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

```
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

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

**Pointer Checker**

**What is it?**
- 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

**Key Benefits**
- 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()`)
**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+0xfd) [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 (/Qcheck-pointers)</td>
<td>Enables pointer checker and adds associated libraries</td>
</tr>
<tr>
<td>-check-pointers-dangling (/Q-check-pointers-dangling)</td>
<td>Enables checking for dangling pointer references</td>
</tr>
<tr>
<td>-check-pointers-undimensioned (Qcheck-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 *)</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 *, 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 (Function/Enumeration)</strong></td>
<td></td>
</tr>
<tr>
<td>void __chkp_report_control(__chkp_report_option_t option, __chkp_callback_t callback)</td>
<td>Determines how errors are reported</td>
</tr>
</tbody>
</table>
| __chkp_report_option_t | Controls how out-of-bounds error are reported.
| {Enumerations: __CHKP_REPORT_LOG, __CHKP_REPORT_TRACEBACK, __CHKP_REPORT_CALLBACK, __CHKP_REPORT_BPT, __CHKP_REPORT_TERM} | Enumerations in header file                                                       |
| **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)

```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?
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>

cchar * 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("first ch = %c\n", *q);    /* Line 17 */
}
```

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

cchar * 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("first ch = %c\n", *q);    /* Line 17 */
}
```

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

cchar * 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("first ch = %c\n", *q);    /* Line 17 */
}
```
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;
}
```

```
% cat arr1.c
int A[5]
%
```
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:**

- `chkp_kill_bounds(void *p)`
  - Kills the descriptor associated with the pointer making all memory accessible via the returned pointer.
- `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).
- `chkp_lower_bound(void **) / chkp_upper_bound(void **)`
  - Retrieves the lower / upper bound associated with a pointer

---

**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);
}
```

**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:
    o \( p = \text{my realloc}(p, \text{old size} + 100); \)

• 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:
  - `__chkp_report_option_t` enumeration
  - `__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:
  - `__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.
Pointer Checker - *Performance Overhead*

- 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.
• Point 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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