH, GATE, 0, "mem",   0, &l_[26], &d     };
/*****************************************************************
 *     Connection lists
 *****************************************************************/
static Gate *  l_[] = {
/* QX0.0 */    &a,       0,        0,
/* QX0.1 */    &mem,     0,        0,
/* a */        &a_2,     &a_1,     0,        0,
/* a_1 */      &IX0_0,   0,        &IX0_1,   0,
/* a_2 */      &IX0_1,   0,        &IX0_0,   0,
/* b */        &IX0_3,   &IX0_2,   0,        0,
/* d */        0,        &IX0_3,   &IX0_2,   0,
/* mem */      &mem,     &b,       0,        &d,       0,
};
```

All this is fairly conventional, except for the ***immcc*** compiler. The C output it produces consists mainly of initialised data definitions, which describe a directed graph of vertices or nodes and edges joining the nodes. Each node of this graph corresponds to an expression in the *iC* program - they are called Expression nodes. The graph produced by the compiler is directed towards the inputs, which are called sources in graph theory (see Fig 1 above). This means that a list of the inputs to each Expression is associated with a particular Expression node. These are the edges of the graph. This direction represents the way in which expressions are usually evaluated by a flow of instructions in a computer – consecutive instructions read the values of all input variables of an expression and arithmetic or logic operators, acting on adjacent operands, determine the result. One is used to think about expressions this way and the (optional) listing file represents all Expression nodes generated by the compiler in this way (see LISTING above).

For *immediate C*, this graph, whose edges point towards the inputs of each node, is loaded into memory and as a first step, all edges are reversed. This means, that each Expression node is associated with a list of follow on Expression nodes, for which the current Expression result is an input. What this means is, that when a particular Expression node changes its value, then all the expressions for the Expression nodes on its output list should be re-evaluated (see NET TOPOLOGY above)

8.1 Combinatorial actions

Combinatorial actions are the evaluation of arithmetic or logical expressions, which excludes the full evaluation of any embedded clocked functions. Expressions contain variables combined with operators, which describe a (possibly) changed result when an input variable to the expression changes. Although the evaluation of an expression takes a certain (small) amount of time – both for hardware IC's and for *iC* expressions, conceptually we are dealing with a mathematical statement, whose evaluation describes a change of state – an operation, which does not necessarily take any time. One completed scan of the Combinatorial action list is such a conceptually timeless combinatorial set of state-changing actions.

To implement this scheme, the *iC* run-time uses Expression nodes, which can be linked into action lists and which store the old value of the node – that is the value before the expression is re-evaluated - as well as the new value after re-evaluation. If these values are equal after a change of input and re-evaluation, no further action is taken – follow on nodes will not change either, because of this particular change of input. If the new value is different from the old value, the Expression node is said to “fire” (a term borrowed from Petri Nets). When this happens, The Expression node is linked to the end of an action list. While on an action list, the old and new values are kept in the node. There are four types of action list to which Expression nodes may be linked when they “fire” during the combinatorial scan:

1. **`o_list`**, to which logical expression nodes are linked.
2. **`a_list`**, to which arithmetic expression nodes are linked.
3. **`A Clock list`**, to which clocked function Master nodes are linked.
4. **`s_list`**, to which external output expression nodes are linked.

To simplify the description, **`o_list`** and **`a_list`** are discussed here as a single Combinatorial action list. For the combinatorial scan, the Expression node at the head of the Combinatorial action list is taken and the output list of that node is scanned. Every Expression node on that output list is re-evaluated, using the new value of the Expression node just taken from the Combinatorial action list, with the result that some Expression nodes on the output list may change and “fire”. These nodes are also linked to the end of an appropriate action list. The old value of the original Expression node is assigned the new value at this time and it is unlinked from the head of the Combinatorial action list – that node is now no longer active. The combinatorial scan is continued with the new head of the Combinatorial action list until the list is empty.

There is another possibility. The target Expression node is already somewhere on some action list, which means its value has recently changed, but the new value has not yet been transmitted to any follow on nodes. Now another Expression node acts on this particular Expression node and re-evaluation changes its value a second time. There are two possibilities:

1. The latest value is still different from the old value (the value it had when its output list was last scanned and follow on nodes were re-evaluated). In this case the Expression node is left on the action list with a (possibly) changed new value.

2. Re-evaluation changes the new value back to the old value again. This situation is called a "glitch". The Expression node is now unlinked from the action list and becomes inactive, before it acts on any follow on nodes. The reasoning behind this strategy is, that any temporary change, which occurs through one path of the graph, which is immediately undone by some expression on another path, should not influence the output.

Initially nodes can only get on the Combinatorial action list due to changes of external inputs (sources) of the graph. Normally such a change will percolate through paths of the graph to one or more external output nodes (sinks). At this stage the Combinatorial action list is usually empty.

Cycles are allowed in the graph – they occur when there is feedback in the *iC* program. Such feedback is often necessary for implementing designs, but the designer should control it. Feedback may result in situations, where continuous oscillations occur. When this happens, certain nodes will change to a new value – act on some follow on node(s), which will then change the original node back to the old value after it has acted on other nodes. This means the action list will never get empty. If nothing were done about this, the *iC* program would lock up the processor.

Continuous oscillations at the Expression node level should not be part of a design and this situation results in a warning message at run-time. Nevertheless for testing purposes, such a program should be able to run without locking up the processor. To achieve this, a strategy is used, where the number of times a particular node may be re-evaluated in one scan is limited – usually to three. This is the *maximum oscillator count*, which may be changed with the -n <count> command-line switch. If the *maximum oscillator count* is exceeded after re-evaluation of a node, that node is not linked to the normal Combinatorial action list, but to an Alternate action list. This way the current Combinatorial action list will always get empty within a finite number of actions. At the end of the scan, when the Combinatorial action list does become empty, the current Combinatorial action list and the Alternate action list are swapped. At this point in time the *iC* run-time process goes to sleep, waiting for new input.

When a new external input interrupts the system, the associated input node is linked to the now current swapped Combinatorial action list and triggers a new scan. Together with the new input and its follow up events, the oscillating nodes, which were linked to the (then alternate) list during the previous scan, will be evaluated again. This way the oscillations do get re-evaluated over and over – but at a rate which does not block the processor. This is similar to the way oscillations manifest themselves in a hardware IC circuit – a large but finite number of oscillations will occur between any two consecutive external input events. In *iC* programs, this number has been reduced to three, which does not change the way these oscillations affect other parts of the program. In practice it has been found useful to make this an odd number, so that rising and falling edges alternate for digital oscillations.

All this takes care of what is called "combinatorial logic" for digital systems. Sequencing requires different mechanisms and they are provided in the *iC* language by clocking and clocked functions.

8.2 Clocked actions

As mentioned before, Clock signals in *iC* are best thought of as timeless pulses, whose occurrence marks the separation of one clock period from the next along the time axis. For these purposes actions in the *iC* run-time occur in two phases – *combinatorial actions*, which were described in the previous section and *clocked actions*, which are always master-slave actions, which occur during the Clock phase.

Clocked functions contain one or more Master nodes and exactly one Slave node. Master nodes are Expression nodes – just like the ones described in the previous section, except their output does not act directly on follow on Expression nodes and therefore are not linked to the current Combinatorial action list when they "fire". There is a Master Node for every non-clock input parameter to a function. Associated with each such non-clock parameter is a clock parameter. If it is not mentioned explicitly in the parameter list, it has a default value – usually **`iClock`**. Master nodes which "fire", are linked to the Clock list associated with the clock parameter for the particular Master node.

Clock lists are similar to action lists – they may be empty or have one or more Expression nodes linked to them. Clock lists are associated with the Slave node of a Clock function or "driver". There is one special Clock list called **`c_list`**, which is associated with the default **`iClock`** and which is scanned every time a combinatorial scan completes unless **`c_list`** is empty. This Clock scan marks the occurrence of **`iClock`**. In other words combinatorial scans and clock scans alternate until both the current Combinatorial action list and **`c_list`** are empty. For the purpose of synchronisation, it is important to remember that during the combinatorial scan new nodes are evaluated and linked to one of the following:

1. the Combinatorial action list – described in the previous section.
2. **c_list** or another Clock list – which receive Master nodes of clocked functions.
3. **s_list** – which receives those Expression nodes whose action is external output.

During the clock scan only **c_list** is scanned. There are several different clock actions, but they only involve the value of a Master node modifying the value of a Slave node and some side effect associated with the clocked function. The different clock actions are:

1. Clocking of a logical or arithmetic function – the new value of the Slave node is determined according to the truth-table of the function. As a side effect the Slave node is linked to the current Combinatorial action list if its value has changed – it then becomes a new logical or arithmetic input, which will not have any effect until after the current clock scan has completed.
2. Clocking of a CLOCK or TIMER driver function – the Clock action nodes linked to the the Clock list associated with the CLOCK or TIMER function Slave node are all linked to **c_list** immediately. This means, that the CLOCK or TIMER function has "fired" and the clock actions, which have accumulated on its Clock list will also be executed during the current clock scan, since they are now on **c_list**, which is currently being scanned.
3. Clocking of a conditional **if else** or **switch** statement function. Since these functions execute C code embedded in the *iC* program, which may involve modifying logical or arithmetic *immediate* variables, the actual execution of the C code must be deferred until after completion of the clock scan. For this purpose the Slave nodes of any conditional **if else** or **switch** statement function is linked to another action list – namely **f_list**. The scan of **c_list** is always finite, since no new Master actions are added to any Clock list during the scan. When the clock scan terminates a single scan of **f_list** follows, unless **f_list** is empty. This **f_list** scan marks the end of a Clock phase and the beginning of a new combinatorial phase.

After a completed clock scan the combinatorial scan is repeated, because both Clock actions and the **f_list** scan may have generated new Combinatorial actions.

8.3 Output actions

Finally, when both the current Combinatorial action list and **c_list** are empty, a scan of **s_list** follows. During that scan the actual external output is performed. Binary outputs are first distributed to an output byte and then the output bytes, words and long words which have changed since the last cycle are transmitted to ***iCserver***, which distributes them to their final output destinations, where they act physically.

8.4 Input actions

External inputs come from physical input device drivers and are transmitted as bytes, words or long words via ***iCserver***, using the same protocol as the output.

TCP/IP is used as the transport protocol from and to the *iC* run-time system and the final physical input and output device(s) in the current implementation. This ensures, that no input or output is lost during transmission. Other safe transmission systems can be used – only the actual input and output driver software needs to be changed.

The run-time system also recognises internal inputs which are mainly interrupts from the processors real-time-clock. These are described in 6.1.3.

External and internal inputs interrupt the run-time system. Initially the source of the interrupt is analysed and Input nodes are "fired" for every changed input and these are linked immediately to the Combinatorial action list. Then a new cycle is initiated starting with a scan of the current Combinatorial action list.

8.5 *Input/Output network*

The network clients around ***iCserver*** can comprise one or more *iC* applications and any number of ***iCboxes***, which simulate real I/O in the current implementation. Input and output can be transmitted not only to and from *iC* applications and ***iCboxes*** but also between *iC* applications. Since all of these elements can run on any processor in a LAN or even in the Internet, this opens up interesting possibilities for the *iC* system.

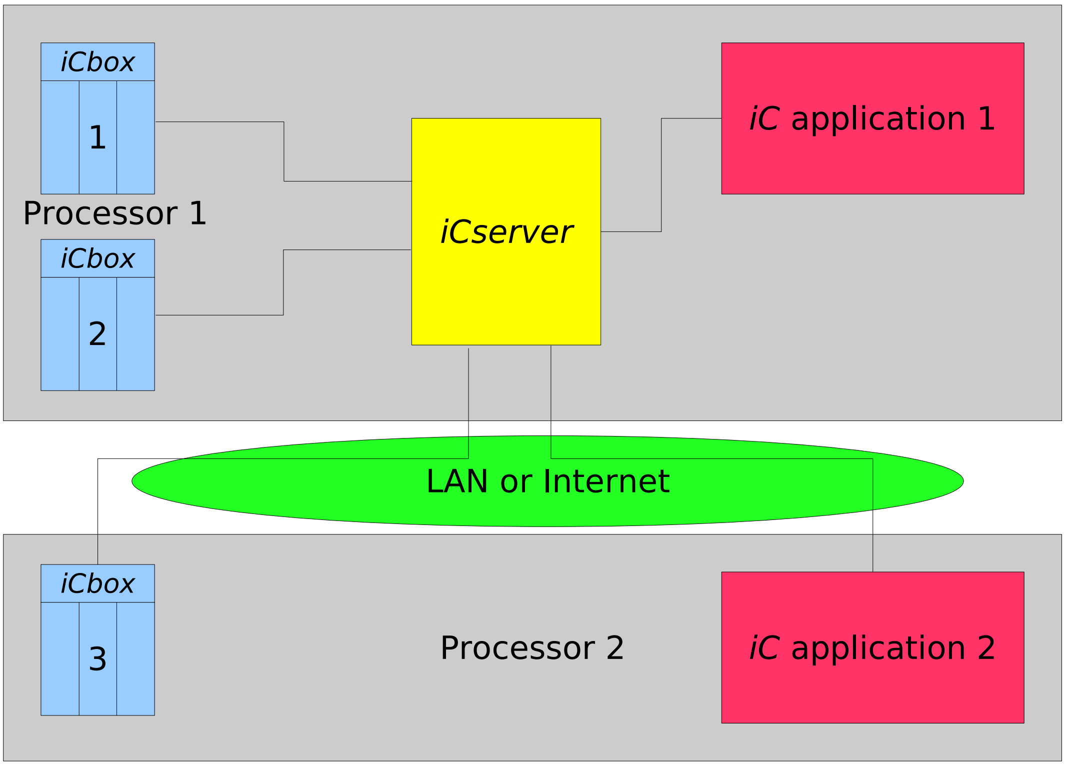


Fig. 2 Input/output network

9 Compiler and Run-time system

9.1 Compiler

The *iC* compiler ***immcc*** generates C code with the extension **`.c`** from *iC* source files with the extension **`.ic`**, which is suggested for *iC* sources. It is also suggested, that *iC* header files have the extension **`.ih`** For larger projects, several **`.ic`** files may be compiled to **`.c`** files, which are then compiled by ***cc*** to **`.o`** files and linked with the library ***libict.a***, which contains the run-time code. This produces a finished application, which can be run in an environment compatible with the features of the run-time library.

The *iCa* pre-compiler ***immac*** generates *iC* source files with the extension **`.ic`** from *iC* with arrays (*iCa*) source files with the extension .ica. The shell script ***iCmake*** executes all these steps automatically – it makes a complete ***iC*** application from one or more *iC* and/or *iCa* sources.

9.2 Run-time libraries

There are several versions of the run time library, depending on the hardware interfaces available for Input and Output. The Demonstration library ***libict.a*** communicates its Input and Output via TCP/IP, which provides a turnaround time of an input change to the arrival of the corresponding output change in a lightly loaded network of less than 2 millisecond (measured on a Pentium 166). The uncertainty of load occurring in such a network forces one to look at specialized bus systems for high speed applications. Currently ***libict.a*** is a static library. For production purposes a dynamic library is envisaged.

Other libraries have been built for industrial field bus systems. The library for **InterBus-S** is complete and has been extensively tested with InterBus-S I/O modules. A library for a proprietary high speed field bus system was used for early tests and provided turnaround times of under a 100 microseconds on a 386 8 MHz processor. A CAN-Bus library is planned and could be implemented at short notice.

9.3 Run-time environment and system

For any applications where hard real time constraints are not a problem, the TCP/IP run-time system provides a very flexible and easy to configure environment where Input and Output may be distributed over a number of computers in a local area network. The system consists of a server called ***iCserver*** and a number of clients for which ***iCserver*** is the hub. An *iC* application linked with the ***libict.a*** library is one type of client, providing control in the system. The other client types are Input and Output modules (or combined I/O modules) and debugging tools.

iCserver has been implemented in Perl, which is very flexible and fast enough to keep up with TCP/IP traffic generated in a local area network. A faster C implementation of ***iCserver*** is possible. The program ***iCbox*** simulates Input/Output modules as Perl/Tk dialog boxes for digital and analog inputs and outputs. For real inputs and outputs ***iCbox*** can serve as a program template. Only the translation of the I/O signals to a short network message for transmission to the ***iCserver*** is necessary to port an I/O device. A simple and very compact protocol for passing messages to and from the ***iCserver*** has been defined.

The program ***iClive*** provides an IDE for editing and debugging ***iC*** programs. It provides an edit window, in which program text can be displayed and optionally edited, searched, saved, made into runnable code, run and stopped. When running and debugging an ***iC*** program, ***iClive*** is a client of ***iCserver*** and indirectly of the running ***iC*** program. ***iClive*** colours words in the program text according to the state of the node named by a word – green/black for bit 0, yellow/red for bit 1 and blue for arithmetic variables. The value of a node is also displayed when the cursor is on a word. To be effective, the displayed text must be either the source of the running ***iC*** program or a text derived from that source, such as the compiler generated listing, which shows all compiler generated extra nodes. With this colour coded display of the statements of the ***iC*** program, it is easy to follow the progress of execution and the related logic at run time. "Live displays" are commonly used in programming units for PLC's in industrial control environments to provide debugging support.

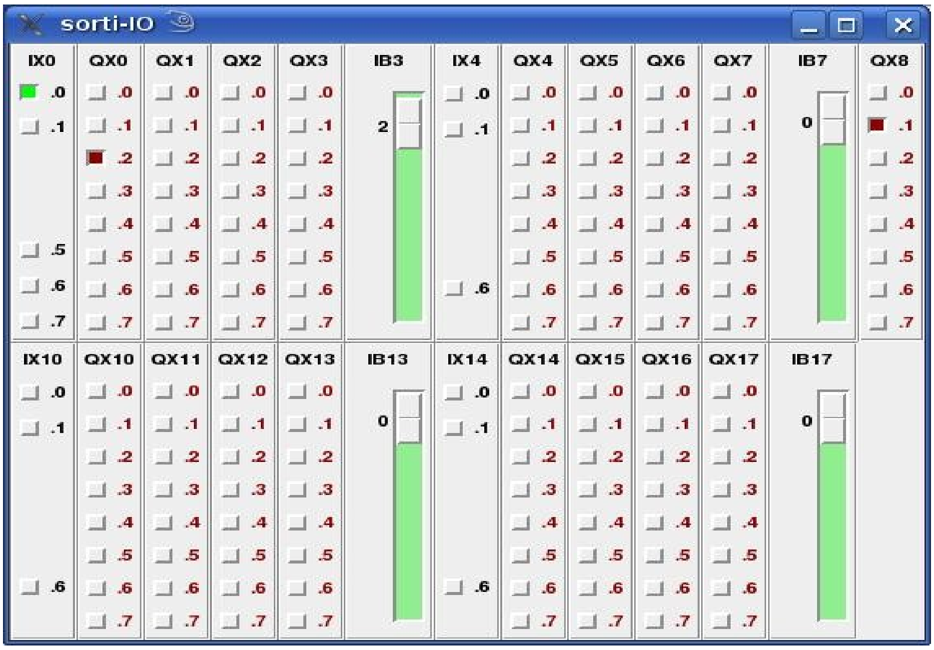


Fig. 3 ***iCbox*** *as IO for "sorti"- IX0.0, QX0.2 and QX8.1 are "on"- the rest are "off".*

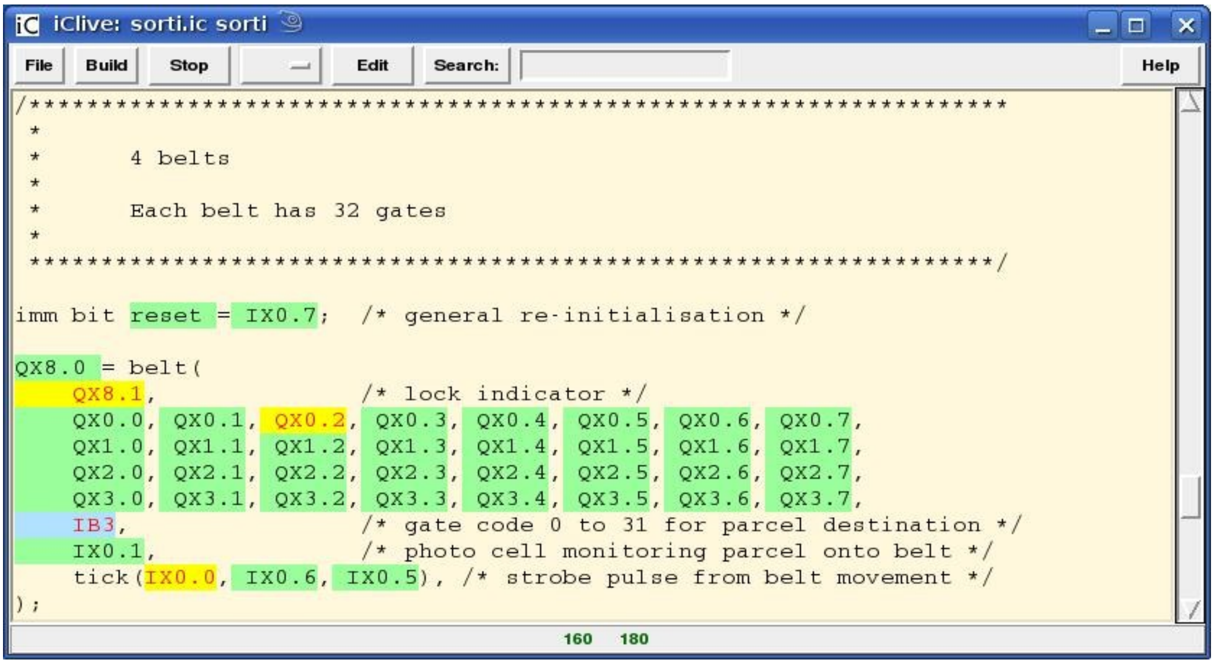


Fig. 4 ***iClive*** *in LIVE mode - QX8.1, QX0.2 and IX0.0 are "on"- the rest are "off".*
"sorti" is running. - it can be stopped by pressing the "Stop" button or switched to Edit mode by pressing the "Edit" button (see Fig. 5).

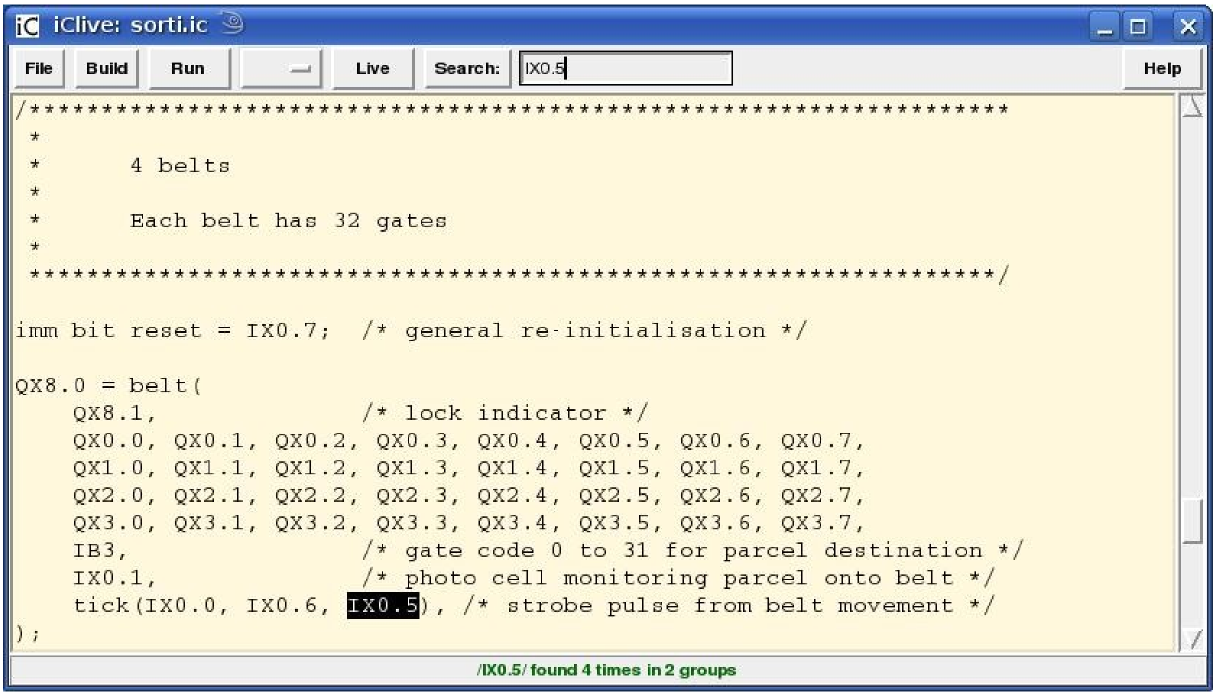


Fig. 5 ***iClive*** *in EDIT mode with a search for IX0.5 shown. The application "sorti" is not running - press "Run" and then "Live" to get to Fig. 4. "Help" to get the following:*

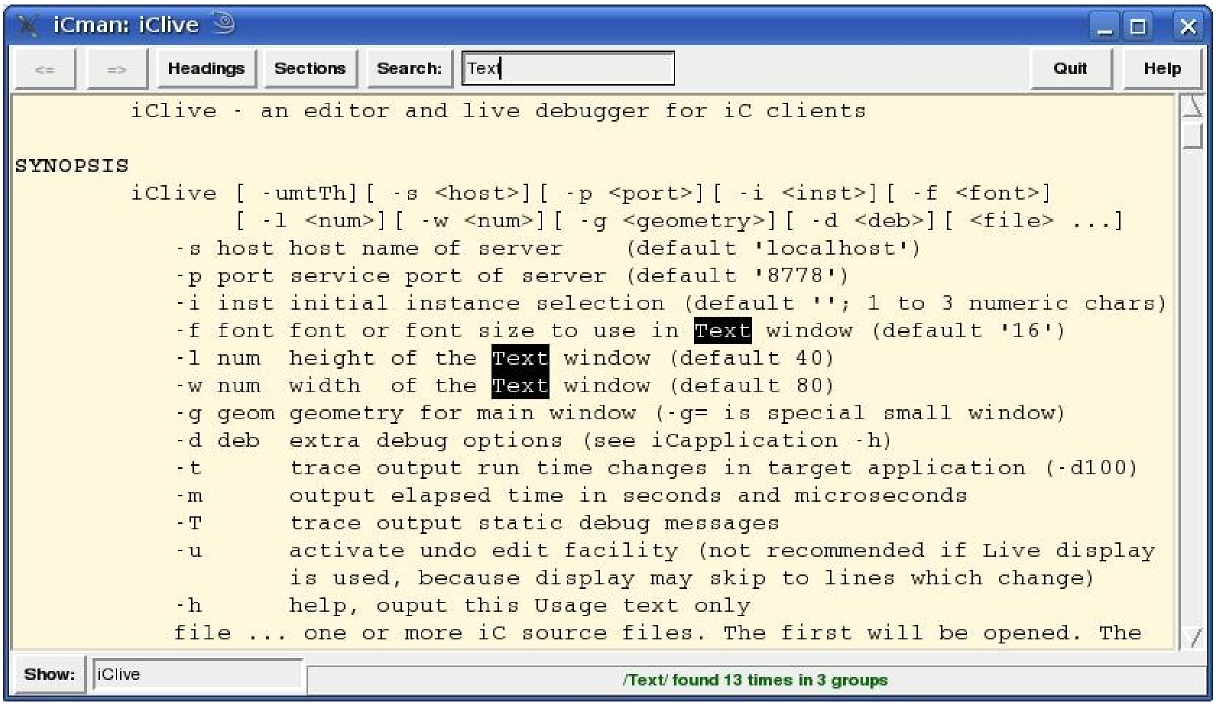


Fig. 6 ***iCman*** *showing the start of the man-page for iClive. A search for "Text" is shown.*

For command line use, a shell script ***iCmake*** builds one or more applications from ***iC*** sources using the static library ***libict.a***. The compiler ***immcc***, the programs ***iCserver***, ***iCbox***, ***iClive*** and ***iCmake*** as well as each compiled and linked ***iC*** application provide a generous help output with the -h switch option. Each of these programs also has a full man page which may be viewed with 'man' in a Unix like environment or with ***iCman***, a man page viewer with interesting search and Hyperlink features.

10 Bibliography

[Aho86] Alfred V. Aho, Ravi Sethi, Jeffrey D. Ullman
Compilers Principles, Techniques, and Tools
Addison-Wesley Publishing Company 1986

[Davis01] John Davis II, et al
Overview of the Ptolemy Project
University of California, Berkeley 2001

[Johnston04] Wesley M. Johnston, J. R. Paul Hanna, and Richard J. Millar
Advances in Dataflow Programming Languages
ACM Computing Surveys, Vol. 36, No. 1, March 2004, pp. 1–34.

[Kernighan84] Brian W. Kernighan, Rob Pike
The UNIX Programming Environment
Prentice Hall, Inc. 1984

[Kernighan88] Brian W. Kernighan, Dennis M. Ritchie
The C Programming Language
Prentice Hall, Inc. 1988

[Kluge92] Werner Kluge
The Organization of Reduction, Data Flow, and Control Flow Systems
The MIT Press 1992

[Lent89] Bogdan Lent
Dataflow Architecture for Machine Control
John Wiley & Sons Inc. 1989

[Phister63] Montgomery Phister, Jr.
Logical design of digital computers
John Wiley & Sons, Inc. 1963

[Sharp85] John A. Sharp
Data flow computing
Ellis Horwood Limited 1985

[Sparkes72] John Sparkes, Ed.
The Heart of Computers
The Open University Press 1972

[Srinivasan97] Sriram Srinivasan
Advanced Perl Programming
O'Reilly 1997

[Wall00] Larry Wall, Tom Christiansen & Jon Orwant
Programming Perl
O'Reilly 2000

[Walsh99] Nancy Walsh
Learning Perl/Tk
O'Reilly 1999

[Wulff72] E. Wulff
A Monitor for Real-Time-Control Systems
University of New South Wales 1972

11 The Author

John E. Wulff studied Electrical Engineering at the University of New South Wales in Sydney, Australia. His first professional experience was in the Telephone industry, developing switching circuits with electro-mechanical relays but also with vacuum tubes, cold cathode tubes and very soon with the emerging transistors. In 1964 he spent 6 months in England, getting know-how on a new family of switching circuits using germanium diodes and transistors, but which already supported clocked flip-flops. These had been developed at the BICC research laboratory near Hampton Court, where John Sparkes had invented the principle of clocking a few years earlier. With this experience, he was chief designer for a special purpose computer with 100 kilobytes of magnetic drum memory, 1 million transistors, 2.5 million diodes for logic and 100,000 silicon controlled rectifiers for power output drivers, switching up to 5 Amps. This machine controlled a letter sorting system with 150 input consoles and a throughput of 5 million letters a day. This system worked reliably for 25 years.

Experience with logic design based on integrated circuits followed. The availability of mini computers led to an interest in programming. A Master of Engineering Science Degree in Information Science at the University of New South Wales provided a solid foundation for future work as a Software Engineer. The design and implementation of a Real Time Operating System (or Monitor, as it was then called), which provided a task context switch in 15 machine instructions was the content of his Masters Thesis [Wulff72], and later provided the basis for some very fast industrial machine control systems.

In the mid 80's John Wulff came in contact with PLC's. He was asked to help during the commissioning of a PLC-system, controlling a parcel sorting complex consisting of 100 standard conveyor systems and 4 high speed conveyors which had mechanical gates along its length, to divert parcels. These high speed belts needed a control resolution of 15 milliseconds, in which time a parcel had moved 3 cm. Unfortunately the function blocks for the standard conveyors, executed 100 times, once for each of the conveyors, brought the total cycle time to over 1 second!! What to do? Fortunately the PLC had just enough (8) interrupt inputs, to allow the implementation of an event driven sub-system based on the assembler instruction set of the PLC. This saved the company a lot of liquidated damages.

This experience spawned the idea for an event driven PLC, which resulted in the current *iC* system. Although this system is demonstrably faster than a PLC with the same memory speed for any reasonable application one can think of, it is difficult to compute a guaranteed maximum response time. Since this is a requirement for hard real time applications, *iC* was never accepted for industrial use. For a PLC the maximum response time is simply the time to execute all instructions making up the program, which is the cycle time of the program. For an *iC* program this time can also be computed. For a 10 MHz PC the execution time is about 2 microseconds per gate node processed. The total number of gate nodes is provided in the listing produced by the compiler. An *iC* program with 10,000 gate nodes, which corresponds to a PLC program of approx. 32 kilobytes would thus have a maximum response time of 20 milliseconds, if all nodes were somehow fired simultaneously. This would be a good response time for a PLC. In practice this can never happen and a maximum response times of < 200 microseconds was measured on such a 10 MHz machine. This corresponds to events which cause 100 follow up nodes to fire. The typical number of follow up events is 7. Assuming this figure is Poisson distributed the above assumption is not unreasonable.

Current plans are, to publish the complete system under an Open Source License and to see if the Open Source Community can make a go of it. With the current emphasis on Linux in embedded Systems, I see great scope here.

`Id: iC.odt 1.30  2008/09/06`

Appendix A README

immediate C, iC rev 1.122

This program is free software; you can redistribute it and/or modify it under the terms of either:

a) the GNU General Public License as published by the Free Software Foundation; either version 2, or (at your option) any later version,

OR

b) the "Artistic License" which comes with this Kit.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See either the GNU General Public License or the Artistic License for more details.

You should have received a copy of the Artistic License with this Kit, in the file named "Artistic". If not, I'll be glad to provide one.

You should also have received a copy of the GNU General Public License along with this program; if not, write to the Free Software Foundation, Inc., 59 Temple Place, Suite 330, Boston, MA 02111-1307, USA.

For those of you that choose to use the GNU General Public License, my interpretation of the GNU General Public License is that no iC source falls under the terms of the GPL unless you explicitly put said source under the terms of the GPL yourself. Furthermore, any object code linked with iC does not automatically fall under the terms of the GPL, provided such object code only adds definitions of subroutines and variables, and does not otherwise impair the resulting interpreter from executing any standard iC source. I consider linking in C subroutines in this manner to be the moral equivalent of defining subroutines in the iC language itself. You may sell such an object file as proprietary provided that you provide or offer to provide the iC source, as specified by the GNU General Public License. (This is merely an alternate way of specifying input to the program.) You may also sell a binary produced by compiling an iC source that belongs to you with the iC compiler and linking it with the iC runtime library, provided that you provide or offer to provide the iC source as specified by the GPL. (The fact that the iC runtime library and your code are in the same binary file is, in this case, a form of mere aggregation.) This is my interpretation of the GPL. If you still have concerns or difficulties understanding my intent, feel free to contact me at <ic@je-wulff.de>.

Of course, the Artistic License spells all this out for your protection, so you may prefer to use that.

Acknowledgements to Larry Wall, whose README I used as a template.
and for Perl - which is just GREAT.

Acknowledgements to Nick Ing-Simmons for Perl/Tk - which is SMOOTH.

Acknowledgements to Linus Torvalds and the Open-Software community
for Linux(R) - which is SOMETHING ELSE.

Notes for the installation of iC rev 1.122

1) Pre-requisites. You need the following on your system:

```
C compiler                          # tested with gcc, MSC and Borland
Perl, Perl/Tk and Time::HiRes       # to build iC applications
```

1) Unpack the iC-archive in a suitable working directory with:

```
tar -xvzf icc_1.122.tgz
cd icc_1.122/src
```

2) Excute the following:

```
  configure    OR  ./configure      # if super user (depricated)
To make a Debug version do
  makeAll -gcl  OR  makeAll -qgcl  # to supress intermediate output
OR to make a Release version do
  make         OR  make quiet       # to supress intermediate output

this should build the files
  immcc                             # the iC to C compiler
  libict.a                          # the run-time library
without any errors
```

3) To compile and compare the test iC files in Test0 execute:

```
make test
```

4) To use the Perl support programs, it is mandatory that you install the Perl packages Tk800.024 or later and Time::HiRes unless they are already installed on your system. Both are included with this distribution. This can be checked by executing the following at this point:

```
iClive -h
```

Skip to point 8) if you get a help output and no error message. The last line tells you which version of Perl/Tk you are using.

5) Unpack build and install the Time::HiRes archive in a suitable working directory with:

```
tar -xvzf Time-HiRes-01.20.tar.gz
cd Time-HiRes-01.20
perl Makefile.PL
make
make test
su                                  ### Password ###
make install
exit                                ### IMPORTANT ###
cd ..
rm -rf Time-HiRes-01.20             # unless you want to keep it
```

6) Perl/Tk is usually contained in Linux distributions and will be installed automatically when the package is selected. If not, unpack, build and install Tk-800.024.tar.gz (or later). Follow the instructions in the README.xxx and INSTALL files. For Cygwin under WinXP a special binary distribution of Tk800.023 is included, which works fine.

7) Return to the immediate C installtion

```
cd icc_1.122/src                    # or the correct iC src directory
```

8) To install the iC-compiler, library and scripts execute the following as super user:

```
su                                  ### Password ###
make install
exit                                ### IMPORTANT ###
```

this copies the essential executables to /usr/local/bin
it also copies the include file icg.h to /usr/local/include
libict.a to /usr/local/lib and Msg.pm to /usr/lib/perl5/site...

(make uninstall as su will remove all these files)

9) To build and run the very simple iC application "hello.ic" do

```
iClive hello.ic                  # starts the IDE with hell0.ic
press Build > Build executable   # displays 'hello' successfully built
press Run                        # opens an iCbox with 1 button IX0.0
press button IX0.0 in iCbox      # button turns HI (input is green)
                                 # 'Hello! world' is output in the window iClive was started from
press Live
                                 # The word IX0.0 (the only immediate variable in hello.ic)
                                 # is coloured yellow/red, because IX0.0 is HI.
                                 # When IX0.0 is pressed again to LO, the colour in the live
                                 # display changes to green/black, indicating LO.
press File > Quit                # 'hello' and iCbox are terminated
```

10) A slightly bigger application is "simple.ic". Build and run it with iClive. An iCbox with 16 inputs and 8 outputs is started automatically. Explore the logic of the statements by changing inputs and following the outputs in iCbox and the live display in iClive.

11) The application "bar.ic" uses flip flops to produce a bar of running lights. The application also explores the use of programmable time delays, giving some idea of the scope of the iC language.

Running 'iClive bar.ic' as a separate process, while 'bar' is running, will display the source listing (in the edit window), connects to iCServer as an auxiliary client to receive updates of all variables from the running iC program (bar). These updates will change the colours of all words, which are immediate variables. (green/black = 0, yellow/red = 1) This "live display" shows the current state of logical relationships in visible statements of the iC program. Arithmetic variables are displayed in a balloon, when the cursor rests on a variable. (Arithmetic variables have a blue background).

In 'Live' mode, when a "live display" is shown, the text is read only. When the 'Edit' button is pressed 'iClive' is a full featured editor. The edit facilities of this program are described in the iClive man page under the Heading 'KEYBOARD BINDINGS' (press Help button in 'iClive').

'iClive' can use the Tk::TextUndo package, an extension of Tk::Text. This allows undoing changes with the Ctrl-u key. (Control-u is <<Undo>>) This is achieved by starting iClive with the -u option. Use this option only for editing. In 'Live' mode the display is very jerky with -u active.

12) Applications can of course be run without iClive. They do need iCserver though, which is a hub server for the TCP/IP packets exchanged between iC applications, I/O apllications (currently only iCbox) and optionally iClive.

```
iCserver &        # server runs on the background
iCbox IX0 &       # start IX0 manually
hello             # start application

ctrl-C            # terminate application
iCstop iCserver   # kill iCserver and iCbox
```

A better way is to start iCserver with the -a (auto-vivify) option, which will start simulated I/O iCbox, every time an iC application is started. Otherwise these must be started manually, which can be tedious for larger applications.

```
iCserver -a &     # auto-vivify iCbox for application
simple            # iCbox with 3 sets of I/O starts
```

If iClive is started first, it does all this automatically. It then kills iCserver automatically when it quits. When iCserver quits it kills all registered applications and I/O's.

13) I have included a script called 'iCstop' from my private toolkit. It can be used effectively to kill iCserver when it is executing in the background, which is appropriate for a server.

```
iCserver &
.....
../iCstop iCserver   # local copy of 'iCstop'
```

I have tried to use 'kill' with named processes as described in the 'kill' manpage, but it does not seem to work, even called as 'command kill iCserver'.
You will have to install 'iCstop' manually in a PATH directory to

use it anywhere in your system. (see 'iCstop -h' for help)

14) To make executable applications from iC sources, use the script iCmake. iCmake is a shell script to compile iC sources into C sources using the 'immcc' compiler. These in turn are compiled and linked into an executable iC applications (currently using gcc - this can be changed). Various options allow partial compilation and generation of listings.

```
iCmake -h  OR  iCman iCmake        # gives a lot of help
```

15) The OpenOffice 2.2 document doc/iC.odt (or doc/iC.pdf, doc/iC.html) is the handbook for the iC Programming Language. It opens the way to use "immediate C" fully.

16) There is a generous help output for every tool in the 'iC Project' initiated with the -h option. Each generated iC application also has a help output:

```
hello -h                           # list available options
```

These options allow connecting to iCserver on another computer in a LAN - or with a differnt port number. Very detailed debugging output, showing the change of state of every event in the system is available for the Debug version of the iC system. (Supressed for Release version)

17) There are 'man' pages for all the tools used in the 'iC Project'. These can be viewed with the normal 'man' command under Linux or with 'iCman'. The man page viewer 'iCman' has some nifty web-browser features to view and search man pages - try it with 'iCman iCman'.

Lots of success

John E. Wulff 2008.08.08 <ic@je-wulff.de>

I currently use SuSE Linux 9.3 with Tk800.024. I have tested the distribution with Cygwin under WinXP and a special binary distribution of Tk800.023 (in the kit). Perl under Windows Vista will not execute forked processes, so the iC support programs don't work.

A test with Tk804.027 under MAC-OSX 1.3 and SuSE Linux 10.2 both work, but live updates in iClive are noticably slow in both systems (about 10x). Tag-handling in Tk::Text is much slower under Tk804.27 than under Tk800.024 with Linux. Therefore I suggest staying with Tk800.024.

I have now switched to openSUSE 11.0, which brings along Tk804.28, which provides fast live updates in iClive again. They seem to be as fast as with Tk800.24. This was only judged by observation - at least the performance is now subjectively good and I suggest you get Tk804.28.

A Test with Knoppix and Tk804.25, which is still available for Debian also provided good performance with fast live updates in iClive.

Appendix B Type Definition Table

The following table defines function types and output types of Gate nodes used in the *iC* run-time system. In particular the abbreviation symbol columns 'os' and 'fos' are useful when interpreting the compiler generated listings. Others help to interpret *iC* source code.

	Define function type					Functp*	Functp	Functp	Functp	Functp
	type	os	-gt_ini	ftypes	yacc token	i_lists	[0]	[1]	[2]	[3]
0	UDF	.		UDFA	YYERRC.	gate_i	pass1	pass2	gate3	pass4
1	ARNC	-		ARITH	**AVARC**	gate_i	pass1	pass2	gate3	pass4
2	ARNF	+		ARITH	YYERRC.	gate_i	pass1	pass2	gate3	pass4
3	ARN	+		ARITH	YYERRC.	gate_i	pass1	pass2	gate3	pass4
4	LOGC	"		GATE	**LVARC**	gate_i	pass1	pass2	gate3	pass4
5	XOR	^	MIN_GT	GATE	YYERRC.	gate_i	pass1	pass2	gate3	pass4
6	AND	&		GATE	YYERRC.	gate_i	pass1	pass2	gate3	pass4
7	OR	|		GATE	YYERRC.	gate_i	pass1	pass2	gate3	pass4
8	LATCH	%		GATE	YYERRC.	gate_i	pass1	pass2	gate3	pass4
9	SH	*	MAX_GT	D_SH	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
10	FF	#		D_FF	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
11	EF	/		RI_BIT	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
12	VF	>		CH_BIT	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
13	SW	(		F_SW	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
14	CF	{		F_CF	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
15	NCONST	=		ARITH	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
16	INPB	]		OUTX	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
17	INPW	[		ARITH	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
18	INPX	<		TRAB	YYERRC.	ff_i	pass1	pass2	i_ff3	pass4
19	CLK	:	MAX_LV	CLCK	YYERRC.	clock_i	pass1	null1	i_ff3	null1
20	TIM	!		TIMR	YYERRC.	clock_i	pass1	null1	i_ff3	null1
21	ALIAS	@	MAX_OP	GATE	YYERRC.	clock_i	pass1	null1	i_ff3	null1
22	ERR	?		GATE	YYERRC.	clock_i	pass1	null1	i_ff3	null1
23	KEYW	;	MAX_LS	24	CTYPE	25	CWORD	26	IFUNCT	31 TM
	Define output type					Functp2	Functp2	Functp2	Functp	uint
	ftype	fos	gt_fni	types	yacc token	initAct	masterAct	slaveAct	init2	bit2
0	UDFA	U		UDF	UNDEF	err_fn	err_fn	err_fn	null1	0
1	ARITH	A		ARN	**AVAR**	arithMa	arithMa	err_fn	gate2	INPT_M
2	GATE		MAX_AR	OR	**LVAR**	link_ol	link_ol	err_fn	gate2	INPT_M
3	GATEX	_		OR	**LVAR**	link_ol	link_ol	err_fn	gate2	INPT_M
4	RI_BIT	E	MIN_ACT	EF	YYERRC.	link_c	riMbit	riSbit	i_ff2	RI_B_M
5	S_SH	s		SH	YYERRC.	link_c	sMsh	sSsh	i_ff2	S_SH_M
6	R_SH	r		SH	YYERRC.	link_c	rMsh	rSsh	i_ff2	R_SH_M
7	D_SH	H		SH	YYERRC.	dMsh	dMsh	dSsh	i_ff2	D_SH_M
8	CH_BIT	V		VF	YYERRC.	chMbit	chMbit	chSbit	i_ff2	CH_B_M
9	S_FF	S	1001	FF	YYERRC.	link_c	sMff	sSff	i_ff2	S_FF_M
10	R_FF	R	1010	FF	YYERRC.	link_c	rMff	rSff	i_ff2	R_FF_M
11	D_FF	D	1011	FF	YYERRC.	link_c	dMff	dSff	i_ff2	D_FF_M
12	F_SW	I		SW	YYERRC.	fMsw	fMsw	fSsw	null1	F_CW_M
13	F_CF	F		CF	YYERRC.	link_c	fMcf	fScf	null1	F_CF_M
14	F_CE	G		CF	YYERRC.	link_c	fMce	fScf	null1	F_CF_M
15	CLCK	C		CLK	YYERRC.	link_c	fMfn	clockSfn	i_ff2	CLCK_M
16	TIMR	T		TIM	YYERRC.	link_c	fMfn	timerSfn	i_ff2	TIMR_M
17	TRAB	B	MAX_ACT	INPX	YYERRC.	err_fn	err_fn	err_fn	null1	0
18	OUTW	W		ARN	**AOUT**	outMw	outMw	err_fn	null1	OUTP_M
19	OUTX	X		AND	**LOUT**	outMx	outMx	err_fn	null1	0
20	CLCKL	:		ERR	**CVAR**	err_fn	err_fn	err_fn	null1	0
21	TIMRL	!		ERR	**TVAR**	err_fn	err_fn	err_fn	null1	0
22	F_ERR	e	MAX_FTY	ERR	YYERRC.	err_fn	err_fn	err_fn	null1	0

23	ARITH_ALIAS	aA
24	GATE_ALIAS	a
25	GATEX_ALIAS	a_
26	INV_ALIAS	~
27	INVX_ALIAS	~_
42	CLCKL_ALIAS	a:
43	TIMRL_ALIAS	a!

Live display
These values are only used in **iClive** to colour names of alias nodes correctly

arithmetic input	arithmetic output
logic input	arithmetic output
arithmetic input	logic output
others: logic input and output	

icc.ods 1.19 2008/07/30