Pointer Checker Feature in Intel® C++ Composer 2013: Catch Out-of-Bounds Memory Accesses easily!

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Agenda

- What is Pointer Checker?
- Pointer Checker Enabling – At a glance
- Pointer Checker Usage Model
- Using Pointer Checker
  - Checking Bounds
  - Checking for Dangling Pointers
  - Checking Arrays
  - Intrinsics
  - Working with Enabled and Non-Enabled Modules
  - Checking Run Time Library (RTL) functions
  - Finding and Reporting Out-of-Bounds Errors
  - Guidelines
- Pointer Checker – Performance Overhead
- Summary
What is Pointer Checker?

- C/C++ pointers have well defined semantics that determine range of memory to access.
  - Compilers typically do not enforce

  ```c
  p = malloc(size);
  • lower_bound(p) is (char *)p
  • upper_bound(p) is lower_bound(p) + size - 1
  ```

- Buffer Overflow/Overrun anomaly
  - Violation of memory safety
  - Data corruption
  - Erratic program behavior
  - Breach of system security
  - Basis of many software vulnerabilities

  ```c
  char *buf = malloc(5);
  for (int i=0; i<=5;i++) {
    buf[i] = ‘A’ + i;
  }
  ```
What is Pointer Checker?

**Key Benefits**

- A key feature of Intel® C++ Composer XE 2013
- Designed for use during application debugging and testing
- Enabled via compile time switches.
- User API allows control over what happens when a violation is detected
- Implemented mostly in a runtime library which is automatically linked in by the compiler
- No change to structure layout or ABIs

- Catches out-of-bounds memory accesses
  - Identifies and reports before memory corruption occurs!
- Finds memory buffer overruns
  - Checks memory accesses through pointers
  - Includes subscripted array accesses
- Finds dangling pointers
  - Checks memory accesses through freed pointers

**Key Benefit: Enable Incrementally**

Pointer Checker can be enabled on a single file, group of files or all files. Pointer Checker enabled code and non-enabled code can coexist!
Pointer Checker – *How it works?*

High Level Design

- **The compiler:**
  - Creates bounds when a pointer is created via the “&” operator or array reference.
  - Copies bounds when a pointer is copied.
  - Stores bounds when a pointer is stored in memory.
  - Loads bounds when a pointer is loaded from memory.
  - Passes bounds with pointer arguments and function returns.
  - Generates checks when a pointer is used for indirect memory references.

- **Runtime library wrappers:**
  - Create bounds when memory is allocated
  - Bounds follows the pointer. Casting doesn’t change the bounds of the pointer.
  - Checks bounds for pointer parameters (Example: `strcpy()`)

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Pointer Checker Enabling - *At a glance*

Getting started is easy...

- Meet requirements:
  - Compile and build your application with:
    - `-check-pointers=[none | write | rw]` (Linux* OS)
    - `/Qcheck-pointers:[none | write | rw]` (Windows* OS)
    - Pointer Checker is off by default
    - Checks all indirect accesses through pointers and accesses to arrays.

<table>
<thead>
<tr>
<th>Supported Languages</th>
<th>Supported Architecture</th>
<th>Supported Platforms</th>
<th>Supported Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, C++</td>
<td>IA-32, Intel® 64</td>
<td>Linux*, Windows*</td>
<td>Intel® Pentium® 4 processor or later, or compatible non-Intel processor</td>
</tr>
</tbody>
</table>

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**Pointer Checker Enabling - At a glance**

**A sample program**

- Compile with Pointer Checker enabling option
- Execute; Check for out-of-bounds errors (OOB)
- Determine if OOB is true or false positive

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

int main () {
    #ifdef REPORT
        __chkp_report_control(__CHKP_REPORT_TRACEBACK, 0);
    #endif

    char *my_chptr = "abc";
    char *another_chptr;
    another_chptr = (char *) malloc(strlen((char *)my_chptr));
    printf("sizeof another_chptr is %d\n", strlen((char *)my_chptr));
    printf("sizeof my_chptr is %d\n", sizeof(my_chptr));
    memset(another_chptr, '@', sizeof(my_chptr)); /* Line 15 */
    printf("after memset = %s\n", another_chptr);
    return 0;
}
```

- Compile without Pointer Checker enabling switch:
  ```
  % icc main.c ./a.out
  sizeof another_chptr is 3
  sizeof my_chptr is 8
  after memset = @@@@@@@@@
  ```

- Compile with Pointer Checker enabling option:
  ```
  % icc main.c -DREPORT -check-pointers=write -rdynamic -g ./a.out
  sizeof another_chptr is 3
  sizeof my_chptr is 8
  CHKP: Bounds check error
  Traceback is:
  ./a.out(__chkp_check_bounds+0x1f1) [0x403a31]
  ./a.out(__chkp_memset+0x68) [0x404078]
  ./a.out(main+0x334) [0x4032b8]
  /lib64/libc.so.6(__libc_start_main+0x7f) [0x7fba1b43ebfd]
  ./a.out() [0x402ec9]
  %
  ```

- Map address to source line where OOB occurs
  ```
  % addr2line -e ./a.out 0x4032b8
  main.c:15
  %
  ```
### Pointer Checker – Usage Model

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Header File</strong></td>
<td>Defines intrinsics and reporting functions (chkp.h)</td>
</tr>
<tr>
<td><strong>Compiler Options</strong></td>
<td></td>
</tr>
<tr>
<td>- check-pointers</td>
<td>Enables pointer checker and adds associated libraries</td>
</tr>
<tr>
<td>- check-pointers-dangling</td>
<td>Enables checking for dangling pointer references</td>
</tr>
<tr>
<td>- check-pointers-undimensioned</td>
<td>Enables the checking of bounds for arrays without dimensions</td>
</tr>
<tr>
<td><strong>Intrinsics</strong></td>
<td></td>
</tr>
<tr>
<td>void * __chkp_lower_bound(void **)</td>
<td>Returns the lower bound associated with the pointer</td>
</tr>
<tr>
<td>void * __chkp_upper_bound(void **)</td>
<td>Returns the upper bound associated with the pointer</td>
</tr>
<tr>
<td>void * __chkp_kill_bounds(void *p)</td>
<td>Removes the bounds information to allow the pointer in the argument to access all memory.</td>
</tr>
<tr>
<td>void * __chkp_make_bounds(void *p, size_t size)</td>
<td>Creates new bounds information within the allocated memory address for the pointer in the argument</td>
</tr>
<tr>
<td><strong>Reporting API</strong></td>
<td></td>
</tr>
<tr>
<td>(<em>Function/Enumeration</em>)</td>
<td>Determines how errors are reported</td>
</tr>
</tbody>
</table>
| __chkp_report_control(__chkp_report_optio
n_t option, __chkp_callback_t callback) | Controls how out-of-bounds error are reported. Enumerations in header file |
| __chkp_report_option_t {Enumerations: __CHKP_REPORT_LOG, __CHKP_REPORT_TRACEBACK, __CHKP_REPORT_CALLBACK, __CHKP_REPORT_BPT, __CHKP_REPORT_TERM} | |
| **RTL Functions**      | Provides checking on C run-time library functions that manipulate memory through pointers |

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Using Pointer Checker - **Checking Bounds**

Checks indirect accesses through pointers for accesses that are out of bounds

- **Check Bounds on Read/Write Operations**
  - check-pointers=[none | write | rw] (Linux* OS)
  - /Qcheck-pointers:[none | write | rw] (Windows* OS)

```
%cat main.c
#include<stdio.h>
#include<malloc.h>
#include<chkp.h>

int main () {
    #ifdef REPORT
        __chkp_report_control(__CHKP_REPORT_TRACEBACK, 0);
    #endif
    char *buf = malloc(4);
    int i;
    for (i=0; i<=4; i++) {
        printf(" %c",buf[i]); /* Line# 12 */
    }
    for (i=0; i<=4; i++) {
        buf[i] = 'A' + i;  /* Line# 15 */
        printf(" %c",buf[i]);
    }
    printf("\n");
    return 0;
}
```

- **Compile without** Pointer Checker enabling switch:
  % icc main.c -g;/a.out
  A B C D E

- **Compile with** Pointer Checker enabling option:
  % icc main.c -DREPORT -check-pointers=write -rdynamic -g;/a.out
  **CHKP: Bounds check error**
  **Traceback is:**
  ./a.out(__chkp_check_bounds+0x1f1) [0x4033c1]
  ./a.out(main+0x21f) [0x402c83]
  /lib64/libc.so.6(__libc_start_main+0xfd) [0x3b7d41ec5d]
  ./a.out() [0x4029a9]

- **Map address to source line where OOB occurs**
  % addr2line -e ./a.out 0x402c83
  **main.c:15**
  %

- **An out-of-bounds error was not reported for line#12. Why?**

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Using Pointer Checker - Checking For Dangling Pointers

• Check for dangling pointers in stack and heap
  -check-pointers-dangling=[none | heap | stack | all] (Linux* OS)
  /Qcheck-pointers-dangling:[none | heap | stack | all] (Windows* OS)

• When enabled:
  ∵ Compiler uses a wrapper for the C runtime function free() and the C++ delete operator.
  ∵ Compiler sets dangling pointer bounds to: lower_bound(dp) = 2; upper_bound(dp)=0;

Why are the bounds set as above?

```c
#include <stdio.h>
#include <malloc.h>
#include <chkp.h>

char * test() {
    char *dp = malloc(6);
    strcpy(dp, "hello");
    free(dp);
    return dp; /* dp is dangling pointer now */
}

int main () {
    #ifdef REPORT
    __chkp_report_control(__CHKP_REPORT_TRACEBACK, 0);
    #endif
    char *q = test();
    printf("
```
Using Pointer Checker - Checking Arrays

- Pointer checker checks arrays in modules that actually define the arrays with bounds
- For checking of bounds for arrays without dimensions:
  - [no-]check-pointers-undimensioned (Linux* OS)
  - /Qcheck-pointers-undimensioned[-] (Windows* OS)

```c
#include<stdio.h>
#include <chkp.h>
extern int A[];
int main () {
    #ifdef REPORT
    __chkp_report_control(__CHKP_REPORT_TRACEBACK, 0);
    #endif
    A[5] = 2; /* OOB Line 10 */
    return 0;
}
```

```c
% cat arr.c
#include<stdio.h>
#include <chkp.h>
extern int A[];
int main () {
    #ifdef REPORT
    __chkp_report_control(__CHKP_REPORT_TRACEBACK, 0);
    #endif
    A[5] = 2; /* OOB Line 10 */
    return 0;
}
```
Using Pointer Checker - **Intrinsics**

- Defined in header file `<chkp.h>`
- Ideal for:
  - Writing your own wrappers for Run-Time Library (RTL) functions
  - Working with enabled and non-enabled Modules
  - Checking and creating correct bounds for Custom Memory Allocators
  - &c

**Intrinsics:**

void * __chkp_kill_bounds(void *p)
- Kills the descriptor associated with the pointer making all memory accessible via the returned pointer.

void * __chkp_make_bounds(void *p, size_t size)
- Make bounds for a pointer. The lower bounds is pointer, and the upper bound is pointer + (size – 1).

void * __chkp_lower_bound(void **)
void * __chkp_upper_bound(void **)
- Retrieves the lower / upper bound associated with a pointer

**For example (setting exact bounds)**

```c
void *myalloc(size_t size) {
    // Code allocating the large chunk of memory
    // into small chunks.
    // Add bounds information to the pointer
    return __chkp_make_bounds(p, size);
}
```

**For example: An Allocation wrapper**

```c
extern void *wrap_malloc(size_t bytes) {
    void* p; p = malloc(bytes);
    if (p) {
        p = (void*)__chkp_make_bounds(p,bytes);
    }
    return p;
}
```
Using Pointer Checker – Working with Enabled and Non-Enabled Modules

• With non-enabled code writes or returns, false positives occur in enabled code, as bounds aren’t set correctly
  – Pointer Checker mitigates this for nearly all cases by checking the stored pointer against a copy of the pointer stored with the bounds.
  – Pointers can still match in some cases such as realloc() returning same pointer but larger object:
    ○ \( p = \text{my realloc}(p, \text{old size} + 100); \)

• Solution:
  – Use wrapper functions when calling non-Pointer Checker code that kills or sets the bounds correctly for any pointer returned or written by the function.
Using Pointer Checker – Checking RTL Functions

• Run-Time Library (RTL) routines dealing with pointers need to be encapsulated or replaced so returned pointers have proper descriptors, and usage of pointers within the RTL routine are checked correctly.

• Pointer Checker provides checking on RTL functions which manipulate memory through pointers
  – Uses library of functions or wrappers
  – Pointer Checker Wrapper Library: <libchkpwrap.a>  [Linux*]
    <libchkpwrap.lib>  [Windows*]

• To find which run-time routines are wrapped:
  – Example (Linux*): %nm libchkpwrap.a | egrep 'T __chkp_
  – The returned list signify wrappers such as:
    __chkp_strcpy  - the wrapper for strcpy()
Using Pointer Checker – Finding and Reporting Out-of-Bounds Errors

• Reporting controlled through:
  o `__chkp_report_option_t` enumeration
  o `__chkp_report_control()` library function

<table>
<thead>
<tr>
<th>Enum Value</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>__CHKP_REPORT_NONE</td>
<td>Do nothing.</td>
</tr>
<tr>
<td>__CHKP_REPORT_BPT</td>
<td>Execute a breakpoint interrupt.</td>
</tr>
<tr>
<td>__CHKP_REPORT_LOG</td>
<td>Log the error and continue; the compiler will report each out-of-bounds pointer it finds.</td>
</tr>
<tr>
<td>__CHKP_REPORT_TERM</td>
<td>Log the error and exit the program; the compiler will only report the first bounds violation and then terminate.</td>
</tr>
<tr>
<td>__CHKP_REPORT_CALLBACK</td>
<td>Call a user defined function; the compiler will invoke a user-defined function to deal with a bounds error.</td>
</tr>
<tr>
<td>__CHKP_REPORT_TRACEBACK</td>
<td>Report stack traceback, including instruction addresses. This is the default report mode. On Windows* OS, specify the /Zi compiler option to get better traceback information, including routine names. On Linux* OS, specify the -rdynamic link command.</td>
</tr>
</tbody>
</table>

• For example, to report all bounds errors:
  o `__chkp_report_control(__CHKP_REPORT_LOG, 0);`
Using Pointer Checker – Guidelines

• Use Debug Configuration when using Pointer Checker for testing and debugging, so symbols are visible for better trace-back functionality. Use –rdynamic linker option when compiling on Linux*.

• Compile to make bounds error occur near bad pointer generation. Compile with:
  – No optimization (avoids optimizing out memory accesses and improves source line correlation)
  – Check both READS and WRITES to reduce fault delay.

• Use __CHKP_REPORT_LOG option to analyze loop issues in conjunction with __CHKP_REPORT_TRACEBACK

• Release application with Pointer Checker disabled:
  – Application size and execution time increases with Pointer Checker enabled.
• Runtime cost is high, about 2X to 5X execution time effect.
• Code size increase from 20% to a very large increase (>100% plus), depending on the application.
• Pointer Checker is seen as a debug tool.
• Deployed applications are expected to have Pointer Checker disabled
• Security benefits from catching vulnerabilities prior to product release is the trade-off.
Summary

• Pointer Checker is a key feature of Intel® C++ Composer XE 2013.
• Pointer Checker is designed for use during application debugging and testing.
• Pointer Checker provides full checking of all memory accesses through pointers.
• A Pointer Checker enabled application will catch any out-of-bounds memory accesses before any memory corruption occurs.
• Pointer Checker enabled code and non-enabled code can coexist.
• Get Started with Pointer Checker!
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