



# Embedded Code in GAMS Using Python as an Example

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### Acknowledgments

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## GAMS System

### GAMS

- New feature, the **Embedded Code Facility**: This extends the connectivity of GAMS to other programming languages. It allows the use of Python code during compile and execution time. GAMS symbols are shared with the external code, so no communication via disk is necessary.
  The embedded code feature is available on Linux, MacOS X, and Windows. For these platforms, a Python 3.6 installation is included with the GAMS distribution. If the user wants to work with a different Python 3.6, installed separately, for models with embedded code the new command line option **pySetup** needs to be set to 0.

  **Note**

  This feature is currently in beta status. Any feedback to support@gams.com is appreciated.
- New command line option **procDirPath**: Specifies the directory where the process directory should be created.

# Motivation –
# Avoid Unreadable/Slow Code

- GAMS code for *parallel assignment* and *equation definition* is compact, elegant, and efficient
- GAMS uses relational data tables as a base data structure
- Traditional data structure are not available in GAMS
  - No arrays, lists, dictionaries, trees, graphs, …
- GAMS can represent such traditional data structures but …
  - GAMS code becomes quickly unreadable
    ```
    t(tt) = t(tt-1); // advances set element t to t+1
    ```
  - Performance with naïve representation is very inefficient
    ```
    t(tt) = ord(tt)=tCnt; // advances set element t to t+1
    ```
  - Writing code that executes efficiently requires deep understanding of underlying GAMS internal data structures and often results in even more unreadable code

# Motivation –
# Data Input/Transformation at Compile Time

- GAMS data input (ASCII) follows strict syntax
- Practical GAMS models get data (via ASCII input files) that is often not in a proper shape
  - Hence GAMS code is often augmented with execution of scripts and programs to get data files into a GAMS readable shape
  - GAMS even ships a selection of POSIX text utilities (sed, grep, awk, …) on Windows to support a somewhat standardized way of transforming text files into GAMS readable format
  - Scripts spawned by GAMS cannot (easily) access data that is already available in GAMS
- GAMS has no string editing facilities to e.g.
  - modify labels
  - change content of compile time variables
    - "Solution": $xxx new and weird compile time constructs, e.g. $setNames, $splitOption, …

# Motivation – Other

- Connecting libraries for special algorithms (e.g. graph algorithms like connected components, matrix operations like Cholesky factorization) to GAMS is not easy
- Current "solution" has issues
  - $unload/$call/$load or execute_unload/execute/execute_load
    - Performance: disk IO + process creation
    - Knowledge of data API (GDX or OO-API)
    - Remapping of relational data (plus concept of UELs) into other data structures
  - Add compile time directives to perform a single special task (e.g. $splitOption)
  - Introduce unreadable option or put_utility syntax to perform a single special task (e.g. option a<b;)
- **Note:** Object Oriented API/Framework versus Embedded Code
  - OO-API: Framework in control
  - Embedded Code: GAMS in control

# Embedded Code

- Support the use of external code during GAMS compile and execution time
- Provide support for off-line debugging of embedded code
- Share GAMS symbols (sets, parameters, variables, and equations) structure and content with the external code in memory
- Communication of the data between GAMS and the embedded code inspired by the existing interface to GDX in many ways:
  - Records access by both labels and label indices
  - Data in GAMS can be merged with or replaced by data from embedded code
  - Data from embedded code can be send to GAMS database filtered or domain checked
- Provide automatically generated, additional source code for common tasks

➔ Allows the user to concentrate on the task at hand and not the *mechanics*

# Quantiles

Calculate |i||j| quantiles of |k| numbers:

```
Set i / ... /, j / ... /,  k / ... /;
Table p(i,j,k)
              k1         k2 ...
i1.j1 18.002966 84.483404 ...
i1.j2  7.644259 50.520856 ...
...                              ;
Set q; Parameter quantiles(i,j,q);
$onEmbeddedCode Python:
  import pandas as pd
  df = pd.DataFrame(list(gams.get('p')))
  q = df.groupby([0,1]).quantile([0,.25,.5,.75,1])
  gams.set('quantiles',
        [ (*k[:-1],str(k[-1]),v[3]) for k,v in q.iterrows() ])
$offEmbeddedCode q<quantiles quantiles
Display q, quantiles;
```

Inspired by E. Kalvelagen

# Split Example – Data

```
Set cc      / "France - Paris",    "France - Lille",
              "France - Toulouse",
              "Spain - Madrid",    "Spain - Cordoba",
              "Spain - Seville",   "Spain - Bilbao",
              "USA - Washington DC",
              "USA - Houston",     "USA - New York",
              "Germany - Berlin",
              "Germany - Munich", "Germany - Bonn" /
    country / system.empty /
    city    / system.empty /
    mccCountry(cc,country)
    mccCity   (cc,city);
```

# Split Example – Embedded Code

```
$onEmbeddedCode Python:
    country = set()
    city = set()
    mccCountry = []
    mccCity = []
    for cc in gams.get("cc"):
        r = str.split(cc, " - ", 1)
        country.add(r[0])
        city.add(r[1])
        mccCountry.append((cc,r[0]))
        mccCity.append((cc,r[1]))
    gams.set("country",list(country))
    gams.set("city",list(city))
    gams.set("mccCountry",mccCountry)
    gams.set("mccCity",mccCity)
$offEmbeddedCode country city mccCountry mccCity
```

# Split Example – Output

```
Display country, city;
```

```
----     27 SET country

France ,    USA    ,    Spain  ,    Germany


----     27 SET city

Seville      ,    Washington DC,    New York     ,    Paris
Munich       ,    Madrid       ,    Toulouse     ,    Berlin
Bonn         ,    Lille        ,    Houston      ,    Bilbao
Cordoba
```

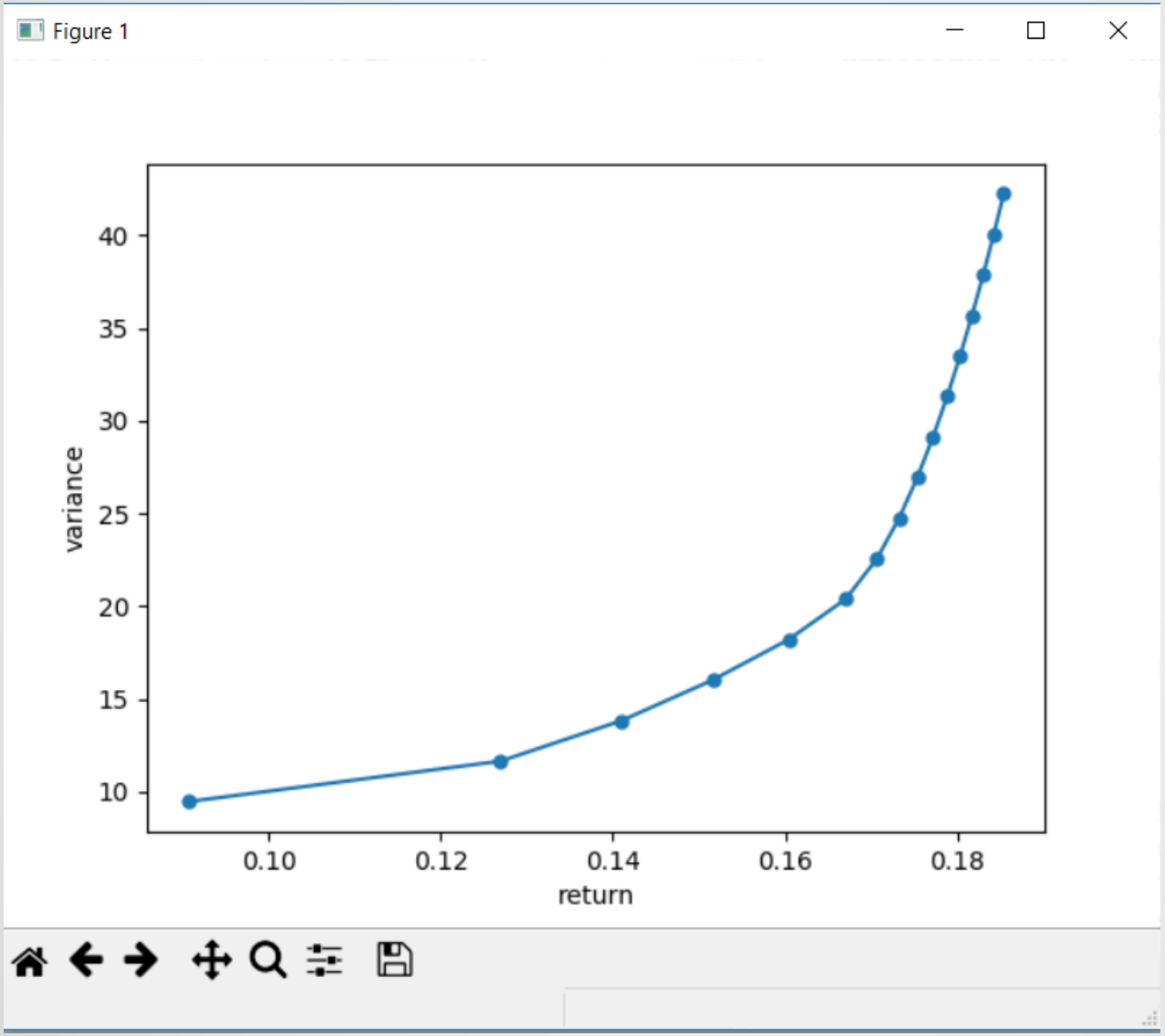
# Plot Example

```
[added after GAMSlib model meanvar]

Parameter mean(p), var(p);
mean(p) = xres('mean',p);
var(p) = xres('var',p);

embeddedCode Python:
  import matplotlib
  matplotlib.use('WXAgg')
  import matplotlib.pyplot as plt
  plt.plot(gams.get('mean', keyFormat=KeyFormat.SKIP), \
           gams.get('var', keyFormat=KeyFormat.SKIP),  \
           marker=".", markersize=10)
  plt.xlabel('return')
  plt.ylabel('variance')
  plt.show()
endEmbeddedCode
```

# Plot Example – Output



# Exchange via Files

```
$onEmbeddedCode Python: 10
  f = open('i.txt', 'w')
  for i in range(int(gams.arguments)):
    f.write('i'+str(i+1)+'\n')
  f.close()
$offEmbeddedCode

Set i /
$include i.txt
/;
Display i;


----      21 SET i


i1 ,     i2 ,     i3 ,     i4 ,     i5 ,
i6 ,     i7 ,     i8 ,     i9 ,     i10
```

# Exchange via Environment Variables

```
Set       i    / i1*i5 /;
Parameter b(i) / i1 2, i2 7, i3 59, i4 2, i5 47 /;
Set       k  "from 0 to max(b)" / k0*k? /;
$onEmbeddedCode Python:
  import os
  kmax = int(max([b[1] for b in list(gams.get("b"))]))
  gams.printLog('max value in b is ' + str(kmax))
  os.environ["MAXB"] = str(kmax)
$offEmbeddedCode

$if x%sysEnv.MAXB%==x $abort MAXB is not set
Set    k   "from 0 to max(b)" / k0*k%sysEnv.MAXB% /;
Scalar card_k;
card_k = card(k);
Display card_k;

----     15 PARAMETER card_k                =       60.000
```

# Performance Considerations

```
Set i / i1*i50 /, p(i,i); Alias (i,ii);
Parameter c(i,i); c(i,ii) = uniform(-50,50);

Set    iter              / 1*100 /;
Scalar tcost, minTCost / +inf  /;
loop(iter,
  embeddedCode Python:
    import random
    i = list(gams.get("i"))
    p = list(i)
    random.shuffle(p)
    for idx in range(len(i)):
      p[idx] = (i[idx], p[idx])
    gams.set("p", p)
  endEmbeddedCode p
  tcost = sum(p, c(p));
  if (tcost < minTCost, minTCost = tcost);
);
Display minTCost;
```

EXECUTION TIME = 16.375 SECONDS

# Performance Considerations

```
Set i / i1*i50 /, p(i,i); Alias (i,ii);
Parameter c(i,i); c(i,ii) = uniform(-50,50);

embeddedCode Python:
  import random
pauseEmbeddedCode


Set    iter            / 1*1000 /;
Scalar tcost, minTCost / +inf   /;
loop(iter,
  continueEmbeddedCode:
    i = list(gams.get("i"))
    p = list(i)
    random.shuffle(p)
    for idx in range(len(i)):
      p[idx] = (i[idx], p[idx])
    gams.set("p", p)
  pauseEmbeddedCode p
  tcost = sum(p, c(p));
  if (tcost < minTCost, minTCost = tcost);
);
continueEmbeddedCode:
  pass
endEmbeddedCode
Display minTCost;
```

EXECUTION TIME = 1.797 SECONDS

# Performance Considerations

```
Set i / i1*i50 /, p(i,i); Alias (i,ii);
Parameter c(i,i); c(i,ii) = uniform(-50,50);

embeddedCode Python:
  import random
  i = list(gams.get("i"))
pauseEmbeddedCode


Set    iter            / 1*1000 /;
Scalar tcost, minTCost / +inf   /;
loop(iter,
  continueEmbeddedCode Python:
    p = list(i)
    random.shuffle(p)
    for idx in range(len(i)):
      p[idx] = (i[idx], p[idx])
    gams.set("p", p)
  pauseEmbeddedCode p
  tcost = sum(p, c(p));
  if (tcost < minTCost, minTCost = tcost);
);
continueEmbeddedCode:
  pass
endEmbeddedCode
Display minTCost;
```

EXECUTION TIME = 1.593 SECONDS

# Performance Considerations

```
Set i / i1*i50 /, p(i,i); Alias (i,ii);
Parameter c(i,i); c(i,ii) = uniform(-50,50);

embeddedCode Python:
  import random
  i = list(gams.get("i",keyType=KeyType.INT))
pauseEmbeddedCode


Set    iter            / 1*1000 /;
Scalar tcost, minTCost / +inf   /;
loop(iter,
  continueEmbeddedCode Python:
    p = list(i)
    random.shuffle(p)
    for idx in range(len(i)):
      p[idx] = (i[idx], p[idx])
    gams.set("p", p)
  pauseEmbeddedCode p
  tcost = sum(p, c(p));
  if (tcost < minTCost, minTCost = tcost);
);
continueEmbeddedCode:
  pass
endEmbeddedCode
Display minTCost;
```

EXECUTION TIME = 1.437 SECONDS

# Some Examples of Python Embedded Code

- Splitting of labels (compile time)
- Permutation
- Sorting
- Calculation of quantiles
- Power set
- Matching
- Parsing of specially structured ASCII input
- TSP subtour elimination
- Benders Decomposition using **Message Passing Interface (MPI)** on **High-Performance Computing (HPC)** infrastructure

# Next steps …

- More examples
  - High Performance Libraries for specific tasks
    - FORTRAN (Factorization of matrix)
    - C/C++ (Expansion Planning Power Systems)
  - Support of other popular frameworks (compiled and interpreted)
    - C/C++
    - C#/.NET, Java, R, …
    - Connect of powerful libraries e.g. boost::graph, …
- Provide a configurable build system that supports building the required libraries (for compiled languages) at GAMS compile time
- Provide a documented API to allow integration of individual user embedded code libraries
- Asynchronous/parallel use of embedded code

This feature is currently in beta status.
Any feedback to support@gams.com is highly appreciated.


# Thank You

# Meet us at the GAMS booth!

# Syntax: GAMS

Compile Time:

```
$onEmbeddedCode[S|V] Python: [arguments]
  Python code
 {Python code}
$offEmbeddedCode {output symbol}
```

- `$onEmbeddedCode[S] Python: [arguments]`
  - Starts a section with Python code
  - Parameter substitution is activated
  - The optional `arguments` can be accessed in the `Python code`
- `$onEmbeddedCodeV Python: [arguments]`
  - Same as `$onEmbeddedCode` but parameter substitution is disabled (the `Python code` is passed on verbatim)
- `$offEmbeddedCode {output symbol}`
  - Ends a section with Python code
  - The optional `output symbol(s)` get updated in the GAMS database

# Syntax: GAMS

Execution Time:

```
EmbeddedCode[S|V] Python: [arguments]
   Python code
  {Python code}
endEmbeddedCode {output symbol}
```

- `EmbeddedCode[S] Python: [arguments]`
  - Starts a section with Python code
  - Parameter substitution is activated
  - The optional `arguments` can be accessed in the `Python code`
- `EmbeddedCodeV Python: [arguments]`
  - Same as `EmbeddedCode` but parameter substitution is disabled (the `Python code` is passed on verbatim)
- `endEmbeddedCode {output symbol}`
  - Ends a section with Python code
  - The optional `output symbol(s)` get updated in the GAMS database

# Syntax: GAMS

Execution Time:

```
pauseEmbeddedCode {output symbols}
continueEmbeddedCode[S|V] [handle]: [arguments]
```

- `pauseEmbeddedCode {output symbol}`
  - Pauses a section with Python code
  - The optional `output symbol(s)` get updated in the GAMS database
- `continueEmbeddedCode[S] [handle]: [arguments]`
  - Continues a previously paused section with Python code
  - Parameter substitution is activated
  - The optional `arguments` can be accessed in the `Python code`
  - The optional `handle` (pointing to a specific paused embedded code section) could be retrieved by the function `embeddedHandle`. If omitted, the last section paused will be continued.
- `continueEmbeddedCodeV [handle]: [arguments]`
  - Same as `continueEmbeddedCode` but parameter substitution is disabled (the `Python code` is passed on verbatim)

# Syntax: Python

The Python Class `ECGamsDatabase` serves as interface between GAMS and Python. An instance of this class is automatically created when an embedded code section is entered and can be accessed using the identifier `gams`. Several methods can be used to interact with GAMS:

- `gams.get(symbolName, […])`
  - Retrieves iterable object representing the symbol `symbolName`
  - Several optional parameters allow to modify format of the data
- `gams.set(symbolName, data[, merge][, domCheck])`
  - Sets data for the GAMS symbol `symbolName`
  - `Data` takes a Python list of items representing records of the symbol
  - Optional parameter `merge` specifies if data in a GAMS symbol is merged or replaced
  - Optional parameter `domCheck` specifies if Domain Checking is applied

# Syntax: Python

- `gams.getUel(idx)`
  - Returns the label corresponding to the label index `idx`
- `gams.mergeUel(label)`
  - Adds `label` to the GAMS universe if it was unknown and returns the corresponding label index
  - Note: New labels cannot be added at execution time
- `gams.getUelCount()`
  - Returns the number of labels
- `gams.printLog(msg)`
  - Print `msg` to log
- `gams.arguments`
  - Contains the arguments that were passed to the Python interpreter at start-up of the embedded code section
- `gams.epsAsZero`
  - Flag to read GAMS EPS as 0 [`True`] or as a small number (4.94066E-300) [`False`]
- `gams._debug`
  - Debug flag for additional output