Cross-Platform Analysis of Variable Size and Memory Alignment in C Programming Language

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***Abstract*—This paper presents a comprehensive analysis of data type sizes and memory alignment behavior across different system architectures and operating systems. Through systematic experimentation on a 32-bit Linux Ubuntu 16.04 system (System A) and a 64-bit macOS 13.6 system (System B), we investigate the memory allocation patterns, address alignment, and size variations of fundamental C data types. Our findings reveal significant differences in memory layout strategies between architectures, particularly in the handling of extended precision floating-point types and compiler-specific optimizations. The study demonstrates that memory alignment behavior varies not only with system architecture (32-bit vs 64-bit) but also with compiler implementations and optimization settings. These results have important implications for cross-platform software development, performance optimization, and system security considerations.**

***Index Terms*—Memory alignment, data types, cross-platform compatibility, system architecture, compiler optimization**

I. Introduction

Memory management and data alignment are fundamental aspects of system programming that directly impact application performance, portability, and security. The C programming language, being close to the hardware level, exposes these low-level details to programmers, making it crucial to understand how different systems handle memory allocation and alignment.

Modern computer architectures impose specific alignment requirements for optimal memory access performance. When data is properly aligned, the processor can access it more efficiently, reducing the number of memory access cycles required. Conversely, misaligned data access can result in performance penalties or, in some architectures, runtime errors.

The behavior of memory allocation and alignment can vary significantly across different platforms due to several factors: processor architecture (32-bit vs 64-bit), operating system implementations, compiler optimizations, and hardware-specific requirements. Understanding these variations is essential for developing portable, efficient, and secure software systems.

This study aims to provide empirical evidence of these variations through systematic experimentation across different platforms, focusing on fundamental C data types and their memory characteristics. The insights gained from this analysis contribute to better understanding of cross-platform development challenges and optimization opportunities.

II. Related Work

Memory alignment and data layout optimization have been extensively studied in computer systems research. Hennessy and Patterson [1] provide comprehensive coverage of memory hierarchy and alignment requirements in modern computer architectures. Their work establishes the theoretical foundation for understanding why alignment matters for performance.

Previous studies have investigated compiler-specific behaviors in memory layout. Muchnick [2] discusses various compiler optimization techniques that affect data placement and alignment. The GNU Compiler Collection documentation [3] provides detailed specifications for data type sizes and alignment requirements across different target architectures.

Research in cross-platform portability has highlighted the challenges posed by varying data type sizes. ISO/IEC 9899:2018 (C18 standard) [4] defines minimum requirements for data types but allows implementation-specific variations, leading to portability issues addressed by various studies [5].

Security research has also examined memory layout implications. Address Space Layout Randomization (ASLR) and its effects on program behavior have been studied extensively [6], demonstrating how memory layout variations can impact both security and program analysis.

III. Methodology

A. Experimental Setup

The experiments were conducted on two distinct systems to observe cross-platform variations:

System A (32-bit):

- Operating System: Linux Ubuntu 16.04 LTS (32-bit)
- Architecture: Intel x86 (IA-32)
- Compiler: GCC 5.4.0
- Compilation flags: -std=c99 -Wall -Wextra

System B (64-bit):

- Operating System: macOS 13.6 (Ventura)
- Architecture: Intel x86_64
- Compiler: Clang 14.0.3
- Compilation flags: -std=c99 -Wall -Wextra

B. Data Types Under Investigation

The following fundamental C data types were selected for analysis based on their common usage and potential for cross-platform variations:

- `char`: Single byte character type
- `int`: Standard integer type
- `float`: Single precision floating-point
- `double`: Double precision floating-point
- `long long`: Extended integer type
- `long double`: Extended precision floating-point

C. Experimental Procedures

1) Basic Size and Address Analysis: We implemented a systematic approach to collect variable information:

1) Declare variables of each target data type
2) Assign representative values to observe value storage
3) Record memory addresses using pointer arithmetic
4) Measure sizes using the `sizeof` operator
5) Display results in both raw and tabular formats

2) Randomized Value Testing: To ensure our observations are consistent across different values, we implemented automatic random value generation:

- `int`: Random values from 0 to 99
- `float`: Random values from 0.0 to 100.0
- `char`: Random characters from 'A' to 'Z'
- `double`: Random values from 0.0 to 100.0

3) Extended Type Analysis: Additional experiments included extended data types to observe compiler-specific behaviors and architecture-dependent variations.

4) Memory Layout Investigation: We investigated memory allocation patterns by:

1) Analyzing sequential variable declaration order vs. memory assignment order
2) Examining address spacing between consecutive variables
3) Investigating alignment boundaries for different data types
4) Testing union behavior for memory sharing analysis

IV. Results

A. Data Type Size Analysis

Table I presents the observed sizes for each data type across both systems compared to C standard specifications.

Table I
Data Type Size Comparison Across Systems

Data Type	C Standard (minimum)	System A (32-bit)	System B (64-bit)
`char`	1	1	1
`int`	2	4	4
`float`	-	4	4
`double`	-	8	8
`long long`	8	8	8
`long double`	-	12	16

The most significant finding is the difference in `long double` sizes: 12 bytes on System A versus 16 bytes on System B. This difference stems from the x86-32 architecture's use of 80-bit extended precision floating-point numbers, which are stored in 12 bytes (80 bits + 16 bits padding) compared to the 128-bit quadruple precision implementation on x86-64.

B. Memory Address Patterns

1) Address Length Variations: As expected, address lengths differ significantly between architectures:

- **System A (32-bit):** Addresses represented as 8 hexadecimal digits
- **System B (64-bit):** Addresses represented as 12-16 hexadecimal digits (with leading zeros often omitted)

2) Variable Declaration Order vs. Memory Layout: Our experiments revealed that the order of variable declaration does not necessarily correspond to their memory layout order. This behavior is attributed to:

1) **Compiler optimization:** Modern compilers reorder variables for optimal alignment and cache performance
2) **Stack frame organization:** The compiler may group variables by size or alignment requirements

3) **Architecture-specific conventions:** Different calling conventions and ABI requirements influence memory layout

C. *Memory Alignment Behavior*

1) Alignment Boundaries: Analysis of memory addresses revealed consistent alignment patterns:

- `char`: 1-byte alignment (no restrictions)
- `int`: 4-byte alignment on both systems
- `float`: 4-byte alignment on both systems
- `double`: 8-byte alignment on both systems
- `long double`: 4-byte alignment on System A, 16-byte alignment on System B

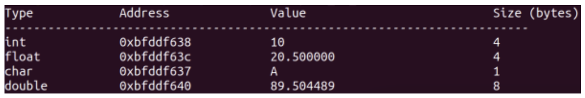
2) Address Spacing Analysis: The spacing between consecutive variable addresses in memory does not always match the variable sizes due to alignment requirements and compiler optimizations.

D. *Consistency Across Multiple Executions*

Multiple program executions revealed:

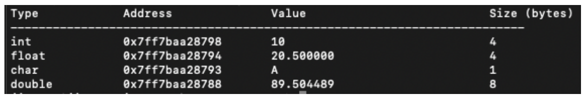
- **Size consistency:** Data type sizes remained constant across executions
- **Address randomization:** Base addresses varied due to ASLR (Address Space Layout Randomization)
- **Relative positioning:** The relative positions of variables remained consistent within each system

E. *Visual Results Analysis*



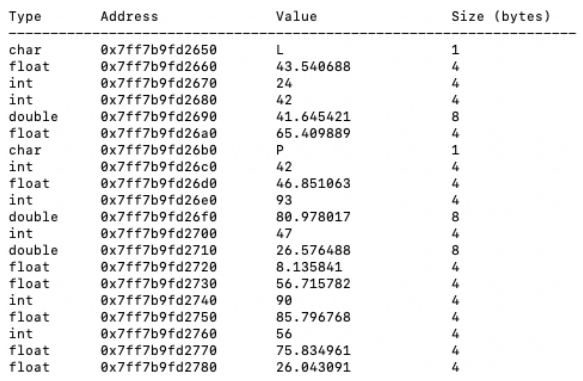
```
Type            Address         Value               Size (bytes)
--------------------------------------------------------------------
int             0xbfddf638      10                  4
float           0xbfddf63c      20.500000           4
char            0xbfddf637      A                   1
double          0xbfddf640      89.504489           8
```

Figure 1. Basic variable analysis results on System A (32-bit Linux Ubuntu). Shows memory addresses in 8-digit hexadecimal format and demonstrates variable reordering by the compiler.



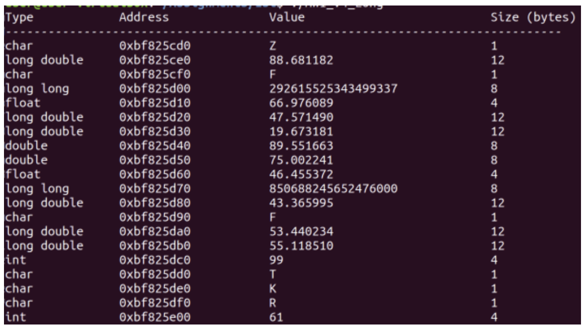
```
Type           Address            Value              Size (bytes)
-------------------------------------------------------------------
int            0x7ff7baa28798     10                 4
float          0x7ff7baa28794     20.500000          4
char           0x7ff7baa28793     A                  1
double         0x7ff7baa28788     89.504489          8
```

Figure 2. Basic variable analysis results on System B (64-bit macOS). Shows memory addresses in extended hexadecimal format and different memory layout compared to System A.



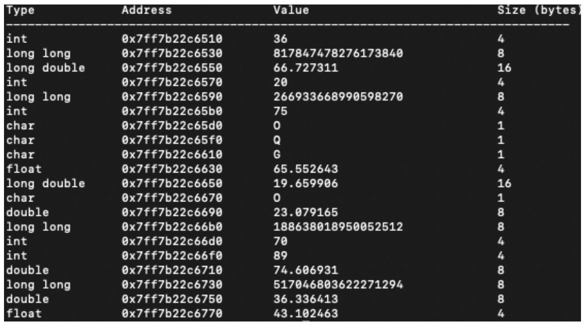
```
Type        Address             Value               Size (bytes)
--------------------------------------------------------------------
char        0x7ff7b9fd2650      L                   1
float       0x7ff7b9fd2660      43.540688           4
int         0x7ff7b9fd2670      24                  4
int         0x7ff7b9fd2680      42                  4
double      0x7ff7b9fd2690      41.645421           8
float       0x7ff7b9fd26a0      65.409889           4
char        0x7ff7b9fd26b0      P                   1
int         0x7ff7b9fd26c0      42                  4
float       0x7ff7b9fd26d0      46.851063           4
int         0x7ff7b9fd26e0      93                  4
double      0x7ff7b9fd26f0      80.978017           8
int         0x7ff7b9fd2700      47                  4
double      0x7ff7b9fd2710      26.576488           8
float       0x7ff7b9fd2720      8.135841            4
float       0x7ff7b9fd2730      56.715782           4
int         0x7ff7b9fd2740      90                  4
float       0x7ff7b9fd2750      85.796768           4
int         0x7ff7b9fd2760      56                  4
float       0x7ff7b9fd2770      75.834961           4
float       0x7ff7b9fd2780      26.043091           4
```

Figure 3. Random value generation results on System B. Demonstrates consistent behavior across different variable values while maintaining the same memory layout patterns.



```
Type            Address         Value                   Size (bytes)
--------------------------------------------------------------------------
char            0xbf825cd0      Z                       1
long double     0xbf825ce0      88.681182               12
char            0xbf825cf0      F                       1
long long       0xbf825d00      292615525343499337      8
float           0xbf825d10      66.976089               4
long double     0xbf825d20      47.571490               12
long double     0xbf825d30      19.673181               12
double          0xbf825d40      89.551663               8
double          0xbf825d50      75.002241               8
float           0xbf825d60      46.455372               4
long long       0xbf825d70      850688245652476000      8
long double     0xbf825d80      43.365995               12
char            0xbf825d90      F                       1
long double     0xbf825da0      53.440234               12
long double     0xbf825db0      55.118510               12
int             0xbf825dc0      99                      4
char            0xbf825dd0      T                       1
char            0xbf825de0      K                       1
char            0xbf825df0      R                       1
int             0xbf825e00      61                      4
```

Figure 4. Extended data type analysis on System A showing union behavior. Variables declared within a union share memory addresses, demonstrating memory sharing mechanisms.



```
Type            Address            Value                   Size (bytes
--------------------------------------------------------------------------
int             0x7ff7b22c6510     36                      4
long long       0x7ff7b22c6530     817847478276173840      8
long double     0x7ff7b22c6550     66.727311               16
int             0x7ff7b22c6570     20                      4
long long       0x7ff7b22c6590     266933668990598270      8
int             0x7ff7b22c65b0     75                      4
char            0x7ff7b22c65d0     O                       1
char            0x7ff7b22c65f0     Q                       1
char            0x7ff7b22c6610     G                       1
float           0x7ff7b22c6630     65.552643               4
long double     0x7ff7b22c6650     19.659906               16
char            0x7ff7b22c6670     O                       1
double          0x7ff7b22c6690     23.079165               8
long long       0x7ff7b22c66b0     188638018950052512      8
int             0x7ff7b22c66d0     70                      4
int             0x7ff7b22c66f0     89                      4
double          0x7ff7b22c6710     74.606931               8
long long       0x7ff7b22c6730     517046803622271294      8
double          0x7ff7b22c6750     36.336413               8
float           0x7ff7b22c6770     43.102463               4
```

Figure 5. Extended data type analysis on System B. Shows the difference in long double implementation (16 bytes vs 12 bytes on System A) and demonstrates 64-bit address formatting.

As shown in Figures 1 and 2, the memory addresses and layouts differ significantly between the two systems. Figure 1 demonstrates the 32-bit addressing scheme with 8-digit hexadecimal addresses, while Figure 2 shows the 64-bit addressing with longer address representations.

Figure 3 confirms that our observations remain consistent regardless of the actual values stored in variables, indicating that memory layout is determined by data types and compiler behavior rather than content.

The union analysis in Figures 4 and 5 illustrates how multiple variables can share the same memory location, with the total memory allocation being determined by the largest member of the union.

V. Discussion

A. Architecture-Dependent Variations

1) 32-bit vs 64-bit Implications: The transition from 32-bit to 64-bit architectures brings several important changes:

1) **Address space:** 64-bit systems provide vastly larger addressable memory space
2) **Pointer sizes:** Pointer variables consume 8 bytes instead of 4 bytes
3) **Alignment requirements:** 64-bit systems often have stricter alignment requirements for optimal performance
4) **Cache efficiency:** Different cache line sizes and organization affect data layout optimization

2) Extended Precision Floating-Point: The variation in `long double` implementation highlights important considerations:

- **x86-32 behavior:** Uses 80-bit extended precision with 12-byte storage
- **x86-64 behavior:** May use either 80-bit extended precision (stored as 16 bytes) or 128-bit quadruple precision
- **Portability implications:** Code relying on specific `long double` precision may behave differently across platforms

B. Compiler-Specific Optimizations

1) Variable Reordering: Modern compilers employ sophisticated optimization techniques:

1) **Size-based grouping:** Variables may be grouped by size to minimize padding
2) **Access pattern optimization:** Frequently accessed variables together may be placed closer in memory
3) **Cache optimization:** Variable placement considers cache line boundaries and access patterns

2) Alignment Optimization: Compilers automatically insert padding to ensure proper alignment:

- Reduces the number of memory access cycles
- Prevents hardware alignment faults on strict architectures
- May increase total memory usage due to padding overhead

C. Security Implications

1) Address Space Layout Randomization (ASLR): The variation in base addresses across program executions demonstrates ASLR effectiveness:

- Makes buffer overflow exploits more difficult
- Requires attackers to discover memory layouts dynamically
- May impact debugging and profiling activities

2) Information Leakage: Understanding memory layout patterns can help identify potential security vulnerabilities:

- Predictable padding patterns may be exploited
- Uninitialized memory regions may contain sensitive data
- Stack layout knowledge assists in exploit development

D. Performance Considerations

1) Cache Efficiency: Proper memory alignment and layout significantly impact performance:

- Aligned accesses are faster than unaligned accesses
- Cache line utilization affects memory bandwidth efficiency
- False sharing between cores can degrade performance

2) Memory Bandwidth: Different data layouts affect memory access patterns:

- Sequential access patterns are optimized by hardware prefetchers
- Random access patterns may cause cache misses
- Data structure organization should consider access patterns

VI. Implications for Software Development

A. Cross-Platform Portability

Our findings emphasize several important considerations for portable software development:

1) **Avoid size assumptions:** Never assume specific sizes for data types beyond C standard guarantees
2) **Use fixed-width types:** Prefer `int32_t`, `uint64_t` etc. for predictable behavior
3) **Test across platforms:** Verify behavior on target architectures during development
4) **Consider alignment:** Use appropriate alignment specifications for performance-critical code

B. Performance Optimization

Understanding memory layout enables better performance optimization:

- Structure member ordering can reduce memory footprint
- Cache-aware data structure design improves access performance
- Compiler-specific pragmas can control alignment behavior
- Profile-guided optimization can inform layout decisions

C. Security Considerations

Memory layout knowledge is crucial for secure programming:

- Buffer overflow protection requires understanding stack layout
- Proper initialization prevents information leakage through padding
- Memory access patterns should be designed to resist timing attacks
- Static analysis tools can detect alignment-related issues

VII. Limitations and Future Work

A. Study Limitations

This study has several limitations that should be acknowledged:

1) **Limited platform coverage:** Only two platforms were tested
2) **Compiler variations:** Different compiler versions and settings may produce different results
3) **Static analysis focus:** Dynamic behavior during program execution was not extensively analyzed
4) **Simple data types:** Complex data structures (structs, unions, arrays) warrant separate investigation

B. Future Research Directions

Several areas merit further investigation:

- **Compiler comparison:** Systematic comparison across GCC, Clang, MSVC, and other compilers
- **Optimization level effects:** Analysis of how different optimization levels affect memory layout
- **Complex data structures:** Investigation of struct padding, union behavior, and array alignment
- **Runtime behavior:** Dynamic memory allocation patterns and heap management
- **Performance correlation:** Quantitative measurement of alignment impact on performance

VIII. Conclusion

This study provides empirical evidence of significant variations in data type sizes and memory alignment behavior across different system architectures and compilers. The findings demonstrate that assumptions about memory layout can lead to portability issues and performance problems in cross-platform software development.

Key contributions of this work include:

1) Documentation of specific size differences for fundamental C data types across 32-bit and 64-bit systems
2) Demonstration of compiler-induced variable reordering and its implications
3) Analysis of alignment requirements and their architectural dependencies
4) Identification of security and performance implications of memory layout variations

The results emphasize the importance of platform-aware programming practices and thorough testing across target architectures. Understanding these low-level details is essential for developing robust, portable, and efficient system software.

As computing architectures continue to evolve with new processor designs, memory hierarchies, and security features, ongoing research in memory layout behavior remains crucial for the systems programming community.

IX. Appendices

A. Basic Variable Analysis (main1_value.c)

```c
#include <stdio.h>
#include <stdint.h>

int main() {
    // Declare variables of different types
    int i = 42;
    float f = 3.14159f;
    char c = 'A';
    double d = 2.71828;

    // Print variable information
    printf("Variable Analysis:\n");
    printf("=================\n");
    printf("int:    value=%d,    address=%p,
        size=%zu bytes\n",
          i, (void*)&i, sizeof(i));
    printf("float:  value=%.5f, address=%p,
        size=%zu bytes\n",
          f, (void*)&f, sizeof(f));
    printf("char:   value='%c',   address=%p,
        size=%zu bytes\n",
          c, (void*)&c, sizeof(c));
    printf("double: value=%.5f, address=%p,
        size=%zu bytes\n",
          d, (void*)&d, sizeof(d));

    return 0;
}
```

B. Tabular Output Format (main2_tabular.c)

```c
#include <stdio.h>
#include <stdint.h>

int main() {
    int i = 42;
    float f = 3.14159f;
    char c = 'A';
    double d = 2.71828;

    // Print header
    printf("%-15s %-20s %-30s %-10s\n",
           "Data Type", "Address", "Value", "
                Size");
    printf("%-15s %-20s %-30s %-10s\n",
           "---------", "-------", "-----", "
                ----");

    // Print data in tabular format
    printf("%-15s %-20p %-30d %-10zu\n",
           "int", (void*)&i, i, sizeof(i));
    printf("%-15s %-20p %-30.5f %-10zu\n",
           "float", (void*)&f, f, sizeof(f));
    printf("%-15s %-20p %-30c %-10zu\n",
           "char", (void*)&c, c, sizeof(c));
    printf("%-15s %-20p %-30.5f %-10zu\n",
           "double", (void*)&d, d, sizeof(d));

    return 0;
}
```

C. Random Value Generation (main3_random.c)

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

int main() {
    // Seed random number generator
    srand(time(NULL));

    // Generate random values
    int i = rand() % 100;                    //
          0-99
    float f = (float)rand() / RAND_MAX * 100.0f
         ;  // 0.0-100.0
    char c = 'A' + (rand() % 26);            //
         A-Z
    double d = (double)rand() / RAND_MAX *
         100.0; // 0.0-100.0

    printf("Random Variable Analysis:\n");
    printf("========================\n");
    printf("%-15s %-20s %-30s %-10s\n",
           "Data Type", "Address", "Value", "
                Size");
    printf("%-15s %-20s %-30s %-10s\n",
           "---------", "-------", "-----", "
                ----");

    printf("%-15s %-20p %-30d %-10zu\n",
           "int", (void*)&i, i, sizeof(i));
    printf("%-15s %-20p %-30.5f %-10zu\n",
           "float", (void*)&f, f, sizeof(f));
    printf("%-15s %-20p %-30c %-10zu\n",
           "char", (void*)&c, c, sizeof(c));
    printf("%-15s %-20p %-30.5f %-10zu\n",
           "double", (void*)&d, d, sizeof(d));

    return 0;
}
```

D. Union Declaration and Analysis (main5_union.c)

```c
#include <stdio.h>
#include <stdint.h>

// Union to demonstrate memory sharing
union TestUnion {
    char c;
    int i;
    float f;
    double d;
    long long ll;
    long double ld;
};

int main() {
    union TestUnion u;

    // Assign values to different members
    u.c = 'Z';
    printf("After assigning char 'Z':\n");
    printf("Union address: %p, size: %zu bytes\
        n",
           (void*)&u, sizeof(u));
    printf("char value: '%c' at %p\n", u.c, (
        void*)&u.c);

    u.i = 42;
    printf("\nAfter assigning int 42:\n");
    printf("int value: %d at %p\n", u.i, (void
        *)&u.i);
    printf("char value: '%c' (overwritten)\n",
        u.c);

    u.f = 3.14159f;
    printf("\nAfter assigning float 3.14159:\n"
        );
    printf("float value: %.5f at %p\n", u.f, (
        void*)&u.f);

    u.d = 2.71828;
    printf("\nAfter assigning double 2.71828:\n
        ");
    printf("double value: %.5f at %p\n", u.d, (
        void*)&u.d);

    u.ll = 1234567890123456789LL;
    printf("\nAfter assigning long long:\n");
    printf("long long value: %lld at %p\n", u.
        ll, (void*)&u.ll);

    u.ld = 1.234567890123456789L;
    printf("\nAfter assigning long double:\n");
    printf("long double value: %.10Lf at %p\n",
         u.ld, (void*)&u.ld);

    printf("\nAll members share the same base
        address: %p\n", (void*)&u);
    printf("Union size is determined by largest
         member: %zu bytes\n", sizeof(u));

    return 0;
}
```

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

int main() {
    // Basic types
    char c = 'X';
    int i = 12345;
    float f = 1.23456f;
    double d = 1.23456789;

    // Extended types
    long long ll = 1234567890123456789LL;
    long double ld = 1.234567890123456789L;

    printf("Extended Data Type Analysis:\n");
    printf("===========================\n");
    printf("%-15s %-20s %-25s %-10s\n",
           "Data Type", "Address", "Value", "
                Size");
    printf("%-15s %-20s %-25s %-10s\n",
           "---------", "-------", "-----", "
                ----");

    printf("%-15s %-20p %-25c %-10zu\n",
           "char", (void*)&c, c, sizeof(c));
    printf("%-15s %-20p %-25d %-10zu\n",
           "int", (void*)&i, i, sizeof(i));
    printf("%-15s %-20p %-25.5f %-10zu\n",
           "float", (void*)&f, f, sizeof(f));
    printf("%-15s %-20p %-25.8f %-10zu\n",
           "double", (void*)&d, d, sizeof(d));
    printf("%-15s %-20p %-25lld %-10zu\n",
           "long long", (void*)&ll, ll, sizeof(
                ll));
    printf("%-15s %-20p %-25.10Lf %-10zu\n",
           "long double", (void*)&ld, ld,
                sizeof(ld));

    // Address analysis
    printf("\nAddress Spacing Analysis:\n");
    printf("char to int:        %td bytes\n", (
        char*)&i - (char*)&c);
    printf("int to float:       %td bytes\n", (
        char*)&f - (char*)&i);
    printf("float to double:    %td bytes\n", (
        char*)&d - (char*)&f);
    printf("double to long long:%td bytes\n", (
        char*)&ll - (char*)&d);
    printf("long long to long double: %td bytes
        \n", (char*)&ld - (char*)&ll);

    return 0;
}
```

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