

使用 GDB 调试 C API 扩展和 CPython 内部代码

發  3.11.13

Guido van Rossum and the Python development team

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Python Software Foundation
Email: docs@python.org

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本文档介绍了如何将 Python GDB 扩展 `python-gdb.py` 与 GDB 调试器一起使用以调试 CPython 扩展以及 CPython 解释器本身。

当调试低层级问题如崩溃或死锁时，低层级的调试器如 GDB 适合被用来诊断和修正错误。在默认情况下，GDB（或其任一种前端）并不支持 CPython 解释器专属的高层级信息。

`python-gdb.py` 扩展可向 GDB 添加 CPython 解释器信息。该扩展能协助对当前执行的 Python 函数栈进行内省。当给定一个由 `PyObject*` 指针代表的 Python 对象时，该扩展将展示对象的类型和值。

开发 CPython 扩展或处理 CPython 中用 C 语言编写的部分的开发人员可以通过本文档学习如何将 `python-gdb.py` 扩展与 GDB 一起使用。

備註： 本文档假定你已熟悉 GDB 和 CPython C API 的基础知识。它对来自 [devguide](#) 和 [Python wiki](#) 的内容进行了整合。

1 前提条件

你需要有：

- GDB 7 or later. (For earlier versions of GDB, see `Misc/gdbinit` in the CPython sources. Note that this file will be removed in Python 3.12.)
- 针对 Python 和你正在调试的任何扩展的 GDB 兼容调试信息。
- `python-gdb.py` 扩展。

此扩展与 Python 一起构建，但可能单独发布或根本不发布。下面，我们将以几个常见系统为例进行说明。请注意即使这些说明与你的系统相匹配，它们也可能已经过时。

1.1 使用从源代码构建的 Python 进行设置

当你从源代码构建 CPython 时，调试信息应当是可用的，并且构建应当在你的代码库根目录中添加一个 `python-gdb.py` 文件。

要激活支持，你必须将包含 `python-gdb.py` 的目录添加到 GDB 的“`auto-load-safe-path`”中。如果你没有这样做，较新版本的 GDB 会打印一个警告来说明如何执行此操作。

備註： 如果你没有看到针对你的 GDB 版本的说明，请将以下内容放到你的配置文件中 (`~/.gdbinit` 或 `~/.config/gdb/gdbinit`):

```
add-auto-load-safe-path /path/to/cpython
```

你还可以添加多个路径，以 `:` 分隔。

1.2 针对 Linux 发行版的 Python 设置

大多数 Linux 系统会在名为 `python-debuginfo`、`python-dbg` 或类似的包中提供系统 Python 的调试信息。例如：

- Fedora：

```
sudo dnf install gdb
sudo dnf debuginfo-install python3
```

- Ubuntu：

```
sudo apt install gdb python3-dbg
```

在一些最新的 Linux 系统上，GDB 可以使用 `debuginfod` 自动下载调试符号。不过，这并不会安装 `python-gdb.py` 扩展；你通常需要单独安装调试信息包。

2 使用调试构建和开发模式

为了方便调试，你可能需要：

- 使用 Python 的 调试构建版。（当从源代码构建时，使用 `configure --with-pydebug`。在 Linux 发行版上，安装并运行 `python-debug` 或 `python-dbg` 之类的包，如果有的话。）
- 使用运行时 开发模式 (`-X dev`)。

两者都将启用额外的断言并禁用某些优化。有时这会隐藏你想要查找的程序错误，但大多数情况下它们都能使调试过程更简单。

3 使用 python-gdb 扩展

当该扩展被加载时，它将提供两个主要特性：Python 值的美化打印，以及附加的命令。

3.1 美化打印

这是当此扩展被启用时 GDB 回溯信息的显示效果（截取部分）：

```
#0  0x000000000041a6b1 in PyObject_Malloc (nbytes=Cannot access memory at address_
↳0x7ffff7fefe8
) at Objects/obmalloc.c:748
#1  0x000000000041b7c0 in _PyObject_DebugMallocApi (id=111 'o', nbytes=24) at_
↳Objects/obmalloc.c:1445
#2  0x000000000041b717 in _PyObject_DebugMalloc (nbytes=24) at Objects/obmalloc.
↳c:1412
#3  0x000000000044060a in _PyUnicode_New (length=11) at Objects/unicodeobject.c:346
#4  0x00000000004466aa in PyUnicodeUCS2_DecodeUTF8Stateful (s=0x5c2b8d "__lltrace__
↳", size=11, errors=0x0, consumed=
0x0) at Objects/unicodeobject.c:2531
#5  0x0000000000446647 in PyUnicodeUCS2_DecodeUTF8 (s=0x5c2b8d "__lltrace__",_
↳size=11, errors=0x0)
at Objects/unicodeobject.c:2495
#6  0x0000000000440d1b in PyUnicodeUCS2_FromStringAndSize (u=0x5c2b8d "__lltrace__
↳", size=11)
at Objects/unicodeobject.c:551
#7  0x0000000000440d94 in PyUnicodeUCS2_FromString (u=0x5c2b8d "__lltrace__") at_
↳Objects/unicodeobject.c:569
#8  0x0000000000584abd in PyDict_GetItemString (v=
{'Yuck': <type at remote 0xad4730>, '__builtins__': <module at remote_
↳0x7ffff7fd5ee8>, '__file__': 'Lib/test/crashers/nasty_eq_vs_dict.py', '__package_
↳': None, 'y': <Yuck(i=0) at remote 0xaaacd80>, 'dict': {0: 0, 1: 1, 2: 2, 3: 3},
↳'__cached__': None, '__name__': '__main__', 'z': <Yuck(i=0) at remote 0xaace60>,
↳'__doc__': None}, key=
0x5c2b8d "__lltrace__") at Objects/dictobject.c:2171
```

请注意传给 `PyDict_GetItemString` 的字典参数被显示为其 `repr()`，而非不透明的 `PyObject *` 指针。

该扩展通过为类型 `PyObject *` 的值提供自定义的打印例程来发挥作用。如果你需要访问一个对象的低层级细节，则要将原值投射为适当类型的指针。例如：

```
(gdb) p globals
$1 = {'__builtins__': <module at remote 0x7ffff7fb1868>, '__name__':
'__main__', 'ctypes': <module at remote 0x7ffff7f14360>, '__doc__': None,
'__package__': None}

(gdb) p *(PyDictObject*)globals
$2 = {ob_refcnt = 3, ob_type = 0x3dbdf85820, ma_fill = 5, ma_used = 5,
ma_mask = 7, ma_table = 0x63d0f8, ma_lookup = 0x3dbdc7ea70
<lookdict_string>, ma_smalltable = {{me_hash = 7065186196740147912,
me_key = '__builtins__', me_value = <module at remote 0x7ffff7fb1868>},
{me_hash = -368181376027291943, me_key = '__name__',
me_value = '__main__'}, {me_hash = 0, me_key = 0x0, me_value = 0x0},
{me_hash = 0, me_key = 0x0, me_value = 0x0},
{me_hash = -9177857982131165996, me_key = 'ctypes',
me_value = <module at remote 0x7ffff7f14360>},
{me_hash = -8518757509529533123, me_key = '__doc__', me_value = None},
{me_hash = 0, me_key = 0x0, me_value = 0x0}, {
me_hash = 6614918939584953775, me_key = '__package__', me_value = None}}}
```

请注意美化打印并不会实际调用 `repr()`。对于基本类型，它将尝试尽量匹配其结果。

一个可能令人困惑的地方是某些类型的自定义打印效果很像是 GDB 针对标准类型的内置打印形式。例如，针对 Python int (PyLongObject*) 的美化打印表示形式与机器层级上常规的整数并无区别：

```
(gdb) p some_machine_integer
$3 = 42

(gdb) p some_python_integer
$4 = 42
```

内部结构可通过投射为 PyLongObject* 来显示：

```
(gdb) p (PyLongObject*)some_python_integer
$5 = {ob_base = {ob_base = {ob_refcnt = 8, ob_type = 0x3dad39f5e0}, ob_size = 1}, ob_digit = {42}}
```

类似的困惑也可能发生于 str 类型，这里的输出看起来很像 gdb 针对 char * 的内置打印形式：

```
(gdb) p ptr_to_python_str
$6 = '__builtins__'
```

针对 str 实例的美化打印默认使用单引号（就像 Python 字符串的 repr 一样）而针对 char * 值的标准打印形式使用双引号并且包含一个十六进制的地址：

```
(gdb) p ptr_to_char_star
$7 = 0x6d72c0 "hello world"
```

同样地，该实现细节可通过投射为 PyUnicodeObject* 来显示：

```
(gdb) p *(PyUnicodeObject*)$6
$8 = {ob_base = {ob_refcnt = 33, ob_type = 0x3dad3a95a0}, length = 12,
str = 0x7ffff2128500, hash = 7065186196740147912, state = 1, defenc = 0x0}
```

3.2 py-list

该扩展添加了一个 py-list 命令，它将列出选定的线程中当前帧的 Python 源代码（如果存在）。当前行将以一个“>”来标记：

```
(gdb) py-list
901         if options.profile:
902             options.profile = False
903             profile_me()
904             return
905
>906         u = UI()
907         if not u.quit:
908             try:
909                 gtk.main()
910             except KeyboardInterrupt:
911                 # properly quit on a keyboard interrupt...
```

使用 py-list START 从不同的行号开始列出 Python 源代码，而 py-list START,END 则从列出指定行范围内的 Python 源代码。

3.3 py-up 和 py-down

py-up 和 py-down 命令类似于 GDB 的常规 up 和 down 命令，但会尝试在 CPython 帧而不是 C 帧的层级上移动。

GDB 并不总是能够读取相关的帧信息，这取决于编译 CPython 时的优化级别。在内部，这些命令会查找正在执行默认帧求值函数（即 CPython 内的的核心字节码解释器循环）的 C 帧并查找相关 `PyFrameObject *` 的值。

它们将发出线程内的帧编号（在 C 层级上）。

例如：

```
(gdb) py-up
#37 Frame 0x9420b04, for file /usr/lib/python2.6/site-packages/
gnome_sudoku/main.py, line 906, in start_game ()
    u = UI()
(gdb) py-up
#40 Frame 0x948e82c, for file /usr/lib/python2.6/site-packages/
gnome_sudoku/gnome_sudoku.py, line 22, in start_game(main=<module at 0xb771b7f4>)
↳ remote 0xb771b7f4>)
    main.start_game()
(gdb) py-up
Unable to find an older python frame
```

这样我们位于 Python 栈的顶部。

帧编号对应于 GDB 的 `backtrace` 命令所显示的内容。该命令将跳过未在执行 Python 代码的 C 帧。

向下回退:

```
(gdb) py-down
#37 Frame 0x9420b04, for file /usr/lib/python2.6/site-packages/gnome_
↳sudoku/main.py, line 906, in start_game ()
    u = UI()
(gdb) py-down
#34 (unable to read python frame information)
(gdb) py-down
#23 (unable to read python frame information)
(gdb) py-down
#19 (unable to read python frame information)
(gdb) py-down
#14 Frame 0x99262ac, for file /usr/lib/python2.6/site-packages/gnome_
↳sudoku/game_selector.py, line 201, in run_swallowed_dialog (self=
↳<NewOrSavedGameSelector(new_game_model=<gtk.ListStore at remote_
↳0x98fab44>, puzzle=None, saved_games=[{'gsd.auto_fills': 0, 'tracking':
↳{'', 'trackers': {}, 'notes': [], 'saved_at': 1270084485, 'game': '7 8 0
↳0 0 0 0 5 6 0 0 9 0 8 0 1 0 0 0 4 6 0 0 0 0 7 0 6 5 0 0 0 4 7 9 2 0 0 0
↳9 0 1 0 0 0 3 9 7 6 0 0 0 1 8 0 6 0 0 0 0 0 2 8 0 0 0 5 0 4 0 6 0 0 0 2 1 0
↳0 0 0 0 4 5\n7 8 0 0 0 0 0 0 5 6 0 0 9 0 8 0 1 0 0 0 4 6 0 0 0 0 7 0 6 5
↳1 8 3 4 7 9 2 0 0 0 9 0 1 0 0 0 3 9 7 6 0 0 0 1 8 0 6 0 0 0 2 8 0 0 0
↳5 0 4 0 6 0 0 2 1 0 0 0 0 0 4 5', 'gsd.impossible_hints': 0, 'timer.__
↳absolute_start_time__': <float at remote 0x984b474>, 'gsd.hints': 0,
↳'timer.active_time': <float at remote 0x984b494>, 'timer.total_time':
↳<float at remote 0x984b464>}], dialog=<gtk.Dialog at remote 0x98faaa4>,
↳saved_game_model=<gtk.ListStore at remote 0x98fad24>, sudoku_maker=
↳<SudokuMaker(terminated=False, played=[], batch_siz...(truncated)
    swallower.run_dialog(self.dialog)
(gdb) py-down
#11 Frame 0x9aead74, for file /usr/lib/python2.6/site-packages/gnome_
↳sudoku/dialog_swallower.py, line 48, in run_dialog (self=
↳<SwappableArea(running=<gtk.Dialog at remote 0x98faaa4>, main_page=0)
↳at remote 0x98fa6e4>, d=<gtk.Dialog at remote 0x98faaa4>)
```

(繼續下一頁)

```

        gtk.main()
(gdb) py-down
#8 (unable to read python frame information)
(gdb) py-down
Unable to find a newer python frame

```

现在我们位于 Python 栈的底部。

3.4 py-bt

py-bt 命令会尝试显示当前线程的 Python 层级回溯。

例如：

```

(gdb) py-bt
#8 (unable to read python frame information)
#11 Frame 0x9aead74, for file /usr/lib/python2.6/site-packages/gnome_
↳ sudoku/dialog_swallow.py, line 48, in run_dialog (self=
↳ <SwappableArea(running=<gtk.Dialog at remote 0x98faaa4>, main_page=0)
↳ at remote 0x98fa6e4>, d=<gtk.Dialog at remote 0x98faaa4>)
    gtk.main()
#14 Frame 0x99262ac, for file /usr/lib/python2.6/site-packages/gnome_
↳ sudoku/game_selector.py, line 201, in run_swallowed_dialog (self=
↳ <NewOrSavedGameSelector(new_game_model=<gtk.ListStore at remote
↳ 0x98fab44>, puzzle=None, saved_games=[{'gsd.auto_fills': 0, 'tracking':
↳ {}, 'trackers': {}, 'notes': [], 'saved_at': 1270084485, 'game': '7 8 0
↳ 0 0 0 5 6 0 0 9 0 8 0 1 0 0 0 4 6 0 0 0 0 7 0 6 5 0 0 0 4 7 9 2 0 0 0
↳ 9 0 1 0 0 0 3 9 7 6 0 0 0 1 8 0 6 0 0 0 0 2 8 0 0 0 5 0 4 0 6 0 0 2 1 0
↳ 0 0 0 4 5\n7 8 0 0 0 0 0 5 6 0 0 9 0 8 0 1 0 0 0 4 6 0 0 0 0 7 0 6 5
↳ 1 8 3 4 7 9 2 0 0 0 9 0 1 0 0 0 3 9 7 6 0 0 0 1 8 0 6 0 0 0 0 2 8 0 0 0
↳ 5 0 4 0 6 0 0 2 1 0 0 0 0 4 5', 'gsd.impossible_hints': 0, 'timer.__
↳ absolute_start_time__': <float at remote 0x984b474>, 'gsd.hints': 0,
↳ 'timer.active_time': <float at remote 0x984b494>, 'timer.total_time':
↳ <float at remote 0x984b464>}], dialog=<gtk.Dialog at remote 0x98faaa4>,
↳ saved_game_model=<gtk.ListStore at remote 0x98fad24>, sudoku_maker=
↳ <SudokuMaker(terminated=False, played=[], batch_siz...(truncated)
    swallow.run_dialog(self.dialog)
#19 (unable to read python frame information)
#23 (unable to read python frame information)
#34 (unable to read python frame information)
#37 Frame 0x9420b04, for file /usr/lib/python2.6/site-packages/gnome_
↳ sudoku/main.py, line 906, in start_game ()
    u = UI()
#40 Frame 0x948e82c, for file /usr/lib/python2.6/site-packages/gnome_
↳ sudoku/gnome_sudoku.py, line 22, in start_game (main=<module at remote
↳ 0xb771b7f4>)
    main.start_game()

```

帧编号对应于 GDB 的 backtrace 命令所显示的内容。

3.5 py-print

py-print 命令会查找一个 Python 名称并尝试打印它。它将先在当前线程的 locals 中查找，然后是 globals，最后是 builtins:

```
(gdb) py-print self
local 'self' = <SwappableArea(running=<gtk.Dialog at remote 0x98faaa4>,
main_page=0) at remote 0x98fa6e4>
(gdb) py-print __name__
global '__name__' = 'gnome_sudoku.dialog_swallowner'
(gdb) py-print len
builtin 'len' = <built-in function len>
(gdb) py-print scarlet_pimpernel
'scarlet_pimpernel' not found
```

3.6 py-locals

py-locals 命令会在选定的线程中查找当前 Python 帧内的所有 Python 的 locals，并打印它们的表示形式:

```
(gdb) py-locals
self = <SwappableArea(running=<gtk.Dialog at remote 0x98faaa4>,
main_page=0) at remote 0x98fa6e4>
d = <gtk.Dialog at remote 0x98faaa4>
```

4 与 GDB 命令一起使用

这些扩展命令是对 GDB 的内置命令的补充。例如，你可以使用 py-bt 显示的帧编号与 frame 命令一起使用以转到所选线程中的特定帧，如下所示:

```
(gdb) py-bt
(output snipped)
#68 Frame 0xaa4560, for file Lib/test/regtest.py, line 1548, in <module> ()
    main()
(gdb) frame 68
#68 0x00000000004cd1e6 in PyEval_EvalFrameEx (f=Frame 0xaa4560, for file Lib/test/
↳ regtest.py, line 1548, in <module> (), throwflag=0) at Python/ceval.c:2665
2665                                     x = call_function(&sp, oparg);
(gdb) py-list
1543             # Run the tests in a context manager that temporary changes the CWD to
↳ a
1544             # temporary and writable directory. If it's not possible to create or
1545             # change the CWD, the original CWD will be used. The original CWD is
1546             # available from test_support.SAVEDCWD.
1547             with test_support.temp_cwd(TESTCWD, quiet=True):
>1548                 main()
```

info threads 命令将向你提供进程内的线程列表，您还可以使用 thread 命令来选择不同的线程:

```
(gdb) info threads
105 Thread 0x7fffffa18710 (LWP 10260)  sem_wait () at ../nptl/sysdeps/unix/sysv/
↳ linux/x86_64/sem_wait.S:86
104 Thread 0x7ffffd5fe710 (LWP 10259)  sem_wait () at ../nptl/sysdeps/unix/sysv/
↳ linux/x86_64/sem_wait.S:86
* 1 Thread 0x7ffff7fe2700 (LWP 10145)  0x00000038e46d73e3 in select () at ../
↳ sysdeps/unix/syscall-template.S:82
```

你可以使用 `thread apply all COMMAND` 或 (简短写法 `t a a COMMAND`) 在所有线程上运行一个命令。配合 `py-bt`, 这将让你在 **Python** 层级上查看看到每个线程在做什么:

```
(gdb) t a a py-bt

Thread 105 (Thread 0x7ffffefa18710 (LWP 10260)):
#5 Frame 0x7ffffd00019d0, for file /home/david/coding/python-svn/Lib/threading.py,
↳line 155, in _acquire_restore (self=<_RLock(_Verbose__verbose=False, _RLock__
↳owner=140737354016512, _RLock__block=<thread.lock at remote 0x858770>, _RLock__
↳count=1) at remote 0xd7ff40>, count_owner=(1, 140737213728528), count=1,
↳owner=140737213728528)
    self.__block.acquire()
#8 Frame 0x7ffffac001640, for file /home/david/coding/python-svn/Lib/threading.py,
↳line 269, in wait (self=<_Condition(_Condition__lock=<_RLock(_Verbose__
↳verbose=False, _RLock__owner=140737354016512, _RLock__block=<thread.lock at
↳remote 0x858770>, _RLock__count=1) at remote 0xd7ff40>, acquire=<instancemethod
↳at remote 0xd80260>, _is_owned=<instancemethod at remote 0xd80160>, _release_
↳save=<instancemethod at remote 0xd803e0>, release=<instancemethod at remote
↳0xd802e0>, _acquire_restore=<instancemethod at remote 0xd7ee60>, _Verbose__
↳verbose=False, _Condition__waiters=[]> at remote 0xd7fd10>, timeout=None, waiter=
↳<thread.lock at remote 0x858a90>, saved_state=(1, 140737213728528))
    self._acquire_restore(saved_state)
#12 Frame 0x7ffffb8001a10, for file /home/david/coding/python-svn/Lib/test/lock_
↳tests.py, line 348, in f ()
    cond.wait()
#16 Frame 0x7ffffb8001c40, for file /home/david/coding/python-svn/Lib/test/lock_
↳tests.py, line 37, in task (tid=140737213728528)
    f()

Thread 104 (Thread 0x7ffffdf5fe710 (LWP 10259)):
#5 Frame 0x7ffffe4001580, for file /home/david/coding/python-svn/Lib/threading.py,
↳line 155, in _acquire_restore (self=<_RLock(_Verbose__verbose=False, _RLock__
↳owner=140737354016512, _RLock__block=<thread.lock at remote 0x858770>, _RLock__
↳count=1) at remote 0xd7ff40>, count_owner=(1, 140736940992272), count=1,
↳owner=140736940992272)
    self.__block.acquire()
#8 Frame 0x7ffffc8002090, for file /home/david/coding/python-svn/Lib/threading.py,
↳line 269, in wait (self=<_Condition(_Condition__lock=<_RLock(_Verbose__
↳verbose=False, _RLock__owner=140737354016512, _RLock__block=<thread.lock at
↳remote 0x858770>, _RLock__count=1) at remote 0xd7ff40>, acquire=<instancemethod
↳at remote 0xd80260>, _is_owned=<instancemethod at remote 0xd80160>, _release_
↳save=<instancemethod at remote 0xd803e0>, release=<instancemethod at remote
↳0xd802e0>, _acquire_restore=<instancemethod at remote 0xd7ee60>, _Verbose__
↳verbose=False, _Condition__waiters=[]> at remote 0xd7fd10>, timeout=None, waiter=
↳<thread.lock at remote 0x858860>, saved_state=(1, 140736940992272))
    self._acquire_restore(saved_state)
#12 Frame 0x7ffffac001c90, for file /home/david/coding/python-svn/Lib/test/lock_
↳tests.py, line 348, in f ()
    cond.wait()
#16 Frame 0x7ffffac0011c0, for file /home/david/coding/python-svn/Lib/test/lock_
↳tests.py, line 37, in task (tid=140736940992272)
    f()

Thread 1 (Thread 0x7fffff7fe2700 (LWP 10145)):
#5 Frame 0xcb5380, for file /home/david/coding/python-svn/Lib/test/lock_tests.py,
↳line 16, in _wait ()
    time.sleep(0.01)
#8 Frame 0x7ffffd00024a0, for file /home/david/coding/python-svn/Lib/test/lock_
↳tests.py, line 378, in _check_notify (self=<ConditionTests(_testMethodName='test_
↳notify', _resultForDoCleanups=<TestResult(_original_stdout=<cStringIO.StringO at
↳remote 0xc191e0>, skipped=[], _mirrorOutput=False, testsRun=39, buffer=False, _
↳original_stderr=<file at remote 0x7fffff7fc6340>, _stdout_buffer=<cStringIO.
```

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```
↪StringO at remote 0xc9c7f8>, _stderr_buffer=<cStringIO.StringO at remote_
↪0xc9c790>, _moduleSetUpFailed=False, expectedFailures=[], errors=[], _
↪previousTestClass=<type at remote 0x928310>, unexpectedSuccesses=[], failures=[],
↪ shouldStop=False, failfast=False) at remote 0xc185a0>, _threads=(0,), _
↪cleanups=[], _type_equality_funcs={<type at remote 0x7eba00>: <instancemethod at_
↪remote 0xd750e0>, <type at remote 0x7e7820>: <instancemethod at remote 0xd75160>,
↪ <type at remote 0x7e30e0>: <instancemethod at remote 0xd75060>, <type at remote_
↪0x7e7d20>: <instancemethod at remote 0xd751e0>, <type at remote 0x7f19e0...
↪(truncated)
    _wait()
```