# EspamAI pthread manual

This is a manual for espamAI extension, that allows to generate C++ pthread applications.

*Note: To run generated pthread applications make sure your OS support pthreads!*

**Requirements & Installation:**
for main espamAI requirements see README.md at the espamAI root folder or at https://git.liacs.nl/lerc/espam

- cnpy library : numpy arrays load to/from C++. pthread applications use cnpy library https://github.com/rogersce/cnpy for weights loading. Before you can use the pthread application you will need to download the cnpy library and compile it for the platform, where you want to run your pthread application.

- python onnx library and python json library. This libraries are used by espamAI to extract weights and biases from onnx model. The json library should be provided in standard python package. To install the onnx library run:

    $ pip install onnx

**Execution from command line (after the tool is configured):**
See espamAIMan.pdf located in the same folder as this document (espam/src/espam/docs)

**Input:**

- Path to single DNN model in .onnx or .json format + options (see below)

**Output:**

C++ pthread application files, generated from DNN model :

- appMain .cpp/ .h files, contatining application definition and high-level logic
- appFunc .cpp/ .h files, contatining API to DNN operators and some standard functions, used by DNN nodes.
- .cpp / .h file for every DNN node, containing description and functionality of the corresponding DNN node

**Tool running progress:**
(1) *Model reading*: read input DNN model

(3) *Model conversion*:

(3.1) conversion of input .onnx/json DNN model to internal Network model
(3.2) conversion of internal Network model to CSDF model:

(3) *Output files generation:* generates for input model output files, according to set files generation options.

**Application execution:**
to run generated application
1. cd folder/with/application (../DNN_name/pthread/app)
2.sh ./configure.sh -b path/to/cnpy-build -s path/to/cnpy-source
3. make
4 ./run

## Command-line options

Command-line options that take arguments
This list contains only the operators, related to pthread application generation. For all other commands see espamAIMan.pdf

| option | abbr | arguments | example |
|---|---|---|---|
| **General options** | | | |
| --generate | -g | Path to DNN/CSDFG model | --generate ./tests/lenet.json |
| **Model representation options (by default --layer-based option is set)** | | | |
| --layer-based | -lb | none | -lb |
| --block-based | -bb | number of blocks | --bb 20 |
| --split-step [optional], for -bb models only | none | Number of child nodes, obtainbed after one layer splitting | --split-step 4 |
| --opt-fi [optional] | none | Level of optimization of application graph for inference<br>0 – do not optimizie<br>1 – remove Dropout and Reshape nodes<br>2 – (default) – remove Dropout and Reshape nodes + incapsulate adding of biases in predcessing nodes | --opt-fi 2 |
| **Hardware specification options** | | | |
| --cores | none | Number of cores for application ( *should be used only if no mapping is provided*) | --cores 5 |
| --mapping | -m | Path to XML mapping file | --mapping ./mapping1.xml |

Command-line flags (The command-line options that are either present or not).

| flag | abbr | description |
|---|---|---|
| **General flags** | | |
| --help | -h | Printout help |
| --debug | none | Generate debug information in pthread application |
| --verbose | -V | Printout program progress information |
| **Application generation flags** | | |
| --pthread | none | Generate pthread application |
| --weights | none | Extract weights in numpy format |

| | | |
|---|---|---|
| *Leiden University internal library (dnnFunc)* | | |
| --libCPU | none | Generate pthread application + dnnFunc for CPU cores |
| --libGPU | none | Generate pthread application + dnnFunc for CPU+GPU cores |
| *Cagliari University internal library (dnnFunc)* | | |
| --libNA | none | Generate pthread application adopted for Neuraghe DNN operators lib |

## CNPY library compilation

**NOTE:* DNN weights and biases as well as I/O data are stored in .npy files and loaded in pthread application during runtime. To load weights/biases/input data into pthread applications the cnpy library https://github.com/rogersce/cnpy is used. Before you can use the pthread application you need to download the cnpy library and compile it for the platform, where you want to run your pthread application (use your specific compiler, if needed). To use pthread application you should have both cnpy-master (sources) and cnpy-build (.so) copied on your board. For examples, given below, the cnpy-master and cnpy_build are located in espam/lib directory and installed as following:

1. Download cnpy from https://github.com/rogersce/cnpy
2. cd to /espam/lib and unzip cnpy-master there
3. $mkdir cnpy_build
4. open README in cnpy-master and follow them

## Pthread C++ project general structure

The general structure of application, ready for compilation and then running is:

```
<app_name>
        -/weights_npz //folder with weights and biases  in .npy array.
        -/data [optional] //folder with I/O data represented as .npy arrays
                -/input  //input .npy arrays that have names input0, input1,...,inputN
                -/output  //output .npy arrays, that have names output0, output1,...,outputN
        -/pthread/app  //pthread application folder with .cpp files, .h files and .sh configuration file
```

Pthread application expects all the external data (input images, weights and biases) to be saved in .npy files. The weights and biases extraction can be done with espamAI. The input data should be generated/obtained manually.

## Weights and biases

Pthread application uses weights and biases, stored separately from the code in .npy (numpy array) format. The weights are extracted from ONNX model and saved in .npy arrays by espamAI and loaded into pthread application by dataLoader file, automatically generated by espamAI. The relative path from the pthread application sources to the weights and biases is *../../weights_npz*. This path should not be changed. The weights are stored in linearizes tensors. The order of dimensions is [OFM * IFM * H * W] for Convolutional nodes, where OFM is number of output feature maps, IFM is number of input feature maps, H and W are height and width and [OFM * input_size] for Dense (fully connected) nodes, where input size is the total number of input values for a dense node.

*Weights and biases partitioning.*

Due to the large size of DNN weights, they are stored and loaded to pthread application by partitions. Each partition has name node_name_w0, node_name_w1,..., node_name_wN. For Conv nodes one partition = one convolutional filter weights tensor. For dense layers one partition = up to 100 dense neurons' weights.

*Extract weights and biases from the ONNX model.*

To extract weights and biases from the ONNX DNN model, use --onnx-weights generation flag.
**NOTE:* For weights extraction you need python + python onnx + python json installed (see Requirements & Installation).
*Example:* Extract weights for ../src/espam/examples/DNN/onnx/mnist.onnx DNN model.
1. $ cd espam/bin
2. $ ./espam --generate ../src/espam/examples/DNN/onnx/mnist.onnx --onnx-weights
Expected output: file directory output_models/CNTKGraph/weights_npz containing .npy arrays with CNTKGraph dnn model weights and biases.

*Reuse weights and biases*

Weights and biases can be generated once for an application and then reused for the same model with any level of exploited parallelism. E.g. weights should NOT be regenerated for the same DNN model with 20 and 30 blocks.

*Load weights and biases into the pthread application.*

The loading of weights and biases into pthread application is done by the dataLoader class, automatically generated by espamAI for every pthread application.

**NOTE:* dataLoader utilizes CNPY library to load weights into pthread application. To use the dataLoader, you need to compile CNPY library as descibed in paragraph CNPY library compilation before running the pthread application.

**Input data**

By default, pthread application uses the input data in .npy (numpy array) format, located in ../../data/inputs folder (from pthread application sources). The ../../data/inputs folder contains npy arrays input0.npy, input1.npy,...,inputN.npy, where every input*.npy corresponds to one DNN input sample. *This arrays should be obtained manually*. The examples of numpy input data, are provided in ../espam/src/espam/examples/DNN_data

*NOTE:* If the defaule data folder is empty, you will see a message: *application repetitions computation error: null* . In this case there are 2 possible solutions:

*Numpy data*

1) 1.1. copy manually obtained inputs examples into ../../data/inputs folder
   1.2 open appMain.cpp of the generated pthread application and find the loop over the input samples:
   for(int inp_img =0; inp_img < 0; inp_img++)
   1.3. Change the number of input samples to the number of samples you copied, e.g.,
   for(int inp_img =0; inp_img < 10; inp_img++)
   1.4. make and ./run your pthread application

*Alternative data*

2) Open appMain.cpp file and add your own data loaduing after the comment "//TODO: load your data here."

## DNN operators libraries

Pthread application do not have its own DNN operators library. However, you can use your own DNN operators. To use your own DNN operators:

1. Create a folder, containing your own DNN operators sources
2. Use -n parameter of configure.sh file, automatically generated by espamAI to copy your library sources into the generated pthread application sources
3. Open appFunc.cpp and write your operators calls in appFunc::execute function
4. Make and run pthread application.

## Configure.sh

Every pthread application containts automatically generated *Configure.sh* file. This file serves to add external source files to the generated pthread application and add libcnpy.so to the LD_LIBRARY_PATH. The external files include some sources of CNPY library (**-s**), compiled CNPY library (**-b**) and [optionally] DNN operators libraries (**-f**).

### *Addition of external sources*

*Example1:* Use of configuration file with no DNN operators libraries:

```
$sh ./configure.sh -b ../cnpy_build -s ../cnpy-master
```

*Expected output:*

```
configuration status: success
```

This command will copy files from cnpy_build and cnpy_master folders and add them to the pthread application sources. The copied files are used for processing application weights, biases and I/O data, stored in .npy arrays.

*Example 2:* Use of configuration file with DNN operators library sources, located in ../DNN_func_libs/CPU_lib

```
$sh ./configure.sh -b ../cnpy_build -s ../cnpy-master -f ../DNN_func_libs/CPU_lib
```

*Expected output:*

```
configuration status: success
```

This command will copy files from cnpy_build and cnpy_master folders as well as every file in ../DNN_func_libs/CPU_lib folder.

### *Addition of libcnpy.so to LD_LIBRARY_PATH*

If configuration status was ‘success, but after the running the generated pthread application (./run) you see “*./run: error while loading shared libraries: libcnpy.so*: *cannot open shared object file: No such file or directory*”, then manually perform the commands:

```
$ LD_LIBRARY_PATH=./:LD_LIBRARY_PATH
$ export LD_LIBRARY_PATH
$./run
```

## Segmentation fault (core dumped)

The standard heapsize for a custom C++ aplication in Linux is 1GB. However as pthread applications, generated for large DNNs might require much more memory, the heapsize should be extended. To extend the heapsize within one Ubuntu terminal use command

```
$ ulimit -s unlimited
```

## Application generation examples

**NOTE: Hereinafter all examples are performed from .../espam/bin directory.* To perform examples from arbitrary directory *my_dir*

- Instead of ./ in espam call provide absolute path to espam/bin or relative path to espam/bin from *my_dir*

- Provide absolute path(s) to input file(s) or relative path(s) to input file(s) from *my_dir*

The data, used for examples, provided below is copied from ../espam/src/espam/examples/DNN_data/CNTKGraph to CNTKGraph folder, already containing weights. Therefore, before Examples 1-5 the CNTKGraph folder already looks like:
<CNTKGraph>
-/weights_npz //folder with weights and biases in .npy array.
-/data //folder with I/O data represented as .npy arrays
-/input //input .npy arrays that have names input0, input1,...,inputN
-/output //output .npy arrays, that have names output0, output1,...,outputN

**Example 1**

*Description:*
Generate application for ../src/espam/examples/DNN/onnx/mnist.onnx DNN model, map application nodes randomly on 4 cores. Use LU DNN operators library. Make and run the generated application.

1. $ ./espam --generate ../src/espam/examples/DNN/onnx/mnist.onnx --pthread --cores 4 --libCPU

*Expected output:*
espamAI-Pthread application generated in: ./output_models/CNTKGraph/pthread/app/

2.$ cd output_models/CNTKGraph/pthread/app/
$ sh ./configure.sh -b ../../../../../lib/cnpy_build -s ../../../../../lib/cnpy-master -f ../../../../../lib/DNN_func_libs/CPU_lib

*Expected output:*
configuration status: success

3. $ cd output_models/CNTKGraph/pthread/app/

4. Provide input data. *NOTE: this step is skipped in examples below, because it can be done only once for one DNN model.*
$ cp -R ../../../../../src/espam/examples/DNN_data/CNTKGraph/data ../../
- open appMain.cpp and manually change
for(int inp_img =0; inp_img < 0; inp_img++)
into
for(int inp_img =0; inp_img < 1; inp_img++)

5 $ make

*Expected output:*
g++ -std=c++11 -pthread -c -g Input3.cpp
g++ -std=c++11 -pthread -c -g Convolution28.cpp
.....
g++ -std=c++11 -pthread -o run Input3.o Convolution28.o ... fifo.o -L./ -lcnpy -lz

6. $ ./run
*Expected output:* // results for 1 input image
app output: 975.670288 -618.724304 6574.567871 668.028442 -917.270813 -1671.635620 -1952.760376 -61.549927 -777.176331 -1439.531494

*NOTE*: If after ./run you see "./run: error while loading shared libraries: libcnpy.so: cannot open shared object file: No such file or directory", performs commands:
$ LD_LIBRARY_PATH=./:LD_LIBRARY_PATH
$ export LD_LIBRARY_PATH
$./run

*DNN topology and mapping:*

core 0 core 1 core 2 core 3 core 0 core 1 core 2 core 3 core 0

Note: DNN topology can be generated as .dot file (see instructions for --dot option in espamAIMan.pdf)

**Example 2**

*Description:*
Generate application for ../src/espam/examples/DNN/onnx/mnist.onnx DNN model, map application nodes randomly on 4 cores. Use LU DNN operators lib. Print debug information.
Make and run the generated application.

*NOTE:* Application assumes, that example input data is provided in ../../data folder (see Example1 )

1. $ ./espam --generate ../src/espam/examples/DNN/onnx/mnist.onnx --pthread --cores 4 --debug --libCPU

*Expected output:* as in Example 1.

2.$ cd output_models/CNTKGraph/pthread/app/
$ sh ./configure.sh -b ../../../../../lib/cnpy_build -s ../../../../../lib/cnpy-master -f ../../../../../lib/DNN_func_libs/CPU_lib

*Expected output:*
configuration status: success

3. $ make

*Expected output:* as in Example 1.

4. $ ./run
./../../weights_npz/Convolution28_w0.npy loaded
./../../weights_npz/Convolution28_w1.npy loaded
.....
./../../weights_npz/Plus214_b.npy loaded

Application topology is constructed!

../../data/inputs/input0.npy loaded
Joined with thread thread_Input3

Joined with thread thread_Convolution28
Successfully set thread 982300416 to cpu core 1
Input3 finished!
Joined with thread thread_ReLU32
Successfully set thread 973907712 to cpu core 2
Successfully set thread 965515008 to cpu core 3
Joined with thread thread_Pooling66
Successfully set thread 957122304 to cpu core 0
Joined with thread thread_Convolution110
Joined with thread thread_ReLU114
Joined with thread thread_Pooling160
Joined with thread thread_Times212
Successfully set thread 855627520 to cpu core 0
Joined with thread thread_Plus214_Output_0
Successfully set thread 847234816 to cpu core 1
Convolution28 finished!
Successfully set thread 872412928 to cpu core 2
ReLU32 finished!
Successfully set thread 864020224 to cpu core 3
Pooling66 finished!
Successfully set thread 948729600 to cpu core 1
Convolution110 finished!
ReLU114 finished!
Pooling160 finished!
Times212 finished!
Plus214_Output_0 finished!
Generated program run 0 is finished!

Input3 output
0 0 0 0 0 0 0 0 0 1
Convolution28 output
-0.16154 -0.16154 -0.16154 -0.16154 -0.16154 -0.16154 -2.20347 -13.6354 -9.81617 7.12668
ReLU32 output
0 0 0 0 0 0 0 0 0 7.12668
Pooling66 output
0 0 0 0 17.5782 3.6093 7.46961 8.82315 4.90488 20.1006
Convolution110 output
-0.185185 3.15493 5.96148 -48.6038 -135.497 -254.373 -621.933 -902.048 -753.847 -764.047
ReLU114 output
0 3.15493 5.96148 0 0 0 0 0 0 0
Pooling160 output
5.96148 0 310.082 773.373 0 0 0 1660.32 0 0
Times212 output
975.67 -618.724 6574.57 668.028 -917.271 -1671.64 -1952.76 -61.5499 -777.176 -1439.53

*DNN topology and mapping:* as in Example 1.

**Example 3**

*Description:*

Generate application for ../src/espam/examples/DNN/onnx/mnist.onnx DNN model, map application nodes randomly on 4 cores. Split DNN graph by performance bottleneck, into<=30 blocks (for split algorithm see espamAIMan.pdf). Make and run the generated application.

*NOTE:* Application assumes, that example input data is provided in ../../data folder (see Example1 )

1. $ ./espam --generate ../src/espam/examples/DNN/onnx/mnist.onnx --pthread -bb 30 --cores 4 --libCPU

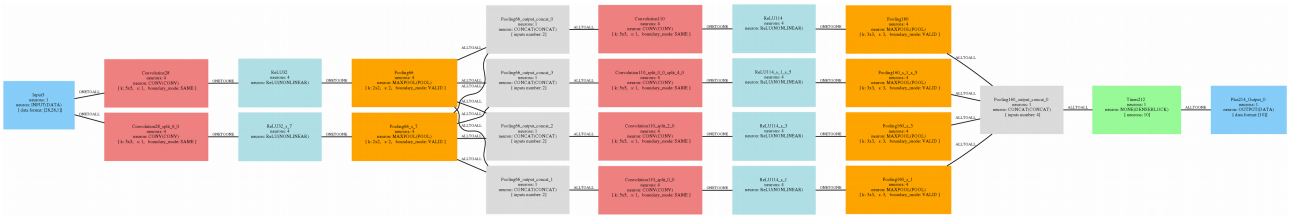
*Expected output:* as in Example 1.

2.$ cd output_models/CNTKGraph/pthread/app/
sh ./configure.sh -b ../../../../../lib/cnpy_build -s ../../../../../lib/cnpy-master -f ../../../../../lib/DNN_func_libs/CPU_lib

*Expected output:*
configuration status: success

3. $ make
   $ ./run
*Expected output:*
app output: 226.048447 655.682007 1505.263794 449.827209 -1047.294556 -63.064754 -360.705994 -22.146065 -369.674591 -421.463135

*DNN topology and mapping:*



| core 0 | core 1<br>core 2 | core 3<br>core 0 | core 1<br>core 2 | core 3<br>core 0<br>core 1<br>core 2 | core 3<br>core 0<br>core 1<br>core 2 | core 3<br>core 0<br>core 1<br>core 2 | core 3<br>core 0<br>core 1<br>core 2 | core 3 | core 0 | core 1 |
|---|---|---|---|---|---|---|---|---|---|---|

**Example 4 (Mapping file usage)**

$ ./espam --generate ../src/espam/examples/DNN/onnx/mnist.onnx --pthread --mapping ../src/espam/examples/mapping/mapping_mnist.xml

A mapping file contains a simple description of proceesors assignment to the pthread application nodes. The mapping file should be written manually with repsect to both DNN application and used platform. The mapping_mnist.xml is designed for a DNN model from Example 1 and a platform with 6 CPU cores and 1 GPU core:

```
<mapping name="myMapping">
        <processor name="cpu_0">
                <process name="Input3"/>
         </processor><processor name="cpu_1">
                <process name="ReLU32"/>
```

```
                <process name="Pooling66"/>
        </processor>
        <processor name="cpu_2">
                <process name="Convolution110"/>
                <process name="ReLU114"/>
        </processor>
        <processor name="cpu_3">
                <process name="Pooling160"/>
                <process name="Times212"/>
        </processor>
        <processor name="cpu_4">
                <process name="Plus214_Output_0"/>
        </processor>
        <processor name="cpu_5">
        </processor>
        <processor name="gpu">
                <process name="Convolution28"/>
        </processor>
</mapping>
```

2. $ cd output_models/CNTKGraph/pthread/app/
   $ sh ./configure sh ./configure.sh -b ../espam/cnpy_build -s espam/cnpy-master

*Expected output:*
configuration status: success

3. $ cd output_models/CNTKGraph/pthread/app/
   $ make

*Expected output:* as in Example 1.

4. $ ./run
*Expected output:* as in Example 1.

*DNN topology and mapping:*

core 0 gpu core 1 core 1 core 2 core 2 core 3 core 3 core 4

**Work in progress**

1. Incapsulating of Concat (grey) nodes into CNN nodes, instead of the separate representation

2. Replacing moc communication operators by real CNN operators

3. Data tiling

4. Solving problems for weights in block-based models