From Handcraft to Unikraft: Simpler Unikernelization of Your Application

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VMs vs Containers

VMs have been around for a long time

- They allow consolidation, isolation, migration, ...
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    My VM takes a minute to boot, my container only a second.”
  - “Containers are much smaller.
    My VM takes 10 GB, my container only a few hundred MB.”
  - “Containers are much easier to create and deploy.
    I just write this Dockerfile and I’m done.”
I don’t want to bash containers.

- Containers can be great!
- For example, I love them for build environments
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- Containers can be great!
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But VMs have their advantages
- Most importantly, strong isolation
Containers vs Unikernels

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![Graph of Linux Release Year vs No. of syscalls]
Containers vs Unikernels

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And they do not have to be large, slow, and complicated
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And they do not have to be large, slow, and complicated
- This is where unikernels come in
Traditional VMs vs. Unikernels

**Traditional VMs**

- **App A**
  - Libs A
- **App B**
  - Libs B
- **Kernel**
- **Hypervisor**
- **Hardware**
Traditional VMs vs. Unikernels

Unikernels are purpose-built

- A single binary containing OS and (single) application
- One application → Flat and single address space
Traditional VMs vs. Unikernels

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Example: unikernel web server
- 5-6x more req/s than standard nginx
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Can be extremely small and blazingly fast

Example: unikernel web server
- 5-6x more req/s than standard nginx
- Nearly saturates 40Gb/s link
- Image: 670kB, RAM: <32MB
Example: Instantiation Time Comparison

Process Create

Server: Intel Xeon E5-1630 v3 CPU@3.7GHz (4 cores), 128GB DDR4 RAM, Xen/Linux versions 4.8

Process: 0.7ms-10ms
Example: Instantiation Time Comparison

Server: Intel Xeon E5-1630 v3 CPU@3.7GHz (4 cores), 128GB DDR4 RAM, Xen/Linux versions 4.8

Process Create: 0.7ms - 10ms
Docker Boot: 150ms - 550ms
Example: Instantiation Time Comparison

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Example: Instantiation Time Comparison

Server: Intel Xeon E5-1630 v3 CPU@3.7GHz (4 cores), 128GB DDR4 RAM, Xen/Linux versions 4.8

MiniOS Boot —— MiniOS Create

- **Debian**: 2.6-82 secs
- **unikernel**: 63ms-1.4secs
- **Docker**: 150ms-550ms
- **Process**: 0.7ms-10ms
Example: Instantiation Time Comparison

Unikernels can instantiate as fast as containers

- Often faster
- Except when many are colocated
  - Speaking of which, what is going wrong there?!
  - If you’re interested, talk to me later
  - Bottom line: this is a solvable implementation problem

Server: Intel Xeon E5-1630 v3 CPU@3.7GHz (4 cores), 128GB DDR4 RAM, Xen/Linux versions 4.8
The Downside

So, unikernels:

- Give you the speed and size of containers
- At the strong isolation of VMs
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So why isn’t everyone using them already?
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The big problem is unikernel development: Optimized unikernels are manually built
- Building takes several months or even longer
  - We’ve done it before, multiple times
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The big problem is unikernel *development*: Optimized unikernels are manually built
- Building takes several months or even longer
  - We’ve done it before, multiple times
- Potentially lather, rinse, repeat for each target application
  - We’ve done that too...
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  - We’ve done that too...

That’s not an effective way of doing things
Unikraft - A Unikernel Framework
Motivation

- Support wide range of use cases
- Provide common code base for unikernel development
- Simplify building and optimizing
- Support different hypervisors and CPU architectures
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Our Approach
- Decompose OS functionality into libraries
- Unikraft’s two components:
  - Library Pool
  - Build Tool
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Our Approach
- Decompose OS functionality into libraries
- Unikraft’s two components:
  - Library Pool
  - Build Tool

Started as an internal project at NEC Labs in early 2017
Made public early on
- Discussed ideas at Xen Summit 2017
- Accepted as a Xen incubator project in October 2017
- First public code release in December 2017
The Unikraft Way

*Decompose* OS into a set of libraries (“Everything is a library”)

*Recompose* them to meet the needs of particular applications
Decompose OS into a set of libraries (“Everything is a library”)

Recompose them to meet the needs of particular applications
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**Decompose** OS into a set of libraries ("Everything is a library")

**Recompose** them to meet the needs of particular applications.
Deconstruct

OS into a set of libraries (“Everything is a library”)  

Reconstruct

them to meet the needs of particular applications

Once decomposed, we can pick and choose which parts/libraries we actually need for our application
Unikraft Overview – Everything as a Library

1. Select / build / port
   Application

myapp
Unikraft Overview – Everything as a Library

1. Select / build / port Application

2. Select and configure libraries

main libs

network stack
- liblwip.o
- libtcpip.o
- libhttp.o

filesystems
- libvfs.o
- libfat.o
- libext3.o

drivers
- libconsole.o
- libblkfront.o
- libnetfront.o

memory allocators
- libbuddy.o
- libheap.o
- libmempool.o

runtimes
- libocaml.o
- libpython.o
- liberlang.o

standard libs
- libc.o
- libnewlib.o
- libopenssl.o

myapp

Application

Select and configure libraries
Unikraft Overview – Everything as a Library

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- **schedulers**
  - libcoop.o
  - libpreempt.o
  - librt.o

- **runtimes**
  - libocaml.o
  - libpython.o
  - liberlang.o

- **standard libs**
  - libc.o
  - libnewlibc.o
  - libopenssl.o

- **platform libs**
  - libxenplat.o
  - libbaremetalplat.o
  - Libkvmplat.o
  - liblinuxuplat.o

myapp

Select and configure libraries
Unikraft Overview – Everything as a Library

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Standard Libraries
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Platform Libraries
- libxenplat.o
- libbaremetalplat.o
- Libkvmpplat.o
- liblinuxuplat.o

Architecture Libraries
- libx86_64arch.o
- libarm32arch.o
- libarm64arm.o

1. Select / build / port Application
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Unikraft Overview – Everything as a Library

1. Select / build / port Application

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3. Build

myapp

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Select and configure libraries

Select / build / port Application

Build
Unikraft Overview – Everything as a Library

1. Select / build / port Application
2. Select and configure libraries
3. Build
4. Run

Unikernels:
- unikraft_bare_x86_64
- unikraft_bare_arm32
- unikraft_bare_arm64
- unikraft_xen_x86_64
- unikraft_xen_arm32
- unikraft_xen_arm64
- unikraft_kvm_x86_64
- unikraft_kvm_arm32
- unikraft_kvm_arm64
- unikraft_linuxu_x86_64
- unikraft_linuxu_arm32
- unikraft_linuxu_arm64

Main libraries:
- Network stack:
  - liblwip.o
  - libtcpip.o
  - libhttp.o
- Filesystems:
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- Schedulers:
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- Standard libraries:
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Unikraft _linuxu_x86_64
unikraft _bare_x86_64
unikraft _xen_x86_64
unikraft _kvm_x86_64
unikraft _linuxu_arm64
unikraft _bare_arm64
unikraft _xen_arm64
unikraft _kvm_arm64
unikraft _linuxu_arm64

Application:
Select and configure libraries
Build
Run
Two Library Types

**Built-in**: functionality specific to Unikraft, live in the main unikraft repo

- `ukboot`
- `ukschedpreempt`
- `...`
Two Library Types

**Built-in:** functionality specific to Unikraft, live in the main unikraft repo
- ukboot
- ukschedpreempt
- ...

**External:** software projects external to Unikraft, have their own unikraft-lib repos
- lwip
- micropython
- ...
Example System

Micropython Unikernel for KVM on x86_64

```
app_my_python.o
```
Example System

Micropython Unikernel for KVM on x86_64

- app_my_python.o
- libmicropython.o
Example System

Micropython Unikernel for KVM on x86_64

- app_my_python.o
- liblwip.o
- libmicropython.o
Example System

Micropython Unikernel for KVM on x86_64

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### Example System

**Micropython Unikernel for KVM on x86_64**

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Unikernel
Putting Things Together – The Unikraft Build Tool
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- Kconfig/Makefile based
Putting Things Together – The Unikraft Build Tool

Kconfig/Makefile based
make menuconfig
Putting Things Together – The Unikraft Build Tool

Kconfig/Makefile based
make menuconfig

• Choose options in the menu that you want for your application
Putting Things Together – The Unikraft Build Tool

Kconfig/Makefile based
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  • Choose options in the menu that you want for your application
  • Choose your target platform(s) (currently: Xen, KVM, Linux) and architectures
Putting Things Together – The Unikraft Build Tool

- Kconfig/Makefile based
- make menuconfig
  - Choose options in the menu that you want for your application
  - Choose your target platform(s) (currently: Xen, KVM, Linux) and architectures
- Save config and make

![Image of .config file]

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A Baseline Example...

Xen PV x86_64 binary
A Baseline Example...

Xen PV x86_64 binary

unikraft_xen-x86_64.o
libxenlat.o
libnolibc.o
libukboot.o
libukdebug.o

Final linking

unikraft_xen-x86_64
(32,7kB)
A Baseline Example...

**Xen PV x86_64 binary**

- `unikraft_xen-x86_64.o`
- `libnolibc.o`
- `libukboot.o`
- `libukdebug.o`
- `libxenplat.o`

Boots and prints messages to debug console (with min. 208kB RAM)

Final linking

`unikraft_xen-x86_64` (32,7kB)
A Baseline Example...

**Xen PV x86_64 binary**

**unikraft\_xen-x86\_64.o**

- libnolibc.o
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- libxenplat.o

Final linking

**unikraft\_xen-x86\_64**

(32,7kB)

Boots and prints messages to debug console (with min. 208kB RAM)

More functional example: routing unikernel (click): 4.5 MB (8 MB RAM)
Building a Unikraft Hello World App
Repo Structure

- Clone the main Unikraft repo
  
  ```
git clone git://xenbits.xen.org/unikraft/unikraft.git
  ```

- Clone any external library repos
  
  ```
git clone git://xenbits.xen.org/unikraft/libs/newlib.git
  ```

- Create repo for the actual application
Repo Structure

- Clone the main Unikraft repo
  
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  ```

- Create repo for the actual application

  ```
  ├── unikraft
  │    └── unikraft-apps
  │         └── helloworld
  ├── unikraft-libs
  │    ├── axtls
  │    ├── lwip
  │    ├── micropython
  │    └── newlib
  │        └── toybox
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Repo Structure

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  ```
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  ```

- Create repo for the actual application

```plaintext
dir|-- unikraft
    |-- unikraft-apps
    |    |-- helloworld
    |-- unikraft-libs
        |-- axtls
        |-- lwip
        |-- micropython
        |-- newlib
        |-- toybox
```

Unikraft repo (+ built-in libs)
Clone the main Unikraft repo

```
git clone git://xenbits.xen.org/unikraft/unikraft.git
```

Clone any external library repos

```
git clone git://xenbits.xen.org/unikraft/libs/newlib.git
```

Create repo for the actual application

```
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├── unikraft-apps
│   └── helloworld
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│   ├── axtls
│   ├── lwip
│   └── micropython
│       └── newlib
│           └── toybox
```

Unikraft repo (+ built-in libs)

Application repo(s)
Clone the main Unikraft repo

```bash
git clone git://xenbits.xen.org/unikraft/unikraft.git
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Clone any external library repos

```bash
git clone git://xenbits.xen.org/unikraft/libs/newlib.git
```

Create repo for the actual application
Hello World – Four Required Files (I)

**Makefile**: specify where the main Unikraft repo is, as well as repos for external libraries

```makefile
UK_ROOT ?= $(PWD)/../../unikraft
UK_LIBS ?= $(PWD)/../../unikraft-libs
LIBS := $(UK_LIBS)/newlib

all:
    @make -C $(UK_ROOT) A=$(PWD) L=$(LIBS)

$(MAKECMDGOALS):
    @make -C $(UK_ROOT) A=$(PWD) L=$(LIBS) $(MAKECMDGOALS)
```
Hello World – Four Required Files (I)

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*path to unikraft repo*
Hello World – Four Required Files (I)

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  @make -C $(UK_ROOT) A=$(PWD) L=$(LIBS)

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```

- path to unikraft repo
- path to external libs
Hello World – Four Required Files (I)

**Makefile**: specify where the main Unikraft repo is, as well as repos for external libraries

```
UK_ROOT ?= $(PWD)/../../unikraft
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$(MAKECMDGOALS):
    @make -C $(UK_ROOT) A=$(PWD) L=$(LIBS) $(MAKECMDGOALS)
```

- **path to unikraft repo**
- **path to external libs**
- **external libs needed**
Hello World – Four Required Files (II)

**Makefile.uk:** specifies the sources to build for the application

```
$(eval $(call addlib,apphelloworld))

APPHELLOWORLD_SRCS-\$y += $(APPHELLOWORLD_BASE)/main.c
```
Hello World – Four Required Files (II)

**Makefile.ux:** specifies the sources to build for the application

```
$(eval $(call addlib,apphelloworld))  # register app with unikraft build system
APPHELLOWORLD_SRCS-y += $(APPHELLOWORLD_BASE)/main.c
```
Hello World – Four Required Files (II)

**Makefile.uk**: specifies the sources to build for the application

```makefile
$(eval $(call addlib,apphelloworld))  # register app with unikraft build system
APPHELLOWORLD_SRCS-y += $(APPHELLOWORLD_BASE)/main.c  # Add main.c to build
```
Hello World – Four Required Files (III)

**Config.uk:** to populate Unikraft’s menu with application-specific option

```bash
### Invisible option for dependencies
config APPHELLOWORLD_DEPENDENCIES
  bool
  default y
  select LIBNOLIBC if !HAVE_LIBC

### App configuration
config APPHELLOWORLD_PRINTARGS
  bool "Print arguments"
  default y
  help
  Prints argument list (argv) to stdout
```
Hello World – Four Required Files (IV)

**main.c:** source file to provide (at least) a `main()` function

```c
#include <stdio.h>
/* Import user configuration: */
#include <uk/config.h>

int main(int argc, char *argv[])
{
    printf("Hello world!\n");
#if CONFIG_APPHELLOWORLD_PRINTARGS
    int i;
    printf("Arguments: ");
    for (i=0; i<argc; ++i)
    {
        printf(" %s", argv[i]);
    }
    printf("\n");
#endif

    return 0;
}
```

**main.c:** source file to provide (at least) a `main()` function

```c
#include <stdio.h>
/* Import user configuration: */
#include <uk/config.h>

int main(int argc, char *argv[]) {
    printf("Hello world!\n");
#if CONFIG_APPHELLOWORLD_PRINTARGS
    int i;
    printf("Arguments:s");
    for (i=0; i<argc; ++i)
        printf(" \"%s\"", argv[i]);
    printf("\n");
#endif
}
```

Unikernel entry point after boot
main.c: source file to provide (at least) a `main()` function

```c
#include <stdio.h>
/* Import user configuration: */
#include <uk/config.h>

int main(int argc, char *argv[]) {
    printf("Hello world!\n");
    #if CONFIG_APPHELLOWORLD_PRINTARGS
        int i;
        printf("Arguments:s");
        for (i=0; i<argc; ++i)
            printf(" \"%s\"", argv[i]);
        printf("\n");
    #endif
}
```

Unikernel entry point after boot

defined by Config.uk
Porting an External Library
How To Port an External Library
How To Port an External Library

- Write Makefile.uk and add the external library source files to it
  - The library’s original Makefile can serve as a template
  - I’ll show how to in a second
How To Port an External Library

Write `Makefile.uk` and add the external library source files to it
- The library’s original Makefile can serve as a template
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Write `Config.uk` with library-specific options
How To Port an External Library

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- Write `Config.uk` with library-specific options
  - Isn’t strictly required
  - But at least a simple “library on/off” option for kbuild is a good idea
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- Isn’t strictly required
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Sometimes a bit of *glue* code is needed
- E.g., in `newlib` to link POSIX thread creation to Unikraft’s thread library
How To Port an External Library

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  - Isn’t strictly required
  - But at least a simple “library on/off” option for kbuild is a good idea

- Sometimes a bit of glue code is needed
  - E.g., in newlib to link POSIX thread creation to Unikraft’s thread library

- In this early phase: implement core unikraft functionality that is required to support your library, for example:
  - File descriptors/sockets
  - Threading support
# Library registration

$(eval $(call addlib_s,libaxtls,$(LIBAXTLS)))
How To Port an External Library – Makefile.uk

# Library registration
$(eval $(call addlib_s,libaxtls,$(LIBAXTLS)))

Register library with unikraft build system
How To Port an External Library – Makefile.uk

# Library registration
$(eval $(call addlib_s,libaxtls,${LIBAXTLS}))

# Source Download
# Nothing here: sources are small and included directly in the uk library repo

Register library with unikraft build system
How To Port an External Library – Makefile.uk

# Library registration
$(eval $(call addlib_s,libaxtls,$(LIBAXTLS)))

# Source Download
$(eval $(call fetch,libaxtls,$(LIBAXTLS_URL)))
$(eval $(call patch,libaxtls,$(LIBAXTLS_PATCHDIR),newlib-$(LIBAXTLS_VERSION)))
How To Port an External Library – Makefile.uk

# Library registration
$(eval $(call addlib_s,libaxtls,$(LIBAXTLS)))

# Source Download
# Nothing here: sources are small and included directly in the uk library repo
$(eval $(call fetch,libaxtls,$(LIBAXTLS_URL)))
$(eval $(call patch,libaxtls,$(LIBAXTLS_PATCHDIR),newlib-$LIBAXTLS_VERSION))

# Library includes
CINCLUDES-y += -I$(LIBAXTLS_BASE)/include \
               -I$(LIBAXTLS_BASE)/crypto \
               -I$(LIBAXTLS_BASE)/ssl

REGISTER library with unikraft build system
Download and patch library code
The library’s original include directories
How To Port an External Library – Makefile.uk

---

# Library registration
$(eval $(call addlib_s,libaxtls,$(LIBAXTLS)))

# Source Download
$(eval $(call fetch,libaxtls,$(LIBAXTLS_URL)))
$(eval $(call patch,libaxtls,$(LIBAXTLS_PATCHDIR),newlib-$LIBAXTLS_VERSION))

# Library includes
CINCLUDES += -I$(LIBAXTLS_BASE)/include \
-I$(LIBAXTLS_BASE)/crypto \
-I$(LIBAXTLS_BASE)/ssl

# sources
LIBAXTLS_SRCS += $(LIBAXTLS_BASE)/crypto/aes.c
LIBAXTLS_SRCS += $(LIBAXTLS_BASE)/crypto/bigint.c
...
LIBAXTLS_SRCS += $(LIBAXTLS_BASE)/crypto/sha512.c

---

Register library with unikraft build system
Download and patch library code
The library’s original include directories
The library’s original source files
This can be a lot of busywork

What about special cases?

- Special build systems
- Additional steps other than compiling/linking
- Preprocessing/dependencies?

# Library registration

```bash
$(eval $(call addlib_s,libaxtls,$(LIBAXTLS)))
```

# Source Download

# Nothing here: sources are small and included directly in the uk library repo

# Library includes

```bash
CINCLUDES-y += -I$(LIBAXTLS_BASE)/include \ 
                   -I$(LIBAXTLS_BASE)/crypto \ 
                   -I$(LIBAXTLS_BASE)/ssl
```

# sources

```bash
LIBAXTLS_SRCS-y += $(LIBAXTLS_BASE)/crypto/aes.c
LIBAXTLS_SRCS-y += $(LIBAXTLS_BASE)/crypto/bigint.c
LIBAXTLS_SRCS-y += $(LIBAXTLS_BASE)/crypto/rsa.c
LIBAXTLS_SRCS-y += $(LIBAXTLS_BASE)/crypto/sha512.c
```
This can be a lot of busywork

What about special cases?
- Special build systems
- Additional steps other than compiling/linking
- Preprocessing/dependencies?

Coming soon:
Build passthrough mode
- Currently under review
- Vastly simplifies Makefile creation work
- Especially for large or complicated libraries

---

```bash
# Library registration
$(eval $(call addlib_s,libaxtls,$(LIBAXTLS)))
```

```bash
# Source Download
# Nothing here: sources are small and included directly in the uk library repo
```

```bash
# Library includes
CINCLUDES += -I$(LIBAXTLS_BASE)/include \
             -I$(LIBAXTLS_BASE)/crypto \
             -I$(LIBAXTLS_BASE)/ssl
```

```bash
# sources
LIBAXTLS_SRCS += $(LIBAXTLS_BASE)/crypto/aes.c
LIBAXTLS_SRCS += $(LIBAXTLS_BASE)/crypto/bigint.c
LIBAXTLS_SRCS += $(LIBAXTLS_BASE)/crypto/sha512.c
```

```bash
# build
```

```bash
UK_SRCS += $(LIBAXTLS_ORIGIN)/$(LIBAXTLS_DIR)/build/libaxtls.o
LIBAXTLS/.prepared:
    $(call verbose_cmd,CONFIGURE,libaxtls: @, \
    mkdir -p $(LIBAXTLS_ORIGIN)/$(LIBAXTLS_DIR) && \n    ./configure && make)
```
Unikraft 0.2 Titan

Current Status
Available Libraries

Core Libraries

- **libfdt**
  - Flat device tree parser
- **libnolibc**
  - A tiny libc replacement
- **libukalloc**
  - Memory allocator abstraction
- **libukallocbbuddy**
  - Binary buddy allocator
- **libukargparse**
  - Argument parser library
- **libukboot**
  - Unikraft bootstrapping
- **libukdebug**
  - Debug and kernel printing
  - Assertions, hexdump
- **libuksched**
  - Scheduler abstraction
- **libukschedcoop**
  - Cooperative scheduler
- **libukbus**
  - Abstraction for device buses, e.g., PCI
- **libuklock**
  - Mutexes and semaphores
- **libukmpi**
  - Message-passing interface
- **libuknetdev**
  - Network device support
- **libukswrand**
  - Pseudo-RNG interface
- **libuktimeconv**
  - Time calculation/conversion
- **libvfscore**
  - Basic file descriptor management / mapping / handling

External Libraries

- **libnewlib**
  - Libc originally aimed at embedded devices
- **liblwip**
  - Lightweight TCP/IP stack

Architecture Libraries

- **libarmmath**
  - 64bit arithmetic on ARMv7
- **libx86ctx**
  - Extended register support for x86 ctx switch

Platform Libraries

- **libxenplat**
  - Xen (PV)
    - x86_64, ARMv7
- **libkvmplat**
  - QEMU/kvm
    - x86_64, ARM64, virtio-net support
- **liblinuxu**
  - Linux userspace
    - x86_64, ARMv7
Current work: coming soon (in the pipeline) or being ported

Core Libraries
- libukschedpreempt
  - Pre-emptive scheduler

External Libraries
- libclick
  - Click modular router (e.g., for NFV)
- libaxtls
  - TLS support aimed at embedded devices
- libstdc++
- libmicropython
  - Python implemented for microcontrollers

Architecture Libraries
- libarmctx
  - Extended register support for Arm ctx switch

Platform Libraries
- libxenplat
  - ARM64 support
  - netfront support
- liblinuxu
  - tap device based networking support
The road ahead

First public alpha release (without much functionality) in December
Released as a Xen incubator project
Initially, mostly internal contributors from NEC Labs

Currently external contributors from
  • Romania (netfront, scheduling; from University Politehnica Bucharest)
  • Israel (bare-metal support)
  • China (ARM64 support; from ARM)

We welcome additional contributors!

Resources:
  • Code: https://xenbits.xen.org/gitweb/?pf=unikraft (make sure you check out staging!)
  • On-line documentation: unikraft.org
  • IRC: #unikraft @ freenode
  • Mailing list: minios-devel@lists.xen.org