Quick Intro to Debugging with GDB

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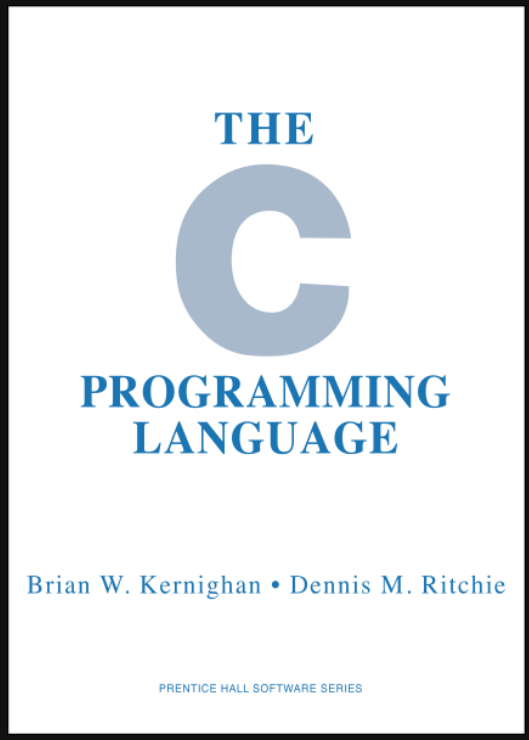
What is C?

C is a **imperative, general-purpose** programming language, developed in 1973 at AT&T Bell Labs by **Ken Thompson** (left) and **Dennis Ritchie** (right):

unknown

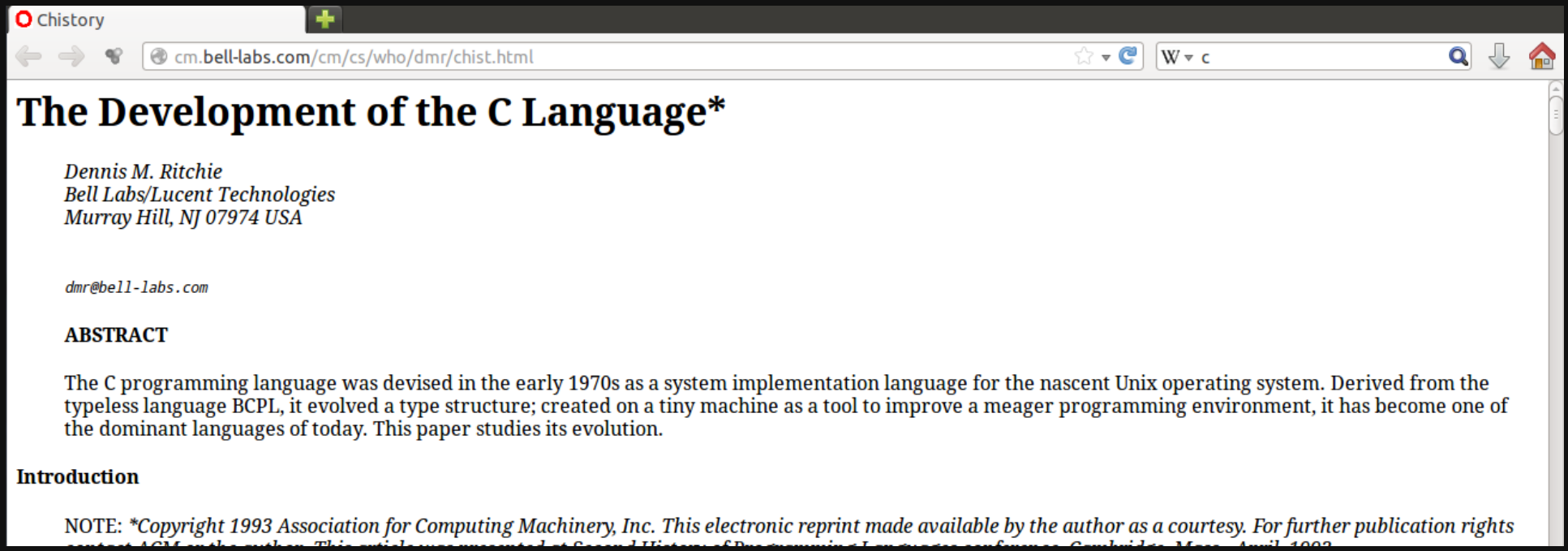


Julesmazur (Wikipedia)

The Development of the C Language

"*The Development of the C Language*", by Dennis Ritchie:

- http://cm.bell-labs.com/cm/cs/who/dmr/chist.html



Features of the C Language

- C is **imperative** (procedural).

  Instructions define the actions of the processor.

- C instructions **map easily** to **machine instructions**.

- C is meant to be **cross-platform**.

  Source code can be compiled to different hardware with minimal modifications.

- C uses **lexical scoping**.

  Variable scope defined by its position in the source code.

Features of the C Language

- C uses **static** type system.

  Types are checked during compile time.

- C supports **recursion**.

  A function can call itself.

- In C, function parameters are **passed by value**.

  Copies.

- C is **weakly** typed.

  Casting.

C Compilers

- There are several **C compilers** around. Some examples are:
  - Open Watcom C/C++.
  - CodeWarrior.
  - Clang (LLVM).
  - GCC.
- More C compilers can be found on:

  https://en.wikipedia.org/wiki/List_of_compilers#C_compilers

Versions of C

- Since its creation, C has undergone several **improvements**.
- Resulting **versions** have been **published** as **standards**:
  - ANSI C (1990), ratified as ISO/IEC 9899:1990.

    `gcc` option: **`-ansi`** or **`-std=c90`**
  - ISO/IEC 9899:1999.

    `gcc` option: **`-std=c99`**
  - ISO/IEC 9899:2011.

    `gcc` option: **`-std=c11`**

At the time of this writing, **my `gcc` defaults** to **`-std=gnu89`**, which stands for the **GNU-extended** version of the **ISO/IEC 9899:1990**.

C Program Example

The program below computes the summation of all integers within a given closed interval:

summation.c

```c
#include <stdio.h>

int Sum( int begin, int end ) {
    int i;
    int acc = 0;
    for ( i = begin; i <= end; i++ )
        acc += i;

    return acc;
}

int main ( void ) {
    int a = 1;
    int b = 5;
    int sum = Sum( a, b );
    printf( "Sum: %i\n", sum );
    return 0;
}
```

Compile and run

```
~$ gcc summation.c
~$ ./a.out
```

or

```
~$ gcc summation.c -o summation
~$ ./summation
```

C Data Types

- Basic types.
- Structured types.
- User defined types.

  They are, basically, combinations of the above data types identified by a user-defined name.

Basic Data Types

- char
- int
- float
- double
- pointers

Optional specifiers*:

- signed
- unsigned
- short
- long

*may not apply to all numeric types.

char	signed int	long long int
signed char	unsigned	signed long long
unsigned char	unsigned int	signed long long int
short	long	unsigned long long
short int	long int	unsigned long long int
signed short	signed long	float
signed short int	signed long int	double
unsigned short	unsigned long	long double
unsigned short int	unsigned long int	
int	long long	

Aggregate Data Types

C offers 2 types of aggregate data types:

- Arrays.
- Structs.

Structs

- Is an **aggregate** that might contain **members** of **different types**.
- Given a variable of type `struct`, its members can be **accessed** through the '`.`' operator.
- Example

`structs.c`

```c
struct Date {
    int day;
    int month;
    int year;
};

int main( void ) {
    struct Date x;
    x.day = 5;
    x.month = 2;
    x.year = 2016;

    return 0;
}
```

Arrays

*"(...) an **array data structure**, or simply an **array**, is a data structure consisting of a **collection** of elements (values or variables), each identified by at least one array **index** or key. An array is stored so that the **position** of each element **can be computed from its index tuple** by a mathematical formula."*

Array data structure, Wikipedia

Arrays in C

- Traditionally of **fixed**, **static** size.
- Usually, **all elements** are of the **same type**.
- **Does not** carry information about its **size**!
- May be **multidimensional**.
- Example:

example_26.c

```c
#include <stdio.h>

int x[4] = { 10, 20, 30, 40 };

int main( void ) {
    int i;
    for ( i = 0; i < 4; i++ )
        printf( "%i ", x[i] );

    return 0;
}
```

Multidimensional Arrays in C

- **Multidimensional** arrays can be obtained by applying the array concept **recursively**.
- Example:

example_27.c

```c
#include <stdio.h>

int x[2][3] = { { 10, 20, 30}, { 40, 50, 60 } };

int main( void ) {
    int i, j;
    for ( i = 0; i < 2; i++ )
        for ( j = 0; j < 3; j++ )
            printf( "%i ", x[i][j] );

    return 0;
}
```

Logical representation of the 2D array.

	0	1	2
0	10	20	30
1	40	50	60

Actual distribution of the array elements in memory.

addr + 0	10
addr + 1	20
addr + 2	30
addr + 3	40
addr + 4	50
addr + 5	60

Another C Program Example

The program below computes the average of the following integers: 2, 2, 3, 4 and 5:

average.c

```c
#include <stdio.h>

float Average( int *w, int n ) {
    int i;
    int avg;
    for ( i = 0; i < n; i++ )
        avg += w[i];

    return avg / n;
}

int main ( void ) {
    int x[5] = {2, 2, 3, 4, 5};
    int num = 5;
    float avg = Average( x, num );
    printf( "Average: %f\n", avg );
    return 0;
}
```

Oops! We were expecting the **average** to be **3.2**! **How do we approach this problem?**

DIY!

Debuggers

- “(...) *a computer program that is used to test and debug other programs* (...).”

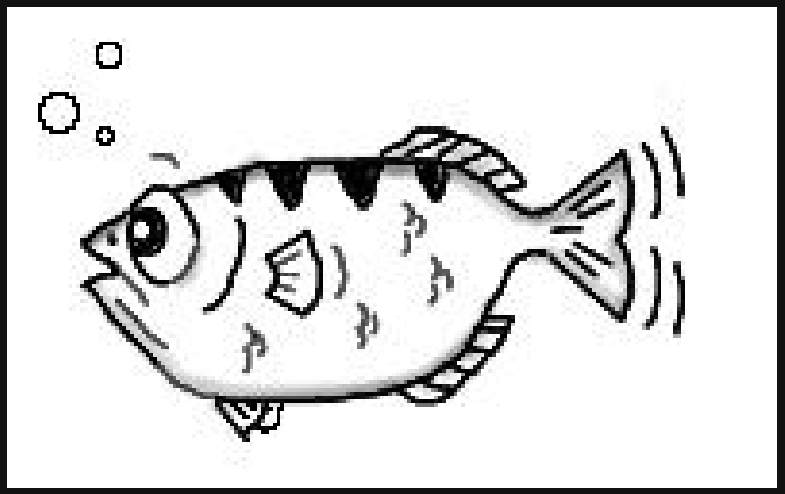
  Debugger, Wikipedia.

- Examples:
  - Microsoft Visual Studio Debugger.
  - LLDB.
  - GDB.

GDB

GDB, or the GNU Project Debugger

- Popular debugger tool used among Unix/Linux programmers.
- It comes, usually, pre-installed in several Linux distributions.



The Archer Fish, the GDB mascot.

GDB

Features (as of version 7.10):

- Can be used to debug C and C++ programs.
- Partial support to some other languages.
- Text-based.
- “Normal”, temporary and conditional breakpoints.
- Single-stepping.
- Resume.
- Watchpoints.
- Variable inspection.
- Call stack inspection.
- Etc.

GDB Usage Example

Back to our broken C program:

average.c

```c
#include <stdio.h>

float Average( int *w, int n ) {
    int i;
    int avg;
    for ( i = 0; i < n; i++ )
        avg += w[i];

    return avg / n;
}

int main ( void ) {
    int x[5] = {2, 2, 3, 4, 5};
    int num = 5;
    float avg = Average( x, num );
    printf( "Average: %f\n", avg );
    return 0;
}
```

Recompile the program with the following command:

```
~$ gcc -g3 average.c -o average
```

Inserts debugging information into the executable.

GDB Usage Example

- After the recompilation, invoke GDB on the executable file:

```
~$ gdb ./average
```

- From within the GDB environment, let's issue the following commands:
  - List the source code from within GDB:

```
(gdb) list 1, 100
```

or

```
(gdb) l 1, 100
```

  - Set a breakpoint at line 13:

```
(gdb) break 13
```

or

```
(gdb) b 13
```

GDB Usage Example

From within the GDB environment, let's issue the following commands (cont.):

- Run the program:

```
(gdb) run
```

or

```
(gdb) r
```

- Lets inspect the value of variable **x**:

```
(gdb) print x
```

or

```
(gdb) p x
```

- Execute line 14 (just one step):

```
(gdb) step
```

or

```
(gdb) s
```

- Lets inspect the value of variable **x** again:

```
(gdb) p x
```

GDB Usage Example

From within the GDB environment, let's issue the following commands (cont.):

- Which is the next line to be executed?

```
(gdb) frame
```

or

```
(gdb) f
```

- One more step:

```
(gdb) s
```

- Step over the call to **`Average()`**:

```
(gdb) next
```

or

```
(gdb) n
```

→ **Differently from `step`, `next` do not step into functions!**

- Inspect the value of variable **`avg`**:

```
(gdb) p avg
```

→ **It seems that the problem is within the `Average()` function!**

GDB Usage Example

From within the GDB environment, let's issue the following commands (cont.):

- Let's restart the program:

```
(gdb) r
```

- We've got stuck at line 13 again! First, let's print breakpoint information for the program:

```
(gdb) info breakpoint
```
or
```
(gdb) info b
```

- Now, delete breakpoint 1:

```
(gdb) delete 1
```
or
```
(gdb) d 1
```

- Step until we reach line 15.

GDB Usage Example

From within the GDB environment, let's issue the following commands (cont.):

- Now, let's step into the function **`Average()`**:

```
(gdb) s
```

→ **`step` steps into functions!**

- Let's check the value of the local variable **`avg`**:

```
(gdb) p avg
```

→ **`avg` was not properly initialized!**

- Initialize **`avg`** with 0!
- Now, recompile the program (do not close GDB!).
- Rerun the program, without breakpoints, and check the answer. → **It seems that we still have a problem!**

GDB Usage Example

From within the GDB environment, let's issue the following commands (cont.):

- Set a breakpoint at the function **`Average()`**:

```
(gdb) b Average
```

- Rerun the program (it will stop within **`Average()`**).
- Set a watchpoint for when the loop finishes (**`i == n`**):

```
(gdb) watch i == n
```

- Continue until next breakpoint / watchpoint.

```
(gdb) continue
```

or

```
(gdb) c
```

GDB Usage Example

From within the GDB environment, let's issue the following commands (cont.):

- Check the value of variables **`avg`** and **`n`**.
- Step until we leave **`Average()`**.
- Check the value that was returned by the function.

Damn! The value is incorrect! So what????

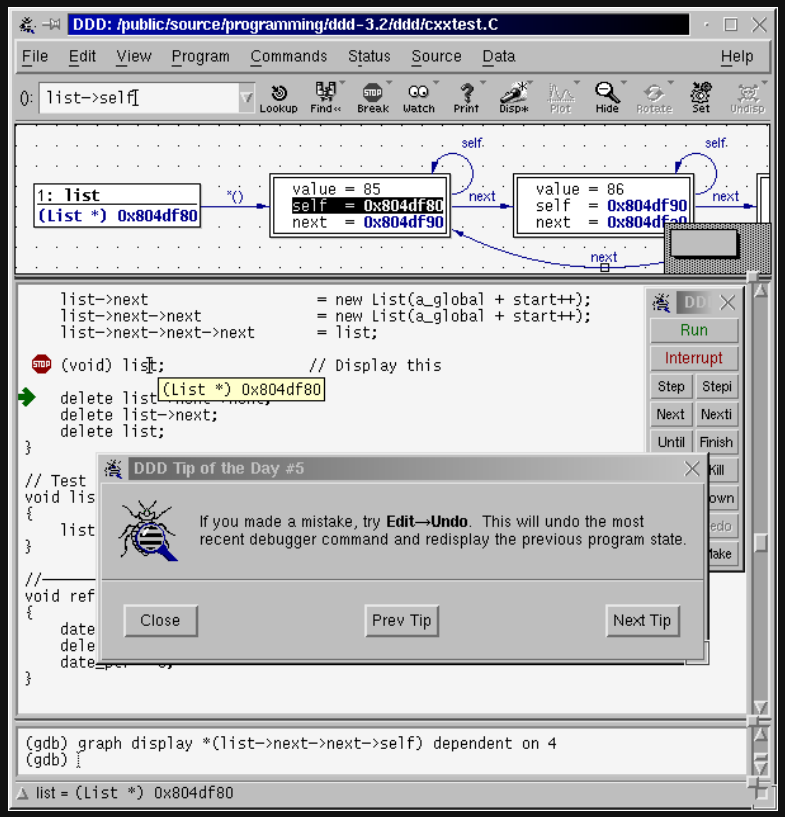
- The value returned by **`Average()`** is the result of a integer division! We have to cast one of the operators (e.g. **`(float) avg/n`**) to force a **float division**!
- Apply cast, recompile, delete all breakpoints and rerun!

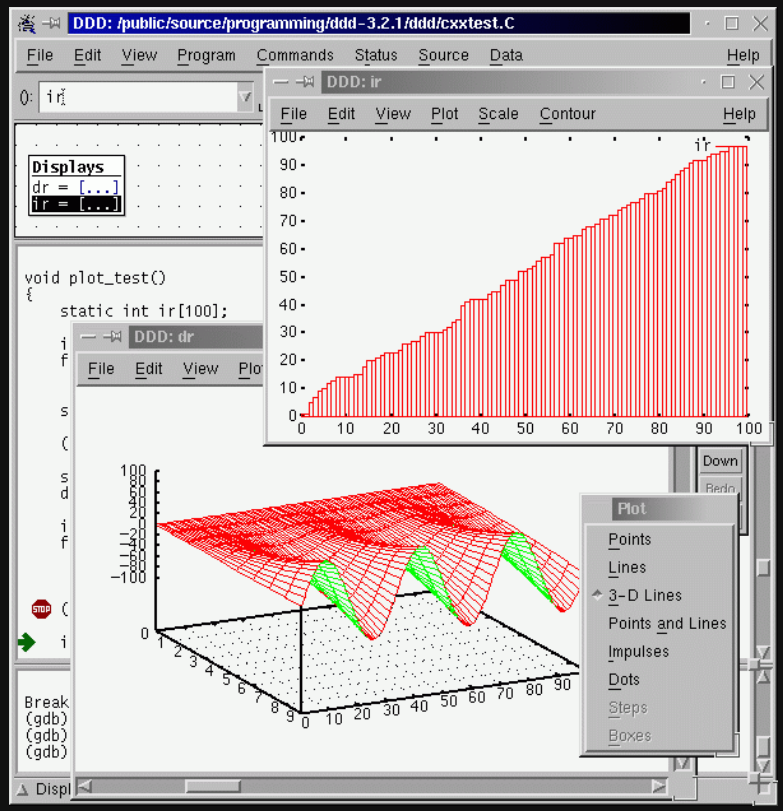
GDB Summary

- GDB is a quite powerful debugger tool.
- However, GDB does no allow one to easily follow the source code during a debug section.
- Some **GDB front ends** were developed, most notably:
  - CTRL + x + a : splits the GDB screen in command and source code windows (buggy!).
  - cgdb: curses based GDB front end.
  - Eclipse: an IDE that may use GDB as its debugging tool.
  - DDD : the Data Display Debugger.

The Data Display Debugger (DDD)

- It is a graphical interface to GDB.





- More on:
  - https://www.gnu.org/software/ddd

Back to C Data Types... Pointers!

A **pointer** variable is a **memory location** into which **data** (i.e. a **memory address**) can be **stored**.

Pointer Variable Example

Compile and run the following code from within GDB:

example_23.c

```
int main( void ) {
    int x;
    int *px;
    x = 25;
    px = &x;

    return 0;
}
```

$00000000000000000000000000011001_2$

```
(gdb) b 4      → Set a breakpoint at line 4.
(gdb) r        → Run (stops at line 4).
(gdb) p &x     → Print the address of x.
(gdb) p x      → Print the integer value stored at x.
(gdb) s
```

DIY!

x

byte

Addr.	Value
addr1 - 1	. . .
addr1 + 0	. . .
addr1 + 1	. . .
addr1 + 2	. . .
addr1 + 3	. . .

addr2 + 0	. . .
addr2 + 1	. . .
addr2 + 2	. . .
addr2 + 3	. . .
addr2 + 4	. . .
addr2 + 5	. . .
addr2 + 6	. . .
addr2 + 7	. . .

Pointer Variable Example

Compile and run the following code from within GDB:

example_23.c

```
int main( void ) {
    int x;
    int *px;
    x = 25;

    px = &x;

    return 0;
}
```

$00000000000000000000000000011001_2$

$00000000000000000111111111111111$
$11111111111111111011010000010 0_2$

```
(gdb) b 4
(gdb) r
(gdb) p &x
(gdb) p x
(gdb) s
(gdb) p x
(gdb) p px
(gdb) s
```

- Set a breakpoint at line 4.
- Run (stops at line 4).
- Print the address of `x`.
- Print the integer value stored at `x`.
- Execute line 4 (`x = 25`).
- Print the integer value stored at `x`.
- Print the address stored at `px`.

byte

	Addr.	Value
x	addr1 - 1	00011001
	addr1 + 0	00000000
	addr1 + 1	00000000
	addr1 + 2	00000000
	addr1 + 3	00000000
px	addr2 + 0	...
	addr2 + 1	...
	addr2 + 2	...
	addr2 + 3	...
	addr2 + 4	...
	addr2 + 5	...
	addr2 + 6	...
	addr2 + 7	...

Pointer Variable Example

Compile and run the following code from within GDB:

example_23.c

```
int main( void ) {
    int x;
    int *px;
    x = 25;
    px = &x;

    return 0;
}
```

$00000000000000000000000000011001_2$

$00000000000000001111111111111111$
$11111111111111111101110100000100_2$

byte

	Addr.	Value
x	addr1 - 1	00011001
	addr1 + 0	00000000
	addr1 + 1	00000000
	addr1 + 2	00000000
	addr1 + 3	00000000
px	addr2 + 0	00000100
	addr2 + 1	11011101
	addr2 + 2	11111111
	addr2 + 3	11111111
	addr2 + 4	11111111
	addr2 + 5	01111111
	addr2 + 6	00000000
	addr2 + 7	00000000

```
(gdb) b 4     → Set a breakpoint at line 4.
(gdb) r       → Run (stops at line 4).
(gdb) p &x    → Print the address of x.
(gdb) p x     → Print the integer value stored at x.
(gdb) s       → Execute line 4 (x = 25).
(gdb) p x     → Print the integer value stored at x.
(gdb) p px    → Print the address stored at px.
(gdb) s       → Execute line 5 (px = &x).
(gdb) p px    → Print the address stored at px.
```

Examining Data with GDB: `print`

- `print` is the most **common** way to **examine data**, and is based on **expression evaluation**.
- `print` is able to **format** the **output!**
- Back to the previous example: set a breakpoint at line 7 (`return 0`) and run.

example_23.c

```
int main( void ) {
    int x;
    int *px;
    x = 25;
    px = &x;

    return 0;
}
```

Experiment `print` with these arguments:

```
(gdb) p x      → Print the integer value stored at x.
(gdb) p /x x   → Print the value at x in hexa format.
(gdb) p /t x   → Print the value at x in binary format.
```

Examining Data with GDB: `x`

- The `x` command allows for **low-level** data examination.
- It prints the **contents** of **memory** positions in a specified **format**.

Examining Data with GDB: `x`

Back to the previous example: set a breakpoint at line 7 (`return 0`) and run.

example_23.c

```
int main( void ) {
    int x;
    int *px;
    x = 25;
    px = &x;

    return 0;
}
```

Experiment `x` with these arguments:

```
(gdb) x &x       → Print the value at address &x (last format).
(gdb) x/t &x     → Print the value at address &x in binary.
(gdb) x/d &x     → Print the value at address &x in decimal.
(gdb) x/4tb &x   → Print 4 bytes in binary starting at addr. &x.
(gdb) x/8tb &px  → Print 8 byt. in binary starting at addr. &px.
```

byte →

	Addr.	Value
	addr1 - 1	00011001
x	addr1 + 0	00000000
	addr1 + 1	00000000
	addr1 + 2	00000000
	addr1 + 3	00000000
px	addr2 + 0	00000100
	addr2 + 1	11011101
	addr2 + 2	11111111
	addr2 + 3	11111111
	addr2 + 4	11111111
	addr2 + 5	01111111
	addr2 + 6	00000000
	addr2 + 7	00000000

Scripting GDB

What if we would like to print the intermediary values of the summation below?

summation.c

```c
#include <stdio.h>

int Sum( int begin, int end ) {
    int i;
    int acc = 0;
    for ( i = begin; i <= end; i++ )
        acc += i;

    return acc;
}

int main ( void ) {
    int a = 1;
    int b = 5;
    int sum = Sum( a, b );
    printf( "Sum: %i\n", sum );
    return 0;
}
```

We can automate it with **GDB scripting**, thus avoiding code modifications!

Scripting GDB

The following GDB script dumps on the screen all intermediary values generated during the summation computation:

sumdebug.gdb

```
set width 0
set height 0
set verbose off

b 8

commands 1
    silent
    printf "acc = %i\n", acc
    continue
end

b 10

commands 2
    silent
    printf "acc = %i\n", acc
    continue
end

run
```

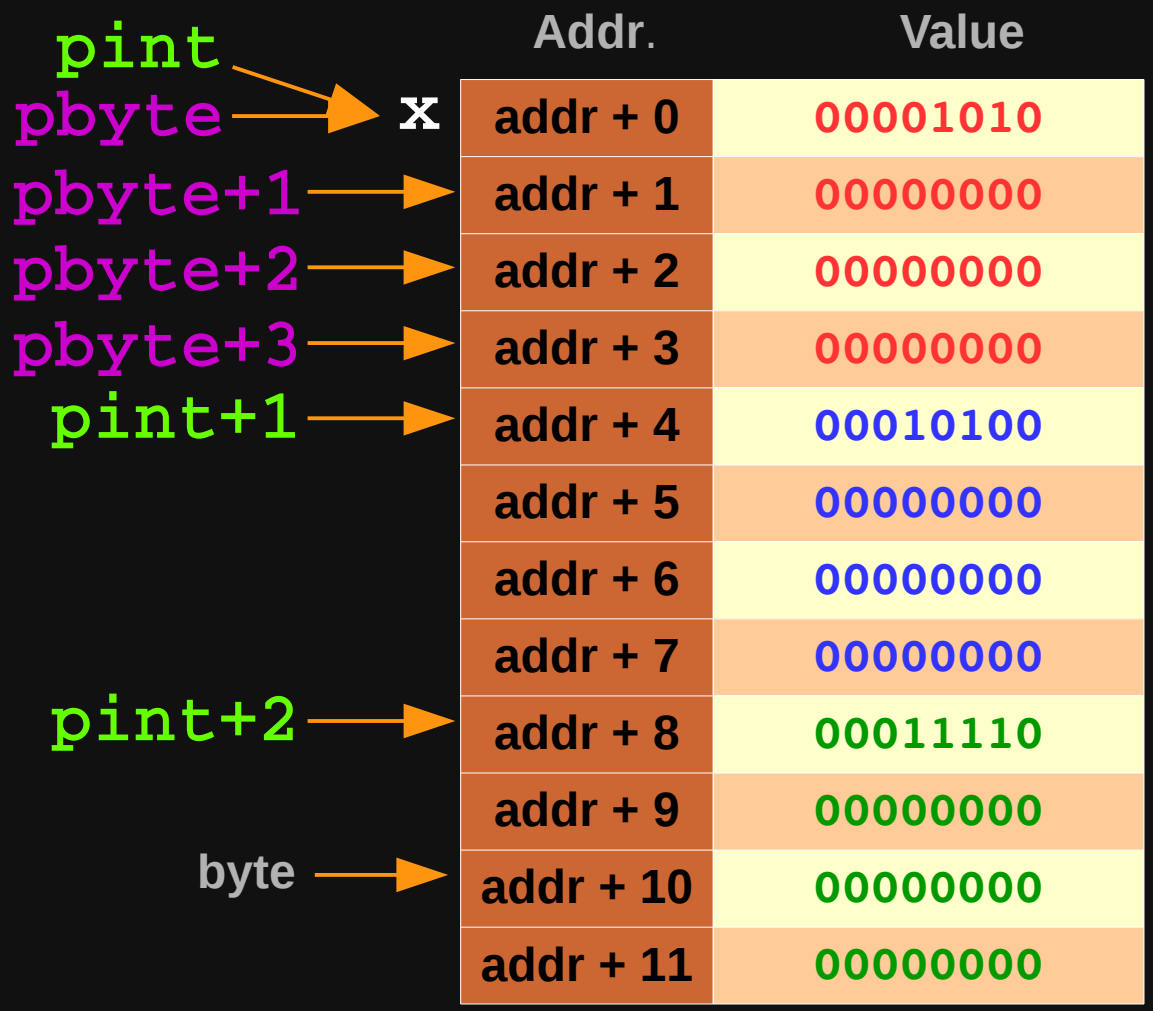
Invoking GDB

```
~$ gdb --batch --command=sumdebug.gdb a.out
```

Pointer Arithmetic

example_24.c

```c
int x[4] = { 10, 20, 30, 40 };

int main( void ) {
    int *pint = x;

    *pint = 0;
    *(pint + 1) = 0;
    *(pint + 2) = 0;
    *(pint + 3) = 0;

    char *pbyte = ( char* ) x;

    *pbyte = 255;
    *(pbyte + 1) = 255;
    *(pbyte + 2) = 255;
    *(pbyte + 3) = 255;

    return 0;
}
```



Pointer Arithmetic

example_24.c

```c
int x[4] = { 10, 20, 30, 40 };

int main( void ) {
    int *pint = x;

    *pint = 0;
    *(pint + 1) = 0;
    *(pint + 2) = 0;
    *(pint + 3) = 0;

    char *pbyte = ( char* ) x;

    *pbyte = 255;
    *(pbyte + 1) = 255;
    *(pbyte + 2) = 255;
    *(pbyte + 3) = 255;

    return 0;
}
```

Dereferencing can be equivalently rewritten with [ ]!

Sounds familiar?

example_25.c

```c
int x[4] = { 10, 20, 30, 40 };

int main( void ) {
    int *pint = x;

    pint[0] = 0;
    pint[1] = 0;
    pint[2] = 0;
    pint[3] = 0;

    char *pbyte = ( char* ) x;

    pbyte[0] = 255;
    pbyte[1] = 255;
    pbyte[2] = 255;
    pbyte[3] = 255;

    return 0;
}
```

Pointers vs. Arrays

- Are arrays **pointers**?
- If there is a difference, **could you point it out**?

Before discussing **how arrays** actually **work** in C, we will first take a look at **assembly**!

References

Learning C with GDB. Alan O' Donnell.

- https://www.recurse.com/blog/5-learning-c-with-gdb