

License Guide - On Premise  
Oracle FLEXCUBE Universal Banking  
Release 14.7.5.0.0  
Part No.G14514-01  
[September] [2024]





License Guide  
[September] [2024]  
Version 14.7.5.0.0

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# 1. Preface

## 1.1 Introduction

This document helps you understand the guiding rules for Oracle FLEXCUBE Universal Banking licensing, the components included in the license, and the units that are separately licensed.

This document also provides information on the third party software that are packaged with Oracle FLEXCUBE Universal Banking.

## 1.2 Audience

This document is intended for the following audience:

- Customers
- Partners

## 1.3 Documentation Accessibility

For information about Oracle's commitment to accessibility, visit the Oracle Accessibility Program website at <http://www.oracle.com/pls/topic/lookupctx=acc&id=docacc>.

## 1.4 Organization

This manual is organized into the following chapters:

| Chapter   | Description                                                                                                                                     |
|-----------|-------------------------------------------------------------------------------------------------------------------------------------------------|
| Chapter 1 | <i>Preface</i> gives information on the intended audience. It also lists the various chapters covered in this license guide.                    |
| Chapter 2 | <i>Oracle FLEXCUBE Universal Banking Licensing</i> provides information on Oracle FLEXCUBE Universal Banking licensing.                         |
| Chapter 3 | <i>Software Pre-requisites</i> consists of the technology pre-requisites required for Oracle FLEXCUBE Universal Banking.                        |
| Chapter 4 | <i>Third Party Licenses</i> provides information on licensing of third party software that are packaged with Oracle FLEXCUBE Universal Banking. |

## 1.5 Related Documents

For more information, refer to the following documents:

- End user license agreement
- Oracle FLEXCUBE User Manuals

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## 2. Oracle FLEXCUBE Universal Banking Licensing

### 2.1 Introduction

This chapter provides information on Oracle FLEXCUBE Universal Banking licensing. It contains the following sections:

- General licensing rules
- Components included in the license
- Separately licensed pre-requisite products and licensing metric
- Restricted use license

### 2.2 General Licensing Rules

The following table lists out the modules, which are primarily retail or corporate. The licensing rule against each of them defines how these modules will get licensed based on the usage of the bank.

| Sl. No.        | Module Description                                                      | Licensing Rule(s)                                                                                                                                                                                                                                                                                                              |
|----------------|-------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Retail Modules |                                                                         |                                                                                                                                                                                                                                                                                                                                |
| 1              | Oracle FLEXCUBE Universal Banking Current Accounts and Savings Accounts | If the customer is using Universal Banking for Retail programs, these applications may only be licensed by the Account metric. However, if the customer is using Universal Banking for Corporate, and is not using Universal Banking for Retail, then a customer may license these programs under the Application User metric. |
| 2              | Oracle FLEXCUBE Universal Banking Standing Instructions                 |                                                                                                                                                                                                                                                                                                                                |

| Sl. No.           | Module Description                                      | Licensing Rule(s)                                                                                                                                                                                                                                                                                                          |
|-------------------|---------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Corporate Modules |                                                         |                                                                                                                                                                                                                                                                                                                            |
| 3                 | Oracle FLEXCUBE Universal Banking Nostro Reconciliation | If the customer is using Universal Banking for Corporate programs, these applications may only be licensed by the Application User. However, if the customer is using Universal Banking for Retail, and is not using Universal Banking for Corporate, then a customer may license these programs under the Account metric. |
| 4                 | Oracle FLEXCUBE Universal Banking Commercial Leasing    |                                                                                                                                                                                                                                                                                                                            |
| 5                 | Oracle FLEXCUBE Integration Gateway                     |                                                                                                                                                                                                                                                                                                                            |

## 2.3 Components Included in License

The following components are included in the Oracle FLEXCUBE Universal Banking license:

1. Signature Verification: is included with Oracle FLEXCUBE Universal Banking Current Accounts and Savings Accounts license.

2. Islamic Banking Support\*\*: The following Oracle FLEXCUBE Universal Banking module licenses have support for Islamic Banking.

- Oracle FLEXCUBE Universal Banking Base
- Oracle FLEXCUBE Universal Banking Asset Management
- Oracle FLEXCUBE Universal Banking Current Accounts and Savings Accounts
- Oracle FLEXCUBE Universal Banking Fixed Assets
- Oracle FLEXCUBE Universal Banking Relationship Pricing
- Oracle FLEXCUBE Universal Banking Retail and Small and Medium Enterprise Loans
- Oracle FLEXCUBE Universal Banking Term Deposits
- Oracle FLEXCUBE Universal Banking Islamic Commercial Lending and Leasing

## 2.4 Separately Licensed Pre-requisite Products and Licensing Metric

The module wise list of separately licensed products and the licensing metric is given below.

*For other separately licensable software pre-requisites, refer to the section Software Pre-requisites.*

| Module Description | Separately Licensed Prerequisites | Licensing Metric(s) |
|--------------------|-----------------------------------|---------------------|
|--------------------|-----------------------------------|---------------------|

|                                                                                |                                                                                                                                                                                                                                                      |                                                                                                                                                             |
|--------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Oracle FLEXCUBE Universal Banking Base*                                        | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Development Workbench</li> <li>• Oracle FLEXCUBE Integration Gateway</li> <li>• Oracle Database Enterprise Edition, Partitioning, and TopLink, Application Development Framework</li> </ul> | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> <li>• Account</li> <li>• Financial Inclusion Account</li> </ul> |
| Oracle FLEXCUBE Universal Banking Current Accounts and Savings Accounts        | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> <li>• Account</li> <li>• Financial Inclusion Account</li> </ul> |
| Oracle FLEXCUBE Universal Banking Relationship Pricing                         | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> <li>• Either Oracle FLEXCUBE Universal Banking Current Accounts &amp; Savings Accounts OR Oracle FLEXCUBE Universal Banking Term Deposits</li> </ul>            | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                                                                 |
| Oracle FLEXCUBE Universal Banking Term Deposits                                | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                                                                 |
| Oracle FLEXCUBE Universal Banking Retail and Small and Medium Enterprise Loans | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> <li>• Financial Inclusion Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Nostro Reconciliation                        | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> <li>• Account</li> </ul>                                        |
| Oracle FLEXCUBE Universal Banking Standing Instructions                        | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> <li>• Account</li> </ul>                                        |
| Oracle FLEXCUBE Universal Banking ATM Interface                                | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> <li>• Financial Inclusion Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Point of Sale Interface                      | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> <li>• Financial Inclusion Account</li> </ul>                                                          |

|                                                                        |                                                                                                                                                                                      |                                                                                                                      |
|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| Oracle FLEXCUBE Universal Banking Interactive Voice Response Interface | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Mortgages                            | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Consumer Leasing                     | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Commercial Leasing                   | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> <li>• Account</li> </ul> |
| Oracle FLEXCUBE Universal Banking Inventory Management                 | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> <li>• Oracle FLEXCUBE Universal Banking Current Accounts &amp; Savings Accounts</li> </ul>      | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Microfinance                         | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> <li>• Oracle FLEXCUBE Universal Banking Retail and Small and Medium Enterprise Loans</li> </ul> | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Safe Deposit Box                     | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Account</li> </ul>                                                          |
| Oracle FLEXCUBE Universal Banking Corporate Deposits                   | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> </ul>                    |
| Oracle FLEXCUBE Universal Banking Fixed Assets                         | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> </ul>                    |
| Oracle FLEXCUBE Universal Banking Asset Management                     | <ul style="list-style-type: none"> <li>• FLEXCUBE Universal Banking Base and Oracle Banking Treasury Management</li> </ul>                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> </ul>                    |
| Oracle FLEXCUBE Universal Banking Expense Processing                   | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                           | <ul style="list-style-type: none"> <li>• Application User</li> <li>• Custom Suite User</li> </ul>                    |



|                                                                          |                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                  |
|--------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Oracle FLEXCUBE Universal Banking Islamic Commercial Lending and Leasing | <ul style="list-style-type: none"> <li>• Oracle FLEXCUBE Universal Banking Base</li> </ul>                                                                                                                                                                                                                                                                                  | <ul style="list-style-type: none"> <li>• Account</li> <li>• Application User</li> <li>• Custom Suite User</li> </ul>                             |
| Oracle FLEXCUBE Open Development Tools                                   |                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                  |
| Oracle FLEXCUBE Development Workbench                                    | <ul style="list-style-type: none"> <li>• Either of Oracle FLEXCUBE Universal Banking Base or Oracle Banking Enterprise Limits Management, Oracle Banking Collateral Management or Oracle Banking Corporate Lending, Oracle Banking Payments, Oracle Banking Trade Finance or Oracle Banking Treasury Management, Development Workbench &amp; Integration Gateway</li> </ul> | <ul style="list-style-type: none"> <li>• Application User</li> </ul>                                                                             |
| Oracle FLEXCUBE Interfaces and Tools                                     |                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                  |
| Oracle FLEXCUBE Integration Gateway                                      | <ul style="list-style-type: none"> <li>• Either of Oracle FLEXCUBE Universal Banking Base or Oracle Banking Enterprise Limits Management, Oracle Banking Collateral Management or Oracle Banking Corporate Lending, Oracle Banking Payments, Oracle Banking Trade Finance or Oracle Banking Treasury Management, Development Workbench &amp; Integration Gateway</li> </ul> | <ul style="list-style-type: none"> <li>• 10K API Calls</li> <li>• Account</li> <li>• Processor</li> <li>• Financial Inclusion Account</li> </ul> |

\* When Component pricing model is used, Oracle FLEXCUBE Universal Banking Base program should be licensed for cumulative number of Application Users of all the Oracle FLEXCUBE Universal Banking for corporate program licensed.

\*\*In case of Islamic Trade Finance and related financing requirements where Oracle FLEXCUBE Universal Banking Islamic Commercial Lending and Leasing is being licensed, Oracle FLEXCUBE Universal Banking Current Accounts and Savings Accounts SKU is included with the order for restricted use such as settlement purpose only.

When licensing Oracle FLEXCUBE Universal Banking modules by Account metric, quantity of Accounts licensed for each Oracle FLEXCUBE Universal Banking module including Base must be same. The sum of Accounts across all licensed modules (excluding Base) on Account metric is to be used as the quantity to be licensed. For example, if customer needs 1,000,000 Accounts of Current Accounts and Savings Accounts, 400,000 Accounts of Term Deposits and 100,000 Accounts of Retail and Small and Medium Enterprise Loans; quantity of 1,500,000 Accounts needs to be licensed for each of Base, Current Accounts and Savings Accounts, Term Deposits and Retail and Small and Medium Enterprise Loans modules.

When licensing Oracle FLEXCUBE Universal Banking modules by Custom Suite User metric, quantity of CAS users licensed for each Oracle FLEXCUBE Universal Banking module including Base must be the same.

NOTE: # For sending SWIFT FIN messages generated in FLEXCUBE to SWIFT network or for sending FIN messages from SWIFT network to FLEXCUBE, Oracle Banking Cross Border SKU needs to be licensed.

## 2.5 Restricted Use License

The following modules have restricted features or functionality for use under the license metric Financial Inclusion Account.

| Product or Component                   | Restrictions/Features Omitted                                                                                                                                                                                                                                                                                                                                       |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Oracle FLEXCUBE Universal Banking Base | <ul style="list-style-type: none"><li>• Customer creation along with account creation is done in a single go without the option of Signature capture and verification.</li><li>• These customers will not have the Limits linkage</li><li>• Only Individual type of customers alone can be created. (Corporate/ Bank kind of customers cannot be created)</li></ul> |

|                                                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>Oracle FLEXCUBE Universal Banking<br/>Current Accounts and Savings<br/>Accounts</p> | <ul style="list-style-type: none"> <li>• System will allow the FI customer to open only a Single Holder savings CASA account and in branch currency only</li> <li>• Temporary OD on FI customer's CASA accounts is allowed for a short term without attaching any collateral or credit line backing.</li> <li>• Allow mapping an account class with only a single IC product of type "Interest". This IC product is restricted to contain only general conditions and One Debit and One Credit product attached to it.</li> <li>• Check book and Debit card features are not available for FI customer accounts.</li> <li>• The account cannot be salary account</li> </ul> |
|----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

| Product or Component                                                           | Restrictions/Features Omitted                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Oracle Banking Branch                                                          | <ul style="list-style-type: none"> <li>• Allow only the below Branch transactions for a FI customer,</li> <li>• Cash Deposit</li> <li>• Cash Withdrawal</li> <li>• Transfers</li> <li>• Utility payment without external Utility Provider interface</li> </ul>                                                                                                                                                                                                                       |
| Oracle FLEXCUBE Universal Banking ATM Interface                                | No restrictions brought in.                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Oracle FLEXCUBE Integration Gateway                                            | No restrictions brought in.                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Oracle FLEXCUBE Universal Banking Retail and Small and Medium Enterprise Loans | <ul style="list-style-type: none"> <li>• Following loan features are not available for Financial Inclusion Customer <ul style="list-style-type: none"> <li>▪ Origination / Onboarding</li> <li>▪ Auto disbursement</li> <li>▪ Rate revisions</li> <li>▪ Provisioning</li> <li>▪ Re-negotiation</li> <li>▪ Amendments</li> </ul> </li> <li>• FI Loans are only created in Branch currency</li> <li>• A new screen is made available for loan account input for FI customer</li> </ul> |
| Oracle FLEXCUBE Universal Banking Point of Sale Interface                      | No restrictions brought in.                                                                                                                                                                                                                                                                                                                                                                                                                                                          |

## 3. Software Pre-requisites

Following are the separately licensable software prerequisites for Oracle FLEXCUBE Universal Banking Products.

### 3.1 Software Prerequisites

#### 3.1.1 Tech Stack – Oracle

| Component                                             | Deployment option       | Machine                                                                                                                                         | Operating System                     | Software                                                | Version Number |
|-------------------------------------------------------|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|---------------------------------------------------------|----------------|
| Oracle FLEXCUBE Universal Banking                     | UI-Host and Centralized | Application Server                                                                                                                              | Oracle Linux Server 8.3 (x86 64 Bit) | Oracle WebLogic Server                                  | 14.1.1.0.0     |
|                                                       |                         |                                                                                                                                                 |                                      | Java HotSpot(TM) JDK (with WebLogic Application Server) | 11.0.16        |
|                                                       |                         |                                                                                                                                                 |                                      | Open Symphony Quartz                                    | 2.3.2          |
|                                                       |                         | Database Server                                                                                                                                 | Oracle Linux Server 8.3 (x86 64 Bit) | Oracle RDBMS Enterprise Edition                         | 19.18.0.0.0    |
|                                                       |                         | <b>Client Machines</b><br><b>Note</b> - Browser Support is strictly tied to the Browser itself, and is no longer based on the Operating System. |                                      | Mozilla Firefox                                         | 102+           |
|                                                       |                         |                                                                                                                                                 |                                      | Microsoft Edge                                          | 107+           |
|                                                       |                         |                                                                                                                                                 |                                      | Safari                                                  | 15+            |
|                                                       |                         |                                                                                                                                                 |                                      | Google Chrome                                           | 107+           |
| Oracle FLEXCUBE Universal Banking Integration Gateway | Web services (incoming) | Integration Server                                                                                                                              | Oracle Linux Server 8.3 (x86 64 Bit) | Oracle WebLogic Server                                  | 14.1.1.0.0     |
|                                                       | HTTP Servlet (incoming) |                                                                                                                                                 |                                      |                                                         |                |
|                                                       | EJB (incoming)          |                                                                                                                                                 |                                      |                                                         |                |
|                                                       | MDB (incoming)          |                                                                                                                                                 |                                      |                                                         |                |
|                                                       | Notificatios (outgoing) |                                                                                                                                                 |                                      |                                                         |                |

|                                                              |                            |                         |                                      |                                        |            |
|--------------------------------------------------------------|----------------------------|-------------------------|--------------------------------------|----------------------------------------|------------|
| Oracle FLEXCUBE Universal Banking Switch Integration Gateway | Switch Integration Gateway | Integration Server      | Oracle Linux Server 8.3 (x86 64 Bit) | JDK                                    | 11.0.16    |
| Oracle FLEXCUBE Universal Banking REST Services              | Web services               | Integration Server      | Oracle Linux Server 8.3 (x86 64 Bit) | JDK                                    | 11.0.16    |
|                                                              |                            |                         |                                      | Oracle WebLogic Server                 | 14.1.1.0.0 |
|                                                              |                            |                         |                                      | Oracle Toplink                         | 14.1.1.0.0 |
| Oracle FLEXCUBE Machine Learning                             | Centralized                | Machine Learning Server | Oracle Linux Server 8.3 (x86 64 Bit) | OML4R (Previously Oracle R Enterprise) | 1.5.1      |
| Oracle FLEXCUBE Oracle Digital Assistant Integration         | Centralized                | Application Server      | Oracle Linux Server 8.3 (x86 64 Bit) | oda-native-client-sdk-js               | 20.3.1     |
| Oracle FLEXCUBE Universal Banking Integration Gateway        | Web services (incoming)    | Integration Server      | Oracle Linux Server 8.3 (x86 64 Bit) | Oracle WebLogic Server                 | 14.1.1.0.0 |
|                                                              | HTTP Servlet (incoming)    |                         |                                      |                                        |            |
|                                                              | EJB (incoming)             |                         |                                      |                                        |            |
|                                                              | MDB (incoming)             |                         |                                      |                                        |            |
|                                                              | Notifications (outgoing)   |                         |                                      |                                        |            |
| Oracle FLEXCUBE Universal Banking                            | Switch Integration Gateway | Integration Server      | Oracle Linux Server 8.3 (x86 64 Bit) | JDK                                    | 11.0.16    |
| Switch Integration Gateway                                   |                            |                         |                                      |                                        |            |
| Oracle FLEXCUBE Universal Banking REST                       | Web services               | Integration Server      | Oracle Linux Server 8.3 (x86 64 Bit) | JDK                                    | 11.0.16    |
|                                                              |                            |                         |                                      | Oracle WebLogic Server                 | 14.1.1.0.0 |
|                                                              |                            |                         |                                      | Oracle Toplink                         | 14.1.1.0.0 |

|                                                      |             |                         |                                      |                                        |        |
|------------------------------------------------------|-------------|-------------------------|--------------------------------------|----------------------------------------|--------|
| Oracle FLEXCUBE Machine Learning                     | Centralized | Machine Learning Server | Oracle Linux server 8.3 (x86 64 bit) | OML4R (Previously Oracle R Enterprise) | 1.5.1  |
| Oracle FLEXCUBE Oracle Digital Assistant Integration | Centralized | Application Server      | Oracle Linux server 8.3 (x86 64 bit) | oda-native-client-sdk-js               | 20.3.1 |

Note:

- i. Browser support is no longer based on Operating Systems but strictly tied to the browser themselves, no matter which Operating Systems they are installed on. Current release is certified on client workstations with Windows 7, 8, 10 and Mac OS X.
- ii. Oracle Applications are developed and tested on Oracle Linux, which is optimized for performance, stability, and security.

### 3.2 Module-wise Software Prerequisites

| Product Name                                            | Product Version | Requirements                                                                                                                                                                   |
|---------------------------------------------------------|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Oracle Fusion Middleware Infrastructure                 | 12.2.1.4.0      | Optional - Oracle FLEXCUBE Universal Banking and Oracle FLEXCUBE Universal Banking Integration Gateway supports both Oracle Weblogic Server (Fusion Middleware) and WebSphere. |
| Java HotSpot(TM) JDK (with WebLogic Application Server) | 11.0.16         | Optional – Required for Oracle FLEXCUBE Universal Banking and Oracle FLEXCUBE Universal Banking Integration Gateway on WebLogic.                                               |
| Open Symphony Quartz                                    | 2.3.2           | Standard requirement                                                                                                                                                           |
| Oracle Toplink                                          | 14.1.1.0.0      | Optional - Required only if limits tracking is required.                                                                                                                       |
| Oracle RDBMS Enterprise Edition                         | 19.18.0.0.0     | Standard requirement                                                                                                                                                           |

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## 4.Third Party Licenses

### **Apache License**

Version 2.0, January 2004

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9.0 thru

1.2 1991-1995 CWI yes

1.3 thru

1.5.2

1.2 1995-1999 CNRI yes

1.6

1.5.2 2000 CNRI no 2.0

1.6 2000 BeOpen.com no 1.6.1

1.6 2001 CNRI yes (2)

2.1 2.0+1.6.1 2001 PSF no 2.0.1 2.0+1.6.1 2001 PSF yes

2.1.1

2.1+2.0.1 2001 PSF yes

2.1.2

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2.1.3

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9.0 thru

1.2 1991-1995 CWI yes

1.3 thru

1.5.2

1.2 1995-1999 CNRI yes

1.6

1.5.2 2000 CNRI no 2.0

1.6 2000 BeOpen.com no 1.6.1

1.6 2001 CNRI yes (2)

2.1 2.0+1.6.1 2001 PSF no 2.0.1 2.0+1.6.1 2001 PSF yes

2.1.1

2.1+2.0.1 2001 PSF yes

2.1.2

2.1.1 2002 PSF yes

2.1.3

2.1.2 2002 PSF yes

2.2 and above

2.1.1 2001-now PSF yes Footnotes: (1) GPL-compatible doesn't mean that we're distributing Python

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This binary distribution of NumPy also bundles the following software:

Name: OpenBLAS Files: `numpy/.dylibs/libopenblas*.so`

Description: bundled as a dynamically linked library

Availability: <https://github.com/OpenMathLib/OpenBLAS/>

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\defepsilon{\varepsilon} \defbigoh{\mathcal{O}} \defphi{\varphi} \defst{{\hbox{\scriptsize{\rm st}}}}
\defth{{\hbox{\scriptsize{\rm th}}}} \defx{\mathbf{x}} \title{ID: A software package for low-rank
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SUCH DAMAGE. } \newpage \tableofcontents \newpage \hrule \medskip \centerline{\Large \bf IMPORTANT} \medskip \hrule \medskip \noindent At the minimum, please read Subsection~\ref{warning} and Section~\ref{naming} below, and beware that the {\it N.B.}'s in the source code comments highlight key information about the routines; {\it N.B.} stands for {\it nota bene} (Latin for ``note well"). \medskip \hrule \bigskip \section{Introduction} This software distribution provides Fortran routines for computing low-rank approximations to matrices, in the forms of interpolative decompositions (IDs) and singular value decompositions (SVDs). The routines use algorithms based on the ID. The ID is also commonly known as the approximation obtained via skeletonization, the approximation obtained via subsampling, and the approximation obtained via subset selection. The ID provides many advantages in many applications, and we suspect that it will become increasingly popular once tools for its computation become more widely available. This software distribution includes some such tools, as well as tools for computing low-rank approximations in the form of SVDs. Section~\ref{defs} below defines IDs and SVDs, and provides references to detailed discussions of the algorithms used in this software package. Please beware that normalized power iterations are better suited than the software in this distribution for computing principal component analyses in the typical case when the square of the signal-to-noise ratio is not orders of magnitude greater than both dimensions of the data matrix; see~\cite{halko-martinsson-tropp}. The algorithms used in this distribution have been optimized for accuracy, efficiency, and reliability; as a somewhat counterintuitive consequence, many must be randomized. All randomized codes in this software package succeed with overwhelmingly high probability (see, for example, \cite{halko-martinsson-tropp}). The truly paranoid are welcome to use the routines {\tt idd\\_diffsnorm} and {\tt idz\\_diffsnorm} to evaluate rapidly the quality of the approximations produced by the randomized algorithms (as done, for example, in the files {\tt idd\\_a\\_test.f}, {\tt idd\\_r\\_test.f}, {\tt idz\\_a\\_test.f}, and {\tt idz\\_r\\_test.f} in the {\tt test} subdirectory of the main directory {\tt id\\_dist}). In most circumstances, evaluating the quality of an approximation via routines {\tt idd\\_diffsnorm} or {\tt idz\\_diffsnorm} is much faster than forming the approximation to be evaluated. Still, we are unaware of any instance in which a properly-compiled routine failed to produce an accurate approximation. To facilitate successful compilation, we encourage the user to read the instructions in the next section, and to read Section~\ref{naming}, too. \section{Compilation instructions} Followed in numerical order, the subsections of this section provide step-by-step instructions for compiling the software under a Unix-compatible operating system. \subsection{Beware that default command-line flags may not be sufficient for compiling the source codes!} \label{warning} The Fortran source codes in this distribution pass {\tt real\*8} variables as integer variables, integers as {\tt real\*8}'s, {\tt real\*8}'s as {\tt complex\*16}'s, and so on. This is common practice in numerical codes, and is not an error; be sure to provide the relevant command-line flags to the compiler (for example, run {\tt f77} and {\tt f2c} with the flag {\tt -!P}). When following the compilation instructions in Subsection~\ref{makefile\_edit} below, be sure to set {\tt FFLAGS} appropriately. \subsection{Install LAPACK} The SVD routines in this distribution depend on LAPACK. Before compiling the present distribution, create the LAPACK and BLAS archive (library) {\tt .a} files; information about installing LAPACK is available at {\tt

<http://www.netlib.org/lapack/> (and several other web sites). \subsection{Decompress and untar the file {\tt id\\_dist.tar.gz}} At the command line, decompress and untar the file {\tt id\\_dist.tar.gz} by issuing a command such as {\tt tar -xvzf id\\_dist.tar.gz}. This will create a directory named {\tt id\\_dist}.

\subsection{Edit the Makefile} \label{makefile\_edit} The directory {\tt id\\_dist} contains a file named {\tt Makefile}. In {\tt Makefile}, set the following: % \begin{itemize} \item {\tt FC} is the Fortran compiler. \item {\tt FFLAGS} is the set of command-line flags (specifying optimization settings, for example) for the Fortran compiler specified by {\tt FC}; please heed the warning in Subsection~\ref{warning} above! \item {\tt BLAS\\_LIB} is the file-system path to the BLAS archive (library) {\tt .a} file. \item {\tt LAPACK\\_LIB} is the file-system path to the LAPACK archive (library) {\tt .a} file. \item {\tt ARCH} is the archiver utility (usually {\tt ar}). \item {\tt ARCHFLAGS} is the set of command-line flags for the archiver specified by {\tt ARCH} needed to create an archive (usually {\tt cr}). \item {\tt RANLIB} is to be set to {\tt ranlib} when {\tt ranlib} is available, and is to be set to {\tt echo} when {\tt ranlib} is not available. \end{itemize}

\subsection{Make and test the libraries} At the command line in a shell that adheres to the Bourne shell conventions for redirection, issue the command ``{\tt make clean; make}'' to both create the archive (library) {\tt id\\_lib.a} and test it. (In most modern Unix distributions, {\tt sh} is the Bourne shell, or else is fully compatible with the Bourne shell; the Korn shell {\tt ksh} and the Bourne-again shell {\tt bash} also use the Bourne shell conventions for redirection.) {\tt make} places the file {\tt id\\_lib.a} in the directory {\tt id\\_dist}; the archive (library) file {\tt id\\_lib.a} contains machine code for all user-callable routines in this distribution. \section{Naming conventions} \label{naming} The names of routines and files in this distribution start with prefixes, followed by an underscore (``\\_"). The prefixes are two to four characters in length, and have the following meanings: % \begin{itemize} \item The first two letters are always ``{\tt id}'' , the name of this distribution. \item The third letter (when present) is either ``{\tt d}'' or ``{\tt z}''; ``{\tt d}'' stands for double precision ({\tt real\*8}), and ``{\tt z}'' stands for double complex ({\tt complex\*16}). \item The fourth letter (when present) is either ``{\tt r}'' or ``{\tt p}''; ``{\tt r}'' stands for specified rank, and ``{\tt p}'' stands for specified precision. The specified rank routines require the user to provide the rank of the approximation to be constructed, while the specified precision routines adjust the rank adaptively to attain the desired precision. \end{itemize} For example, {\tt iddr\\_aid} is a {\tt real\*8} routine which computes an approximation of specified rank. {\tt idz\\_snorm} is a {\tt complex\*16} routine. {\tt id\\_randperm} is yet another routine in this distribution. \section{Example programs} For examples of how to use the user-callable routines in this distribution, see the source codes in subdirectory {\tt test} of the main directory {\tt id\\_dist}. \section{Directory structure} The main {\tt id\\_dist} directory contains a Makefile, the auxiliary text files {\tt README.txt} and {\tt size.txt}, and the following subdirectories, described in the subsections below: % \begin{enumerate} \item {\tt bin} \item {\tt development} \item {\tt doc} \item {\tt src} \item {\tt test} \item {\tt tmp} \end{enumerate} % If a ``{\tt make all}'' command has completed successfully, then the main {\tt id\\_dist} directory will also contain an archive (library) file {\tt id\\_lib.a} containing machine code for all of the user-callable routines. \subsection{Subdirectory {\tt bin}} Once all of the libraries have been made via the Makefile in the main {\tt id\\_dist} directory, the subdirectory {\tt bin} will contain object files

(machine code), each compiled from the corresponding file of source code in the subdirectory `{\tt src}` of `{\tt id\_dist}`.

**Subdirectory `{\tt development}`** Each Fortran file in the subdirectory `{\tt development}` (except for `{\tt dfft.f}` and `{\tt prini.f}`) specifies its dependencies at the top, then provides a main program for testing and debugging, and finally provides source code for a library of user-callable subroutines. The Fortran file `{\tt dfft.f}` is a copy of P. N. Swarztrauber's FFTPACK library for computing fast Fourier transforms. The Fortran file `{\tt prini.f}` is a copy of V. Rokhlin's library of formatted printing routines. Both `{\tt dfft.f}` (version 4) and `{\tt prini.f}` are in the public domain. The shell script `{\tt RUNME.sh}` runs shell scripts `{\tt make\_src.sh}` and `{\tt make\_test.sh}`, which fill the subdirectories `{\tt src}` and `{\tt test}` of the main directory `{\tt id\_dist}` with source codes for user-callable routines and with the main program testing codes.

**Subdirectory `{\tt doc}`** Subdirectory `{\tt doc}` contains this documentation, supplementing comments in the source codes.

**Subdirectory `{\tt src}`** The files in the subdirectory `{\tt src}` provide source code for software libraries. Each file in the subdirectory `{\tt src}` (except for `{\tt dfft.f}` and `{\tt prini.f}`) is the bottom part of the corresponding file in the subdirectory `{\tt development}` of `{\tt id\_dist}`. The file `{\tt dfft.f}` is just a copy of P. N. Swarztrauber's FFTPACK library for computing fast Fourier transforms. The file `{\tt prini.f}` is a copy of V. Rokhlin's library of formatted printing routines. Both `{\tt dfft.f}` (version 4) and `{\tt prini.f}` are in the public domain.

**Subdirectory `{\tt test}`** The files in subdirectory `{\tt test}` provide source code for testing and debugging. Each file in subdirectory `{\tt test}` is the top part of the corresponding file in subdirectory `{\tt development}` of `{\tt id\_dist}`, and provides a main program and a list of its dependencies. These codes provide examples of how to call the user-callable routines.

**Catalog of the routines** The main routines for decomposing `{\tt real*8}` matrices are:

- % \begin{enumerate} % \item IDs of arbitrary (generally dense) matrices: `{\tt iddp\_id}`, `{\tt iddr\_id}`, `{\tt iddp\_aid}`, `{\tt iddr\_aid}` % \item IDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' transposes): `{\tt iddp\_rid}`, `{\tt iddr\_rid}` % \item SVDs of arbitrary (generally dense) matrices: `{\tt iddp\_svd}`, `{\tt iddr\_svd}`, `{\tt iddp\_asvd}`, `{\tt iddr\_asvd}` % \item SVDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' transposes): `{\tt iddp\_rsvd}`, `{\tt iddr\_rsvd}` % \end{enumerate}

Similarly, the main routines for decomposing `{\tt complex*16}` matrices are:

- % \begin{enumerate} % \item IDs of arbitrary (generally dense) matrices: `{\tt idzp\_id}`, `{\tt idzr\_id}`, `{\tt idzp\_aid}`, `{\tt idzr\_aid}` % \item IDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' adjoints): `{\tt idzp\_rid}`, `{\tt idzr\_rid}` % \item SVDs of arbitrary (generally dense) matrices: `{\tt idzp\_svd}`, `{\tt idzr\_svd}`, `{\tt idzp\_asvd}`, `{\tt idzr\_asvd}` % \item SVDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' adjoints): `{\tt idzp\_rsvd}`, `{\tt idzr\_rsvd}` % \end{enumerate}

This distribution also includes routines for constructing pivoted QR\$ decompositions (in `{\tt idd\_qrpiv.f}` and `{\tt idz\_qrpiv.f}`), for estimating the spectral norms of matrices that may be applied rapidly to arbitrary vectors as may their adjoints (in `{\tt idd\_snorm.f}` and `{\tt idz\_snorm.f}`), for converting IDs to SVDs (in `{\tt idd\_id2svd.f}` and `{\tt idz\_id2svd.f}`), and for computing rapidly arbitrary subsets of the entries of the discrete Fourier transforms of vectors (in `{\tt idd\_sfft.f}` and `{\tt idz\_sfft.f}`).

**List of the routines** The following

is an alphabetical list of the routines in this distribution, together with brief descriptions of their functionality and the names of the files containing the routines' source code:

```
\begin{center} %
\tablehead{\bf Routine & \bf Description & \bf Source file \\\tabletail{\hline} %
\begin{supertabular}{>\raggedright}p{
1.2in} p{.53\textwidth} l} % \hline {\tt id\_frand} & generates pseudorandom numbers drawn uniformly from
the interval  $[0,1]$ ; this routine is more efficient than routine {\tt id\_srand}, but cannot generate fewer
than 55 pseudorandom numbers per call & {\tt id\_rand.f} \\\hline % {\tt id\_frandi} & initializes the seed
values for routine {\tt id\_frand} to specified values & {\tt id\_rand.f} \\\hline % {\tt id\_frando} & initializes
the seed values for routine {\tt id\_frand} to their original, default values & {\tt id\_rand.f} \\\hline % {\tt
id\_randperm} & generates a uniformly random permutation & {\tt id\_rand.f} \\\hline % {\tt id\_srand} &
generates pseudorandom numbers drawn uniformly from the interval  $[0,1]$ ; this routine is less efficient
than routine {\tt id\_frand}, but can generate fewer than 55 pseudorandom numbers per call & {\tt
id\_rand.f} \\\hline % {\tt id\_srandi} & initializes the seed values for routine {\tt id\_srand} to specified
values & {\tt id\_rand.f} \\\hline % {\tt id\_srando} & initializes the seed values for routine {\tt id\_srand} to
their original, default values & {\tt id\_rand.f} \\\hline % {\tt idd\_copycols} & collects together selected
columns of a matrix & {\tt idd\_id.f} \\\hline % {\tt idd\_diffsnorm} & estimates the spectral norm of the
difference between two matrices specified by routines for applying the matrices and their transposes to
arbitrary vectors; this routine uses the power method with a random starting vector & {\tt idd\_snorm.f}
\\hline % {\tt idd\_enorm} & calculates the Euclidean norm of a vector & {\tt idd\_snorm.f} \\\hline % {\tt
idd\_estrank} & estimates the numerical rank of an arbitrary (generally dense) matrix to a specified
precision; this routine is randomized, and must be initialized with routine {\tt idd\_frm} & {\tt iddp\_aid.f}
\\hline % {\tt idd\_frm} & transforms a vector into a vector which is sufficiently scrambled to be
subsampled, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier
transform & {\tt idd\_frm.f} \\\hline % {\tt idd\_frm} & initializes routine {\tt idd\_frm} & {\tt idd\_frm.f} \\\hline
% {\tt idd\_getcols} & collects together selected columns of a matrix specified by a routine for applying the
matrix to arbitrary vectors & {\tt idd\_id.f} \\\hline % {\tt idd\_house} & calculates the vector and scalar
needed to apply the Householder transformation reflecting a given vector into its first entry & {\tt
idd\_house.f} \\\hline % {\tt idd\_houseapp} & applies a Householder matrix to a vector & {\tt idd\_house.f}
\\hline % {\tt idd\_id2svd} & converts an approximation to a matrix in the form of an ID into an
approximation in the form of an SVD & {\tt idd\_id2svd.f} \\\hline % {\tt idd\_ldiv} & finds the greatest
integer less than or equal to a specified integer, that is divisible by another (larger) specified integer & {\tt
idd\_sfft.f} \\\hline % {\tt idd\_pairsamps} & calculates the indices of the pairs of integers that the individual
integers in a specified set belong to & {\tt idd\_frm.f} \\\hline % {\tt idd\_permmult} & multiplies together a
bunch of permutations & {\tt idd\_qrpiv.f} \\\hline % {\tt idd\_qinqr} & reconstructs the  $Q$  matrix in a
 $QR$  decomposition from the output of routines {\tt iddp\_qrpiv} or {\tt iddr\_qrpiv} & {\tt idd\_qrpiv.f}
\\hline % {\tt idd\_qrmatrix} & applies to multiple vectors collected together as a matrix the  $Q$  matrix
(or its transpose) in the  $QR$  decomposition of a matrix, as described by the output of routines {\tt
```

`idp\_qrpiv` or `{\tt iddr\_qrpiv}`; to apply  $Q^T$  (or its transpose) to a single vector without having to provide a work array, use routine `{\tt idd\_qrmatvec}` instead & `{\tt idd\_qrpiv.f}` \\hline % `{\tt idd\_qrmatvec}` & applies to a single vector the  $Q^T$  matrix (or its transpose) in the  $QR$  decomposition of a matrix, as described by the output of routines `{\tt iddp\_qrpiv}` or `{\tt iddr\_qrpiv}`; to apply  $Q$  (or its transpose) to several vectors efficiently, use routine `{\tt idd\_qrmatmat}` instead & `{\tt idd\_qrpiv.f}` \\hline % `{\tt idd\_random\_}` & `{\tt transf}` & applies rapidly a random orthogonal matrix to a user-supplied vector & `{\tt id\_rtrans.f}` \\hline % `{\tt idd\_random\_transf\_init}` & \raggedright initializes routines `{\tt idd\_random\_transf}` and `{\tt idd\_random\_transf\_inverse}` & `{\tt id\_rtrans.f}` \\hline % `{\tt idd\_random\_transf\_inverse}` & applies rapidly the inverse of the operator applied by routine `{\tt idd\_random\_transf}` & `{\tt id\_rtrans.f}` \\hline % `{\tt idd\_reconid}` & reconstructs a matrix from its ID & `{\tt idd\_id.f}` \\hline % `{\tt idd\_reconint}` & constructs  $PP^T$  in the ID  $A = B \cdot P$ , where the columns of  $B$  are a subset of the columns of  $A$ , and  $P$  is the projection coefficient matrix, given `{\tt list}`, `{\tt krank}`, and `{\tt proj}` output by routines `{\tt iddr\_id}`, `{\tt iddp\_id}`, `{\tt iddr\_aid}`, `{\tt iddp\_aid}`, `{\tt iddr\_rid}`, or `{\tt iddp\_rid}` & `{\tt idd\_id.f}` \\hline % `{\tt idd\_sfft}` & rapidly computes a subset of the entries of the discrete Fourier transform of a vector, composed with permutation matrices both on input and on output & `{\tt idd\_sfft.f}` \\hline % `{\tt idd\_sfft}` & initializes routine `{\tt idd\_sfft}` & `{\tt idd\_sfft.f}` \\hline % `{\tt idd\_sfrm}` & transforms a vector into a scrambled vector of specified length, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier transform & `{\tt idd\_frm.f}` \\hline % `{\tt idd\_sfrm}` & initializes routine `{\tt idd\_sfrm}` & `{\tt idd\_frm.f}` \\hline % `{\tt idd\_snorm}` & estimates the spectral norm of a matrix specified by routines for applying the matrix and its transpose to arbitrary vectors; this routine uses the power method with a random starting vector & `{\tt idd\_snorm.f}` \\hline % `{\tt iddp\_aid}` & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idd\_frmi}` & `{\tt iddp\_aid.f}` \\hline % `{\tt iddp\_asvd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idd\_frmi}` & `{\tt iddp\_asvd.f}` \\hline % `{\tt iddp\_id}` & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine `{\tt iddp\_aid}` & `{\tt idd\_id.f}` \\hline % `{\tt iddp\_qrpiv}` & computes the pivoted  $QR$  decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified precision of the decomposition & `{\tt idd\_qrpiv.f}` \\hline % `{\tt iddp\_rid}` & computes the ID, to a specified precision, of a matrix specified by a routine for applying its transpose to arbitrary vectors; this routine is randomized & `{\tt iddp\_rid.f}` \\hline % `{\tt iddp\_rsvd}` & computes the SVD, to a specified precision, of a matrix specified by routines for applying the matrix and its transpose to arbitrary vectors; this routine is randomized & `{\tt iddp\_rsvd.f}` \\hline % `{\tt iddp\_svd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine `{\tt iddp\_asvd}` & `{\tt idd\_svd.f}` \\hline % `{\tt iddr\_aid}` & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is randomized, and must be initialized by routine `{\tt iddr\_aidi}` & `{\tt iddr\_aid.f}` \\hline % `{\tt iddr\_aidi}` & initializes routine `{\tt iddr\_aid}` & `{\tt iddr\_aid.f}` \\hline %

`iddr_asvd` & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine is randomized, and must be initialized with routine `{\tt idd_aid}` & `{\tt iddr_asvd.f}` \\hline % `{\tt iddr_id}` & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine `{\tt iddr_aid}` & `{\tt idd_id.f}` \\hline % `{\tt iddr_qrpiv}` & computes the pivoted \$QR\$ decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified rank of the decomposition & `{\tt idd_qrpiv.f}` \\hline % `{\tt iddr_rid}` & computes the ID, to a specified rank, of a matrix specified by a routine for applying its transpose to arbitrary vectors; this routine is randomized & `{\tt iddr_rid.f}` \\hline % `{\tt iddr_rsvd}` & computes the SVD, to a specified rank, of a matrix specified by routines for applying the matrix and its transpose to arbitrary vectors; this routine is randomized & `{\tt iddr_rsvd.f}` \\hline % `{\tt iddr_svd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine `{\tt iddr_asvd}` & `{\tt idd_svd.f}` \\hline % `{\tt idz_copycols}` & collects together selected columns of a matrix & `{\tt idz_id.f}` \\hline % `{\tt idz_diffsnorm}` & estimates the spectral norm of the difference between two matrices specified by routines for applying the matrices and their adjoints to arbitrary vectors; this routine uses the power method with a random starting vector & `{\tt idz_snorm.f}` \\hline % `{\tt idz_enorm}` & calculates the Euclidean norm of a vector & `{\tt idz_snorm.f}` \\hline % `{\tt idz_estrank}` & estimates the numerical rank of an arbitrary (generally dense) matrix to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idz_frmi}` & `{\tt idzp_aid.f}` \\hline % `{\tt idz_frm}` & transforms a vector into a vector which is sufficiently scrambled to be subsampled, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier transform & `{\tt idz_frm.f}` \\hline % `{\tt idz_frmi}` & initializes routine `{\tt idz_frm}` & `{\tt idz_frm.f}` \\hline % `{\tt idz_getcols}` & collects together selected columns of a matrix specified by a routine for applying the matrix to arbitrary vectors & `{\tt idz_id.f}` \\hline % `{\tt idz_house}` & calculates the vector and scalar needed to apply the Householder transformation reflecting a given vector into its first entry & `{\tt idz_house.f}` \\hline % `{\tt idz_houseapp}` & applies a Householder matrix to a vector & `{\tt idz_house.f}` \\hline % `{\tt idz_id2svd}` & converts an approximation to a matrix in the form of an ID into an approximation in the form of an SVD & `{\tt idz_id2svd.f}` \\hline % `{\tt idz_idiv}` & finds the greatest integer less than or equal to a specified integer, that is divisible by another (larger) specified integer & `{\tt idz_sfft.f}` \\hline % `{\tt idz_permmult}` & multiplies together a bunch of permutations & `{\tt idz_qrpiv.f}` \\hline % `{\tt idz_qinqr}` & reconstructs the \$Q\$ matrix in a \$QR\$ decomposition from the output of routines `{\tt idzp_qrpiv}` or `{\tt idzr_qrpiv}` & `{\tt idz_qrpiv.f}` \\hline % `{\tt idz_qrmatmat}` & applies to multiple vectors collected together as a matrix the \$Q\$ matrix (or its adjoint) in the \$QR\$ decomposition of a matrix, as described by the output of routines `{\tt idzp_qrpiv}` or `{\tt idzr_qrpiv}`; to apply \$Q\$ (or its adjoint) to a single vector without having to provide a work array, use routine `{\tt idz_qrmatvec}` instead & `{\tt idz_qrpiv.f}` \\hline % `{\tt idz_qrmatvec}` & applies to a single vector the \$Q\$ matrix (or its adjoint) in the \$QR\$ decomposition of a matrix, as described by the output of routines `{\tt idzp_qrpiv}` or `{\tt idzr_qrpiv}`; to apply \$Q\$ (or its adjoint) to several vectors efficiently, use routine `{\tt idz_qrmatmat}` instead & `{\tt idz_qrpiv.f}` \\hline % `{\tt idz_random_transf}` & applies rapidly



a random unitary matrix to a user-supplied vector & \tt id\\_rtrans.f} \\hline % \tt id\\_random\\_transf\\_init} & \raggedright initializes routines \tt id\\_random\\_transf} and \tt id\\_random\\_transf\\_inverse} & \tt id\\_rtrans.f} \\hline % \tt id\\_random\\_transf\\_inverse} & applies rapidly the inverse of the operator applied by routine \tt id\\_random\\_transf} & \tt id\\_rtrans.f} \\hline % \tt id\\_reconid} & reconstructs a matrix from its ID & \tt id\\_id.f} \\hline % \tt id\\_reconint} & constructs  $P$  in the ID  $A = B \setminus, P$ , where the columns of  $B$  are a subset of the columns of  $A$ , and  $P$  is the projection coefficient matrix, given \tt list}, \tt krank}, and \tt proj} output by routines \tt idzr\\_id}, \tt idzp\\_id}, \tt idzr\\_aid}, \tt idzp\\_aid}, \tt idzr\\_rid}, or \tt idzp\\_rid} & \tt id\\_id.f} \\hline % \tt id\\_sfft} & rapidly computes a subset of the entries of the discrete Fourier transform of a vector, composed with permutation matrices both on input and on output & \tt id\\_sfft.f} \\hline % \tt id\\_sffti} & initializes routine \tt id\\_sfft} & \tt id\\_sfft.f} \\hline % \tt id\\_sfrm} & transforms a vector into a scrambled vector of specified length, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier transform & \tt id\\_frm.f} \\hline % \tt id\\_sfrmi} & initializes routine \tt id\\_sfrm} & \tt id\\_frm.f} \\hline % \tt id\\_snorm} & estimates the spectral norm of a matrix specified by routines for applying the matrix and its adjoint to arbitrary vectors; this routine uses the power method with a random starting vector & \tt id\\_snorm.f} \\hline % \tt idzp\\_aid} & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine \tt id\\_frmi} & \tt idzp\\_aid.f} \\hline % \tt idzp\\_asvd} & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine \tt id\\_frmi} & \tt idzp\\_asvd.f} \\hline % \tt idzp\\_id} & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine \tt idzp\\_aid} & \tt idz\\_id.f} \\hline % \tt idzp\\_qrpiv} & computes the pivoted  $QR$  decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified precision of the decomposition & \tt idz\\_qrpiv.f} \\hline % \tt idzp\\_rid} & computes the ID, to a specified precision, of a matrix specified by a routine for applying its adjoint to arbitrary vectors; this routine is randomized & \tt idzp\\_rid.f} \\hline % \tt idzp\\_rsvd} & computes the SVD, to a specified precision, of a matrix specified by routines for applying the matrix and its adjoint to arbitrary vectors; this routine is randomized & \tt idzp\\_rsvd.f} \\hline % \tt idzp\\_svd} & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine \tt idzp\\_asvd} & \tt idz\\_svd.f} \\hline % \tt idzr\\_aid} & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is randomized, and must be initialized by routine \tt idzr\\_aidi} & \tt idzr\\_aid.f} \\hline % \tt idzr\\_aidi} & initializes routine \tt idzr\\_aid} & \tt idzr\\_aid.f} \\hline % \tt idzr\\_asvd} & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine is randomized, and must be initialized with routine \tt idz\\_aidi} & \tt idzr\\_asvd.f} \\hline % \tt idzr\\_id} & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine \tt idzr\\_aid} & \tt idz\\_id.f} \\hline % \tt idzr\\_qrpiv} & computes the pivoted  $QR$  decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified rank of the decomposition & \tt



`idz\_qr piv.f` \\hline % `{\tt idz\_rid}` & computes the ID, to a specified rank, of a matrix specified by a routine for applying its adjoint to arbitrary vectors; this routine is randomized & `{\tt idz\_rid.f}` \\hline % `{\tt idz\_rsvd}` & computes the SVD, to a specified rank, of a matrix specified by routines for applying the matrix and its adjoint to arbitrary vectors; this routine is randomized & `{\tt idz\_rsvd.f}` \\hline % `{\tt idz\_svd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine `{\tt idz\_asvd}` & `{\tt idz\_svd.f}` \\ % \end{supertabular} \end{center}

\section{Documentation in the source codes} Each routine in the source codes includes documentation in the comments immediately following the declaration of the subroutine's calling sequence. This documentation describes the purpose of the routine, the input and output variables, and the required work arrays (if any). This documentation also cites relevant references. Please pay attention to the `{\it N.B.}`'s; `{\it N.B.}` stands for `{\it nota bene}` (Latin for "note well") and highlights important information about the routines.

\section{Notation and decompositions} \label{defs} This section sets notational conventions employed in this documentation and the associated software, and defines both the singular value decomposition (SVD) and the interpolative decomposition (ID). For information concerning other mathematical objects used in the code (such as Householder transformations, pivoted  $QR$  decompositions, and discrete and fast Fourier transforms --- DFTs and FFTs), see, for example, \cite{golub-van\_loan}. For detailed descriptions and proofs of the mathematical facts discussed in the present section, see, for example, \cite{golub-van\_loan} and the references in \cite{halko-martinsson-tropp}. Throughout this document and the accompanying software distribution,  $\|x\|$  always denotes the Euclidean norm of the vector  $x$ , and  $\|A\|$  always denotes the spectral norm of the matrix  $A$ . Subsection~\ref{Euclidean} below defines the Euclidean norm; Subsection~\ref{spectral} below defines the spectral norm. We use  $A^*$  to denote the adjoint of the matrix  $A$ .

\subsection{Euclidean norm} \label{Euclidean} For any positive integer  $n$ , and vector  $x$  of length  $n$ , the Euclidean ( $l^2$ ) norm  $\|x\|$  is % \begin{equation} \|x\| = \sqrt{\sum\_{k=1}^n |x\_k|^2}, \end{equation} % where  $x_1, \dots, x_{n-1}, \dots, x_n$  are the entries of  $x$ .

\subsection{Spectral norm} \label{spectral} For any positive integers  $m$  and  $n$ , and  $m \times n$  matrix  $A$ , the spectral ( $l^2$  operator) norm  $\|A\|$  is % \begin{equation} \|A\_{m \times n}\| = \max \frac{\|A\_{m \times n} v\|}{\|v\|} \end{equation} % where the  $\max$  is taken over all  $n \times 1$  column vectors  $v$  such that  $\|v\| \neq 0$ .

\subsection{Singular value decomposition (SVD)} For any positive real number  $\epsilon$ , positive integers  $k, m$ , and  $n$  with  $k \leq m$  and  $k \leq n$ , and any  $m \times n$  matrix  $A$ , a rank- $k$  approximation to  $A$  in the form of an SVD (to precision  $\epsilon$ ) consists of an  $m \times k$  matrix  $U$  whose columns are orthonormal, an  $n \times k$  matrix  $V$  whose columns are orthonormal, and a diagonal  $k \times k$  matrix  $\Sigma$  with diagonal entries  $\Sigma_{1,1} \geq \Sigma_{2,2} \geq \dots \geq \Sigma_{n-1,n-1} \geq \Sigma_{n,n} \geq 0$ , such that % \begin{equation} \|A\_{m \times n} - U\_{m \times k} \Sigma\_{k \times k} V\_{n \times k}^\*\| \leq \epsilon. \end{equation} % The product  $U \Sigma V^*$  is known as an SVD. The columns of  $U$  are known as left singular vectors; the columns of  $V$  are known as right singular vectors. The

diagonal entries of  $\Sigma$  are known as singular values. When  $k = m$  or  $k = n$ , and  $A = U \Sigma V^*$ , then  $U \Sigma V^*$  is known as the SVD of  $A$ ; the columns of  $U$  are the left singular vectors of  $A$ , the columns of  $V$  are the right singular vectors of  $A$ , and the diagonal entries of  $\Sigma$  are the singular values of  $A$ . For any positive integer  $k$  with  $k < m$  and  $k < n$ , there exists a rank- $k$  approximation to  $A$  in the form of an SVD, to precision  $\sigma_{k+1}$ , where  $\sigma_{k+1}$  is the  $(k+1)^{\text{st}}$  greatest singular value of  $A$ .

**Interpolative decomposition (ID)** For any positive real number  $\epsilon$ , positive integers  $k$ ,  $m$ , and  $n$  with  $k \leq m$  and  $k \leq n$ , and any  $m \times n$  matrix  $A$ , a rank- $k$  approximation to  $A$  in the form of an ID (to precision  $\epsilon$ ) consists of a  $k \times n$  matrix  $P$ , and an  $m \times k$  matrix  $B$  whose columns constitute a subset of the columns of  $A$ , such that

- $A - B P \leq \epsilon$ , where  $\leq$  is the Frobenius norm.
- some subset of the columns of  $P$  makes up the  $k \times k$  identity matrix, and
- every entry of  $P$  has an absolute value less than or equal to a reasonably small positive real number, say

2. The product  $B P$  is known as an ID. The matrix  $P$  is known as the projection or interpolation matrix of the ID. Property~1 above approximates each column of  $A$  via a linear combination of the columns of  $B$  (which are themselves columns of  $A$ ), with the coefficients in the linear combination given by the entries of  $P$ . The interpolative decomposition is "interpolative" due to Property~2 above. The ID is numerically stable due to Property~3 above. It follows from Property~2 that the least (i.e., smallest) singular value of  $P$  is at least 1. Combining Properties~2 and~3 yields that

$$\|P\|_F \leq \sqrt{4k(n-k)+1}.$$

When  $k = m$  or  $k = n$ , and  $A = B P$ , then  $B P$  is known as the ID of  $A$ . For any positive integer  $k$  with  $k < m$  and  $k < n$ , there exists a rank- $k$  approximation to  $A$  in the form of an ID, to precision  $\sqrt{k(n-k)+1} \epsilon$ ;  $\sigma_{k+1}$ , where  $\sigma_{k+1}$  is the  $(k+1)^{\text{st}}$  greatest singular value of  $A$  (in fact, there exists an ID in which every entry of the projection matrix  $P$  has an absolute value less than or equal to 1).

**Bug reports, feedback, and support** Please let us know about errors in the software or in the documentation via e-mail to [tygert@aya.yale.edu](mailto:tygert@aya.yale.edu). We would also appreciate hearing about particular applications of the codes, especially in the form of journal articles e-mailed to [tygert@aya.yale.edu](mailto:tygert@aya.yale.edu). Mathematical and technical support may also be available via e-mail. Enjoy!

**Bibliography** **End of document** \*\*\*\*\*

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camel-base, camel-core-engine, camel-core-model, camel-core-processor, camel-core-reifier, camel-
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cxf-rt-databinding-jaxb, cxf-rt-features-logging, cxf-rt-frontend-jaxrs, cxf-rt-frontend-jaxws, cxf-rt-frontend-
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based on an original transform by Eddie Robertsson 2001/04/21 fn: added support for included schemas 2001/06/27 er: changed XML Schema prefix from xsd: to xs: and changed to the Rec namespace

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jackson-module-jaxb-annotations # Jackson JSON processor Jackson is a high-performance, Free/Open
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jackson-jaxrs-json-provider (Apache 2.0) Copyright: # Jackson JSON processor Jackson is a high-
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jackson-jaxrs-base # Jackson JSON processor Jackson is a high-performance, Free/Open Source JSON
processing library. It was originally written by Tatu Saloranta (tatu.saloranta@iki.fi), and has been in
development since 2007. It is currently developed by a community of developers, as well as supported
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3.19/dnsinfo/dnsinfo.h

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SUCH DAMAGE. } \newpage \tableofcontents \newpage \hrule \medskip \centerline{\Large \bf
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IMPORTANT} \medskip \hrule \medskip \noindent At the minimum, please read Subsection~\ref{warning} and Section~\ref{naming} below, and beware that the {\it N.B.}'s in the source code comments highlight key information about the routines; {\it N.B.} stands for {\it nota bene} (Latin for ``note well"). \medskip \hrule \bigskip \section{Introduction} This software distribution provides Fortran routines for computing low-rank approximations to matrices, in the forms of interpolative decompositions (IDs) and singular value decompositions (SVDs). The routines use algorithms based on the ID. The ID is also commonly known as the approximation obtained via skeletonization, the approximation obtained via subsampling, and the approximation obtained via subset selection. The ID provides many advantages in many applications, and we suspect that it will become increasingly popular once tools for its computation become more widely available. This software distribution includes some such tools, as well as tools for computing low-rank approximations in the form of SVDs. Section~\ref{defs} below defines IDs and SVDs, and provides references to detailed discussions of the algorithms used in this software package. Please beware that normalized power iterations are better suited than the software in this distribution for computing principal component analyses in the typical case when the square of the signal-to-noise ratio is not orders of magnitude greater than both dimensions of the data matrix; see~\cite{halko-martinsson-tropp}. The algorithms used in this distribution have been optimized for accuracy, efficiency, and reliability; as a somewhat counterintuitive consequence, many must be randomized. All randomized codes in this software package succeed with overwhelmingly high probability (see, for example, \cite{halko-martinsson-tropp}). The truly paranoid are welcome to use the routines {\tt idd\\_diffsnorm} and {\tt idz\\_diffsnorm} to evaluate rapidly the quality of the approximations produced by the randomized algorithms (as done, for example, in the files {\tt idd\\_a\\_test.f}, {\tt idd\\_r\\_test.f}, {\tt idz\\_a\\_test.f}, and {\tt idz\\_r\\_test.f} in the {\tt test} subdirectory of the main directory {\tt id\\_dist}). In most circumstances, evaluating the quality of an approximation via routines {\tt idd\\_diffsnorm} or {\tt idz\\_diffsnorm} is much faster than forming the approximation to be evaluated. Still, we are unaware of any instance in which a properly-compiled routine failed to produce an accurate approximation. To facilitate successful compilation, we encourage the user to read the instructions in the next section, and to read Section~\ref{naming}, too. \section{Compilation instructions} Followed in numerical order, the subsections of this section provide step-by-step instructions for compiling the software under a Unix-compatible operating system. \subsection{Beware that default command-line flags may not be sufficient for compiling the source codes!} \label{warning} The Fortran source codes in this distribution pass {\tt real\*8} variables as integer variables, integers as {\tt real\*8}'s, {\tt real\*8}'s as {\tt complex\*16}'s, and so on. This is common practice in numerical codes, and is not an error; be sure to provide the relevant command-line flags to the compiler (for example, run {\tt fort77} and {\tt f2c} with the flag {\tt -!P}). When following the compilation instructions in Subsection~\ref{makefile\_edit} below, be sure to set {\tt FFLAGS} appropriately. \subsection{Install LAPACK} The SVD routines in this distribution depend on LAPACK. Before compiling the present distribution, create the LAPACK and BLAS archive (library) {\tt .a} files; information about installing LAPACK is available at {\tt http://www.netlib.org/lapack/} (and several other web sites). \subsection{Decompress and untar the file {\tt

id\\_dist.tar.gz}} At the command line, decompress and untar the file {\tt id\\_dist.tar.gz} by issuing a command such as {\tt tar -xvzf id\\_dist.tar.gz}. This will create a directory named {\tt id\\_dist}.

\subsection{Edit the Makefile} \label{makefile\_edit} The directory {\tt id\\_dist} contains a file named {\tt Makefile}. In {\tt Makefile}, set the following: % \begin{itemize} \item {\tt FC} is the Fortran compiler. \item {\tt FFLAGS} is the set of command-line flags (specifying optimization settings, for example) for the Fortran compiler specified by {\tt FC}; please heed the warning in Subsection~\ref{warning} above! \item {\tt BLAS\\_LIB} is the file-system path to the BLAS archive (library) {\tt .a} file. \item {\tt LAPACK\\_LIB} is the file-system path to the LAPACK archive (library) {\tt .a} file. \item {\tt ARCH} is the archiver utility (usually {\tt ar}). \item {\tt ARCHFLAGS} is the set of command-line flags for the archiver specified by {\tt ARCH} needed to create an archive (usually {\tt cr}). \item {\tt RANLIB} is to be set to {\tt ranlib} when {\tt ranlib} is available, and is to be set to {\tt echo} when {\tt ranlib} is not available. \end{itemize}

\subsection{Make and test the libraries} At the command line in a shell that adheres to the Bourne shell conventions for redirection, issue the command ``{\tt make clean; make}'' to both create the archive (library) {\tt id\\_lib.a} and test it. (In most modern Unix distributions, {\tt sh} is the Bourne shell, or else is fully compatible with the Bourne shell; the Korn shell {\tt ksh} and the Bourne-again shell {\tt bash} also use the Bourne shell conventions for redirection.) {\tt make} places the file {\tt id\\_lib.a} in the directory {\tt id\\_dist}; the archive (library) file {\tt id\\_lib.a} contains machine code for all user-callable routines in this distribution.

\section{Naming conventions} \label{naming} The names of routines and files in this distribution start with prefixes, followed by an underscore (``\\_"). The prefixes are two to four characters in length, and have the following meanings: % \begin{itemize} \item The first two letters are always ``{\tt id}'' , the name of this distribution. \item The third letter (when present) is either ``{\tt d}'' or ``{\tt z}''; ``{\tt d}'' stands for double precision ({\tt real\*8}), and ``{\tt z}'' stands for double complex ({\tt complex\*16}). \item The fourth letter (when present) is either ``{\tt r}'' or ``{\tt p}''; ``{\tt r}'' stands for specified rank, and ``{\tt p}'' stands for specified precision. The specified rank routines require the user to provide the rank of the approximation to be constructed, while the specified precision routines adjust the rank adaptively to attain the desired precision. \end{itemize} For example, {\tt iddr\\_aid} is a {\tt real\*8} routine which computes an approximation of specified rank. {\tt idz\\_snorm} is a {\tt complex\*16} routine. {\tt id\\_randperm} is yet another routine in this distribution.

\section{Example programs} For examples of how to use the user-callable routines in this distribution, see the source codes in subdirectory {\tt test} of the main directory {\tt id\\_dist}.

\section{Directory structure} The main {\tt id\\_dist} directory contains a Makefile, the auxiliary text files {\tt README.txt} and {\tt size.txt}, and the following subdirectories, described in the subsections below: % \begin{enumerate} \item {\tt bin} \item {\tt development} \item {\tt doc} \item {\tt src} \item {\tt test} \item {\tt tmp} \end{enumerate} % If a ``{\tt make all}'' command has completed successfully, then the main {\tt id\\_dist} directory will also contain an archive (library) file {\tt id\\_lib.a} containing machine code for all of the user-callable routines.

\subsection{Subdirectory {\tt bin}} Once all of the libraries have been made via the Makefile in the main {\tt id\\_dist} directory, the subdirectory {\tt bin} will contain object files (machine code), each compiled from the corresponding file of source code in the subdirectory {\tt src} of



{\tt id\\_dist}. \subsection{Subdirectory {\tt development}} Each Fortran file in the subdirectory {\tt development} (except for {\tt dfft.f} and {\tt prini.f}) specifies its dependencies at the top, then provides a main program for testing and debugging, and finally provides source code for a library of user-callable subroutines. The Fortran file {\tt dfft.f} is a copy of P. N. Swarztrauber's FFTPACK library for computing fast Fourier transforms. The Fortran file {\tt prini.f} is a copy of V. Rokhlin's library of formatted printing routines. Both {\tt dfft.f} (version 4) and {\tt prini.f} are in the public domain. The shell script {\tt RUNME.sh} runs shell scripts {\tt make\\_src.sh} and {\tt make\\_test.sh}, which fill the subdirectories {\tt src} and {\tt test} of the main directory {\tt id\\_dist} with source codes for user-callable routines and with the main program testing codes. \subsection{Subdirectory {\tt doc}} Subdirectory {\tt doc} contains this documentation, supplementing comments in the source codes. \subsection{Subdirectory {\tt src}} The files in the subdirectory {\tt src} provide source code for software libraries. Each file in the subdirectory {\tt src} (except for {\tt dfft.f} and {\tt prini.f}) is the bottom part of the corresponding file in the subdirectory {\tt development} of {\tt id\\_dist}. The file {\tt dfft.f} is just a copy of P. N. Swarztrauber's FFTPACK library for computing fast Fourier transforms. The file {\tt prini.f} is a copy of V. Rokhlin's library of formatted printing routines. Both {\tt dfft.f} (version 4) and {\tt prini.f} are in the public domain. \subsection{Subdirectory {\tt test}} The files in subdirectory {\tt test} provide source code for testing and debugging. Each file in subdirectory {\tt test} is the top part of the corresponding file in subdirectory {\tt development} of {\tt id\\_dist}, and provides a main program and a list of its dependencies. These codes provide examples of how to call the user-callable routines. \section{Catalog of the routines} The main routines for decomposing {\tt real\*8} matrices are: % \begin{enumerate} % \item IDs of arbitrary (generally dense) matrices: {\tt iddp\\_id}, {\tt iddr\\_id}, {\tt iddp\\_aid}, {\tt iddr\\_aid} % \item IDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' transposes): {\tt iddp\\_rid}, {\tt iddr\\_rid} % \item SVDs of arbitrary (generally dense) matrices: {\tt iddp\\_svd}, {\tt iddr\\_svd}, {\tt iddp\\_asvd}, {\tt iddr\\_asvd} % \item SVDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' transposes): {\tt iddp\\_rsvd}, {\tt iddr\\_rsvd} % \end{enumerate} Similarly, the main routines for decomposing {\tt complex\*16} matrices are: % \begin{enumerate} % \item IDs of arbitrary (generally dense) matrices: {\tt idzp\\_id}, {\tt idzr\\_id}, {\tt idzp\\_aid}, {\tt idzr\\_aid} % \item IDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' adjoints): {\tt idzp\\_rid}, {\tt idzr\\_rid} % \item SVDs of arbitrary (generally dense) matrices: {\tt idzp\\_svd}, {\tt idzr\\_svd}, {\tt idzp\\_asvd}, {\tt idzr\\_asvd} % \item SVDs of matrices that may be rapidly applied to arbitrary vectors (as may the matrices' adjoints): {\tt idzp\\_rsvd}, {\tt idzr\\_rsvd} % \end{enumerate} This distribution also includes routines for constructing pivoted QR\$ decompositions (in {\tt idd\\_qrpiv.f} and {\tt idz\\_qrpiv.f}), for estimating the spectral norms of matrices that may be applied rapidly to arbitrary vectors as may their adjoints (in {\tt idd\\_snorm.f} and {\tt idz\\_snorm.f}), for converting IDs to SVDs (in {\tt idd\\_id2svd.f} and {\tt idz\\_id2svd.f}), and for computing rapidly arbitrary subsets of the entries of the discrete Fourier transforms of vectors (in {\tt idd\\_sfft.f} and {\tt idz\\_sfft.f}). \subsection{List of the routines} The following is an alphabetical list of the routines in this distribution, together with brief descriptions of their



functionality and the names of the files containing the routines' source code: \begin{center} %

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\tablehead{\bf Routine & \bf Description & \bf Source file \} \tabletail{\hline} %
\begin{supertabular}{>\raggedright}p{
1.2in} p{.53\textwidth} l} % \hline {\tt id\_frand} & generates pseudorandom numbers drawn uniformly from
the interval  $[0,1]$ ; this routine is more efficient than routine {\tt id\_srand}, but cannot generate fewer
than 55 pseudorandom numbers per call & {\tt id\_rand.f} \\\hline % {\tt id\_frandi} & initializes the seed
values for routine {\tt id\_frand} to specified values & {\tt id\_rand.f} \\\hline % {\tt id\_frando} & initializes
the seed values for routine {\tt id\_frand} to their original, default values & {\tt id\_rand.f} \\\hline % {\tt
id\_randperm} & generates a uniformly random permutation & {\tt id\_rand.f} \\\hline % {\tt id\_srand} &
generates pseudorandom numbers drawn uniformly from the interval  $[0,1]$ ; this routine is less efficient
than routine {\tt id\_frand}, but can generate fewer than 55 pseudorandom numbers per call & {\tt
id\_rand.f} \\\hline % {\tt id\_srandi} & initializes the seed values for routine {\tt id\_srand} to specified
values & {\tt id\_rand.f} \\\hline % {\tt id\_srando} & initializes the seed values for routine {\tt id\_srand} to
their original, default values & {\tt id\_rand.f} \\\hline % {\tt idd\_copycols} & collects together selected
columns of a matrix & {\tt idd\_id.f} \\\hline % {\tt idd\_diffsnorm} & estimates the spectral norm of the
difference between two matrices specified by routines for applying the matrices and their transposes to
arbitrary vectors; this routine uses the power method with a random starting vector & {\tt idd\_snorm.f}
\\hline % {\tt idd\_enorm} & calculates the Euclidean norm of a vector & {\tt idd\_snorm.f} \\\hline % {\tt
idd\_estrank} & estimates the numerical rank of an arbitrary (generally dense) matrix to a specified
precision; this routine is randomized, and must be initialized with routine {\tt idd\_frm} & {\tt iddp\_aid.f}
\\hline % {\tt idd\_frm} & transforms a vector into a vector which is sufficiently scrambled to be
subsampled, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier
transform & {\tt idd\_frm.f} \\\hline % {\tt idd\_frm} & initializes routine {\tt idd\_frm} & {\tt idd\_frm.f} \\\hline
% {\tt idd\_getcols} & collects together selected columns of a matrix specified by a routine for applying the
matrix to arbitrary vectors & {\tt idd\_id.f} \\\hline % {\tt idd\_house} & calculates the vector and scalar
needed to apply the Householder transformation reflecting a given vector into its first entry & {\tt
idd\_house.f} \\\hline % {\tt idd\_houseapp} & applies a Householder matrix to a vector & {\tt idd\_house.f}
\\hline % {\tt idd\_id2svd} & converts an approximation to a matrix in the form of an ID into an
approximation in the form of an SVD & {\tt idd\_id2svd.f} \\\hline % {\tt idd\_ldiv} & finds the greatest
integer less than or equal to a specified integer, that is divisible by another (larger) specified integer & {\tt
idd\_sfft.f} \\\hline % {\tt idd\_pairsamps} & calculates the indices of the pairs of integers that the individual
integers in a specified set belong to & {\tt idd\_frm.f} \\\hline % {\tt idd\_permmult} & multiplies together a
bunch of permutations & {\tt idd\_qrpiv.f} \\\hline % {\tt idd\_qinqr} & reconstructs the  $Q$  matrix in a
 $QR$  decomposition from the output of routines {\tt iddp\_qrpiv} or {\tt iddr\_qrpiv} & {\tt idd\_qrpiv.f}
\\hline % {\tt idd\_qrmatmat} & applies to multiple vectors collected together as a matrix the  $Q$  matrix
(or its transpose) in the  $QR$  decomposition of a matrix, as described by the output of routines {\tt
iddp\_qrpiv} or {\tt iddr\_qrpiv}; to apply  $Q$  (or its transpose) to a single vector without having to provide

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a work array, use routine `{\tt idd\_qrmatvec}` instead & `{\tt idd\_qrpiv.f}` \\hline % `{\tt idd\_qrmatvec}` & applies to a single vector the  $Q$  matrix (or its transpose) in the  $QR$  decomposition of a matrix, as described by the output of routines `{\tt iddp\_qrpiv}` or `{\tt iddr\_qrpiv}`; to apply  $Q$  (or its transpose) to several vectors efficiently, use routine `{\tt idd\_qrmatmat}` instead & `{\tt idd\_qrpiv.f}` \\hline % `{\tt idd\_random\_}` `{\tt transf}` & applies rapidly a random orthogonal matrix to a user-supplied vector & `{\tt id\_rtrans.f}` \\hline % `{\tt idd\_random\_transf\_init}` & \raggedright initializes routines `{\tt idd\_random\_transf}` and `{\tt idd\_random\_transf\_inverse}` & `{\tt id\_rtrans.f}` \\hline % `{\tt idd\_random\_}` `{\tt transf\_inverse}` & applies rapidly the inverse of the operator applied by routine `{\tt idd\_random\_transf}` & `{\tt id\_rtrans.f}` \\hline % `{\tt idd\_reconid}` & reconstructs a matrix from its ID & `{\tt idd\_id.f}` \\hline % `{\tt idd\_reconint}` & constructs  $P$  in the ID  $A = B \ P$ , where the columns of  $B$  are a subset of the columns of  $A$ , and  $P$  is the projection coefficient matrix, given `{\tt list}`, `{\tt krank}`, and `{\tt proj}` output by routines `{\tt iddr\_id}`, `{\tt iddp\_id}`, `{\tt iddr\_aid}`, `{\tt iddp\_aid}`, `{\tt iddr\_rid}`, or `{\tt iddp\_rid}` & `{\tt idd\_id.f}` \\hline % `{\tt idd\_sfft}` & rapidly computes a subset of the entries of the discrete Fourier transform of a vector, composed with permutation matrices both on input and on output & `{\tt idd\_sfft.f}` \\hline % `{\tt idd\_sftti}` & initializes routine `{\tt idd\_sfft}` & `{\tt idd\_sfft.f}` \\hline % `{\tt idd\_sfrm}` & transforms a vector into a scrambled vector of specified length, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier transform & `{\tt idd\_frm.f}` \\hline % `{\tt idd\_sfrmi}` & initializes routine `{\tt idd\_sfrm}` & `{\tt idd\_frm.f}` \\hline % `{\tt idd\_snorm}` & estimates the spectral norm of a matrix specified by routines for applying the matrix and its transpose to arbitrary vectors; this routine uses the power method with a random starting vector & `{\tt idd\_snorm.f}` \\hline % `{\tt iddp\_aid}` & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idd\_frmi}` & `{\tt iddp\_aid.f}` \\hline % `{\tt iddp\_asvd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idd\_frmi}` & `{\tt iddp\_asvd.f}` \\hline % `{\tt iddp\_id}` & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine `{\tt iddp\_aid}` & `{\tt idd\_id.f}` \\hline % `{\tt iddp\_qrpiv}` & computes the pivoted  $QR$  decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified precision of the decomposition & `{\tt idd\_qrpiv.f}` \\hline % `{\tt iddp\_rid}` & computes the ID, to a specified precision, of a matrix specified by a routine for applying its transpose to arbitrary vectors; this routine is randomized & `{\tt iddp\_rid.f}` \\hline % `{\tt iddp\_rsvd}` & computes the SVD, to a specified precision, of a matrix specified by routines for applying the matrix and its transpose to arbitrary vectors; this routine is randomized & `{\tt iddp\_rsvd.f}` \\hline % `{\tt iddp\_svd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine `{\tt iddp\_asvd}` & `{\tt idd\_svd.f}` \\hline % `{\tt iddr\_aid}` & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is randomized, and must be initialized by routine `{\tt iddr\_aid}` & `{\tt iddr\_aid.f}` \\hline % `{\tt iddr\_aid}` & initializes routine `{\tt iddr\_aid}` & `{\tt iddr\_aid.f}` \\hline % `{\tt iddr\_asvd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine

is randomized, and must be initialized with routine `{\tt idd\_aid}` & `{\tt iddr\_asvd.f}` \\hline % `{\tt iddr\_id}` & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine `{\tt iddr\_aid}` & `{\tt idd\_id.f}` \\hline % `{\tt iddr\_qrpiv}` & computes the pivoted  $QR$  decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified rank of the decomposition & `{\tt idd\_qrpiv.f}` \\hline % `{\tt iddr\_rid}` & computes the ID, to a specified rank, of a matrix specified by a routine for applying its transpose to arbitrary vectors; this routine is randomized & `{\tt iddr\_rid.f}` \\hline % `{\tt iddr\_rsvd}` & computes the SVD, to a specified rank, of a matrix specified by routines for applying the matrix and its transpose to arbitrary vectors; this routine is randomized & `{\tt iddr\_rsvd.f}` \\hline % `{\tt iddr\_svd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine `{\tt iddr\_asvd}` & `{\tt idd\_svd.f}` \\hline % `{\tt idz\_copycols}` & collects together selected columns of a matrix & `{\tt idz\_id.f}` \\hline % `{\tt idz\_diffsnorm}` & estimates the spectral norm of the difference between two matrices specified by routines for applying the matrices and their adjoints to arbitrary vectors; this routine uses the power method with a random starting vector & `{\tt idz\_snorm.f}` \\hline % `{\tt idz\_enorm}` & calculates the Euclidean norm of a vector & `{\tt idz\_snorm.f}` \\hline % `{\tt idz\_estrank}` & estimates the numerical rank of an arbitrary (generally dense) matrix to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idz\_frmi}` & `{\tt idzp\_aid.f}` \\hline % `{\tt idz\_frm}` & transforms a vector into a vector which is sufficiently scrambled to be subsampled, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier transform & `{\tt idz\_frm.f}` \\hline % `{\tt idz\_frmi}` & initializes routine `{\tt idz\_frm}` & `{\tt idz\_frm.f}` \\hline % `{\tt idz\_getcols}` & collects together selected columns of a matrix specified by a routine for applying the matrix to arbitrary vectors & `{\tt idz\_id.f}` \\hline % `{\tt idz\_house}` & calculates the vector and scalar needed to apply the Householder transformation reflecting a given vector into its first entry & `{\tt idz\_house.f}` \\hline % `{\tt idz\_houseapp}` & applies a Householder matrix to a vector & `{\tt idz\_house.f}` \\hline % `{\tt idz\_id2svd}` & converts an approximation to a matrix in the form of an ID into an approximation in the form of an SVD & `{\tt idz\_id2svd.f}` \\hline % `{\tt idz\_ldiv}` & finds the greatest integer less than or equal to a specified integer, that is divisible by another (larger) specified integer & `{\tt idz\_sfft.f}` \\hline % `{\tt idz\_permmult}` & multiplies together a bunch of permutations & `{\tt idz\_qrpiv.f}` \\hline % `{\tt idz\_qinqr}` & reconstructs the  $QR$  matrix in a  $QR$  decomposition from the output of routines `{\tt idzp\_qrpiv}` or `{\tt idzr\_qrpiv}` & `{\tt idz\_qrpiv.f}` \\hline % `{\tt idz\_qrmatrix}` & applies to multiple vectors collected together as a matrix the  $QR$  matrix (or its adjoint) in the  $QR$  decomposition of a matrix, as described by the output of routines `{\tt idzp\_qrpiv}` or `{\tt idzr\_qrpiv}`; to apply  $QR$  (or its adjoint) to a single vector without having to provide a work array, use routine `{\tt idz\_qrmatrixvec}` instead & `{\tt idz\_qrpiv.f}` \\hline % `{\tt idz\_qrmatrixvec}` & applies to a single vector the  $QR$  matrix (or its adjoint) in the  $QR$  decomposition of a matrix, as described by the output of routines `{\tt idzp\_qrpiv}` or `{\tt idzr\_qrpiv}`; to apply  $QR$  (or its adjoint) to several vectors efficiently, use routine `{\tt idz\_qrmatrix}` instead & `{\tt idz\_qrpiv.f}` \\hline % `{\tt idz\_random\_transf}` & applies rapidly a random unitary matrix to a user-supplied vector & `{\tt id\_rtrans.f}` \\hline % `{\tt idz\_random\_transf}`

`transf_init` & \raggedright initializes routines `{\tt idz\_random\_transf}` and `{\tt idz\_random\_transf\_inverse}` & `{\tt id\_rtrans.f}` \\hline % `{\tt idz\_random\_transf\_inverse}` & applies rapidly the inverse of the operator applied by routine `{\tt idz\_random\_transf}` & `{\tt id\_rtrans.f}` \\hline % `{\tt idz\_reconid}` & reconstructs a matrix from its ID & `{\tt idz\_id.f}` \\hline % `{\tt idz\_reconint}` & constructs  $PP^T$  in the ID  $A = B \setminus, P$ , where the columns of  $B$  are a subset of the columns of  $A$ , and  $P$  is the projection coefficient matrix, given `{\tt list}`, `{\tt krank}`, and `{\tt proj}` output by routines `{\tt idzr\_id}`, `{\tt idzp\_id}`, `{\tt idzr\_aid}`, `{\tt idzp\_aid}`, `{\tt idzr\_rid}`, or `{\tt idzp\_rid}` & `{\tt idz\_id.f}` \\hline % `{\tt idz\_sfft}` & rapidly computes a subset of the entries of the discrete Fourier transform of a vector, composed with permutation matrices both on input and on output & `{\tt idz\_sfft.f}` \\hline % `{\tt idz\_sffti}` & initializes routine `{\tt idz\_sfft}` & `{\tt idz\_sfft.f}` \\hline % `{\tt idz\_sfrm}` & transforms a vector into a scrambled vector of specified length, via a composition of Rokhlin's random transform, random subselection, and a fast Fourier transform & `{\tt idz\_frm.f}` \\hline % `{\tt idz\_sfrmi}` & initializes routine `{\tt idz\_sfrm}` & `{\tt idz\_frm.f}` \\hline % `{\tt idz\_snorm}` & estimates the spectral norm of a matrix specified by routines for applying the matrix and its adjoint to arbitrary vectors; this routine uses the power method with a random starting vector & `{\tt idz\_snorm.f}` \\hline % `{\tt idzp\_aid}` & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idz\_frmi}` & `{\tt idzp\_aid.f}` \\hline % `{\tt idzp\_asvd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is randomized, and must be initialized with routine `{\tt idz\_frmi}` & `{\tt idzp\_asvd.f}` \\hline % `{\tt idzp\_id}` & computes the ID of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine `{\tt idzp\_aid}` & `{\tt idz\_id.f}` \\hline % `{\tt idzp\_qrpiv}` & computes the pivoted  $QR$  decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified precision of the decomposition & `{\tt idz\_qrpiv.f}` \\hline % `{\tt idzp\_rid}` & computes the ID, to a specified precision, of a matrix specified by a routine for applying its adjoint to arbitrary vectors; this routine is randomized & `{\tt idzp\_rid.f}` \\hline % `{\tt idzp\_rsvd}` & computes the SVD, to a specified precision, of a matrix specified by routines for applying the matrix and its adjoint to arbitrary vectors; this routine is randomized & `{\tt idzp\_rsvd.f}` \\hline % `{\tt idzp\_svd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified precision; this routine is often less efficient than routine `{\tt idzp\_asvd}` & `{\tt idz\_svd.f}` \\hline % `{\tt idzr\_aid}` & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is randomized, and must be initialized by routine `{\tt idzr\_aidi}` & `{\tt idzr\_aid.f}` \\hline % `{\tt idzr\_aidi}` & initializes routine `{\tt idzr\_aid}` & `{\tt idzr\_aid.f}` \\hline % `{\tt idzr\_asvd}` & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine is randomized, and must be initialized with routine `{\tt idz\_aidi}` & `{\tt idzr\_asvd.f}` \\hline % `{\tt idzr\_id}` & computes the ID of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine `{\tt idzr\_aid}` & `{\tt idz\_id.f}` \\hline % `{\tt idzr\_qrpiv}` & computes the pivoted  $QR$  decomposition of an arbitrary (generally dense) matrix via Householder transformations, stopping at a specified rank of the decomposition & `{\tt idz\_qrpiv.f}` \\hline % `{\tt idzr\_rid}` & computes the ID, to a specified rank, of a matrix specified by a

routine for applying its adjoint to arbitrary vectors; this routine is randomized & \tt idzr\\_rid.f} \\hline % \tt idzr\\_rsvd} & computes the SVD, to a specified rank, of a matrix specified by routines for applying the matrix and its adjoint to arbitrary vectors; this routine is randomized & \tt idzr\\_rsvd.f} \\hline % \tt idzr\\_svd} & computes the SVD of an arbitrary (generally dense) matrix, to a specified rank; this routine is often less efficient than routine \tt idzr\\_asvd} & \tt idz\\_svd.f} \\ % \end{supertabular} \end{center}

\section{Documentation in the source codes} Each routine in the source codes includes documentation in the comments immediately following the declaration of the subroutine's calling sequence. This documentation describes the purpose of the routine, the input and output variables, and the required work arrays (if any). This documentation also cites relevant references. Please pay attention to the \i{N.B.}'s; \i{N.B.} stands for \i{nota bene} (Latin for "note well") and highlights important information about the routines.

\section{Notation and decompositions} \label{defs} This section sets notational conventions employed in this documentation and the associated software, and defines both the singular value decomposition (SVD) and the interpolative decomposition (ID). For information concerning other mathematical objects used in the code (such as Householder transformations, pivoted QR\$ decompositions, and discrete and fast Fourier transforms --- DFTs and FFTs), see, for example, \cite{golub-van\_loan}. For detailed descriptions and proofs of the mathematical facts discussed in the present section, see, for example, \cite{golub-van\_loan} and the references in \cite{halko-martinsson-tropp}. Throughout this document and the accompanying software distribution,  $\|x\|$  always denotes the Euclidean norm of the vector  $x$ , and  $\|A\|$  always denotes the spectral norm of the matrix  $A$ . Subsection~\ref{Euclidean} below defines the Euclidean norm; Subsection~\ref{spectral} below defines the spectral norm. We use  $A^*$  to denote the adjoint of the matrix  $A$ .

\subsection{Euclidean norm} \label{Euclidean} For any positive integer  $n$ , and vector  $x$  of length  $n$ , the Euclidean ( $\ell^2$ ) norm  $\|x\|$  is % \begin{equation} \|x\| = \sqrt{\sum\_{k=1}^n |x\_k|^2}, \end{equation} % where  $x_1, \dots, x_{n-1}, \dots, x_n$  are the entries of  $x$ .

\subsection{Spectral norm} \label{spectral} For any positive integers  $m$  and  $n$ , and  $m \times n$  matrix  $A$ , the spectral ( $\ell^2$  operator) norm  $\|A\|$  is % \begin{equation} \|A\_{m \times n}\| = \max \left\{ \|A\_{m \times n} v\|, \|x\_{n \times 1}\| \right\} \left\{ \|x\_{n \times 1}\| \right\}, \end{equation} % where the  $\max$  is taken over all  $n \times 1$  column vectors  $x$  such that  $\|x\| \leq 0$ .

\subsection{Singular value decomposition (SVD)} For any positive real number  $\epsilon$ , positive integers  $k$ ,  $m$ , and  $n$  with  $k \leq m$  and  $k \leq n$ , and any  $m \times n$  matrix  $A$ , a rank- $k$  approximation to  $A$  in the form of an SVD (to precision  $\epsilon$ ) consists of an  $m \times k$  matrix  $U$  whose columns are orthonormal, an  $n \times k$  matrix  $V$  whose columns are orthonormal, and a diagonal  $k \times k$  matrix  $\Sigma$  with diagonal entries  $\Sigma_{1,1} \geq \Sigma_{2,2} \geq \dots \geq \Sigma_{n-1,n-1} \geq \Sigma_{n,n} \geq 0$ , such that % \begin{equation} \|A\_{m \times n} - U\_{m \times k} \Sigma\_{k \times k} (V^\*)\_{k \times n}\| \leq \epsilon. \end{equation} % The product  $U \Sigma V^*$  is known as an SVD. The columns of  $U$  are known as left singular vectors; the columns of  $V$  are known as right singular vectors. The diagonal entries of  $\Sigma$  are known as singular values. When  $k = m$  or  $k = n$ , and  $A = U$ ,

$\Sigma$ ,  $V^*$ , then  $U$ ,  $\Sigma$ ,  $V^*$  is known as the SVD of  $A$ ; the columns of  $U$  are the left singular vectors of  $A$ , the columns of  $V$  are the right singular vectors of  $A$ , and the diagonal entries of  $\Sigma$  are the singular values of  $A$ . For any positive integer  $k$  with  $k < m$  and  $k < n$ , there exists a rank- $k$  approximation to  $A$  in the form of an SVD, to precision  $\sigma_{k+1}$ , where  $\sigma_{k+1}$  is the  $(k+1)^{\text{st}}$  greatest singular value of  $A$ .

**Interpolative decomposition (ID)** For any positive real number  $\epsilon$ , positive integers  $k$ ,  $m$ , and  $n$  with  $k \leq m$  and  $k \leq n$ , and any  $m \times n$  matrix  $A$ , a rank- $k$  approximation to  $A$  in the form of an ID (to precision  $\epsilon$ ) consists of a  $k \times n$  matrix  $P$ , and an  $m \times k$  matrix  $B$  whose columns constitute a subset of the columns of  $A$ , such that

- $A - B \cdot P$  has an absolute value less than or equal to  $\epsilon$ .
- some subset of the columns of  $P$  makes up the  $k \times k$  identity matrix, and
- every entry of  $P$  has an absolute value less than or equal to a reasonably small positive real number, say

2. The product  $B \cdot P$  is known as an ID. The matrix  $P$  is known as the projection or interpolation matrix of the ID. Property~1 above approximates each column of  $A$  via a linear combination of the columns of  $B$  (which are themselves columns of  $A$ ), with the coefficients in the linear combination given by the entries of  $P$ . The interpolative decomposition is "interpolative" due to Property~2 above. The ID is numerically stable due to Property~3 above. It follows from Property~2 that the least ( $k^{\text{th}}$  greatest) singular value of  $P$  is at least

1. Combining Properties~2 and~3 yields that  $\sigma_k(P) \geq \frac{1}{\sqrt{4k(n-k)+1}}$ . When  $k = m$  or  $k = n$ , and  $A = B \cdot P$ , then  $B \cdot P$  is known as the ID of  $A$ . For any positive integer  $k$  with  $k < m$  and  $k < n$ , there exists a rank- $k$  approximation to  $A$  in the form of an ID, to precision  $\frac{1}{\sqrt{k(n-k)+1}}$ ;  $\sigma_{k+1}$ , where  $\sigma_{k+1}$  is the  $(k+1)^{\text{st}}$  greatest singular value of  $A$  (in fact, there exists an ID in which every entry of the projection matrix  $P$  has an absolute value less than or equal to 1).

**Bug reports, feedback, and support** Please let us know about errors in the software or in the documentation via e-mail to [tygert@aya.yale.edu](mailto:tygert@aya.yale.edu). We would also appreciate hearing about particular applications of the codes, especially in the form of journal articles e-mailed to [tygert@aya.yale.edu](mailto:tygert@aya.yale.edu). Mathematical and technical support may also be available via e-mail. Enjoy!

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