

# Package ‘cTMed’

May 10, 2024

**Title** Continuous Time Mediation

**Version** 0.9.1

**Description** Calculates standard errors and confidence intervals  
for effects in continuous time mediation models.

**URL** <https://github.com/jeksterslab/cTMed>,  
<https://jeksterslab.github.io/cTMed/>

**BugReports** <https://github.com/jeksterslab/cTMed/issues>

**License** MIT + file LICENSE

**Encoding** UTF-8

**Roxygen** list(markdown = TRUE)

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**Suggests** knitr, rmarkdown, testthat, simStateSpace, expm

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|                    |  |
|--------------------|--|
| confint.ctmeddelta | <i>Delta Method Confidence Intervals</i> |
|--------------------|--|

---

## Description

Delta Method Confidence Intervals

## Usage

```
## S3 method for class 'ctmeddelta'
confint(object, parm = NULL, level = 0.95, ...)
```

**Arguments**

|                     |   |
|---------------------|---|
| <code>object</code> | Object of class <code>ctmeddelta</code> .   |
| <code>parm</code>   | a specification of which parameters are to be given confidence intervals, either a vector of numbers or a vector of names. If missing, all parameters are considered. |
| <code>level</code>  | the confidence level required.  |
| <code>...</code>    | additional arguments.   |

**Value**

Returns a matrix of confidence intervals.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
  )
)
```

```

-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m"
)
confint(delta)

# Range of time intervals -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
confint(delta)

```

---

confint.ctmedmc

*Monte Carlo Method Confidence Intervals*


---

## Description

Monte Carlo Method Confidence Intervals

## Usage

```

## S3 method for class 'ctmedmc'
confint(object, parm = NULL, level = 0.95, ...)

```

## Arguments

object                      Object of class ctmedmc.

|                    |   |
|--------------------|---|
| <code>parm</code>  | a specification of which parameters are to be given confidence intervals, either a vector of numbers or a vector of names. If missing, all parameters are considered. |
| <code>level</code> | the confidence level required.  |
| <code>...</code>   | additional arguments.   |

**Value**

Returns a matrix of confidence intervals.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
    0.000820587, -0.002532849, 0.001634917,
    -0.001096684, 0.003328692, -0.001926088,
```

```

      0.000297815, -0.000871547, 0.002271711,
      -0.000517524, 0.001475579, -0.003705661,
      0.000686386, -0.001926088, 0.004726235
    ),
    nrow = 9
  )

# Specific time interval -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
confint(mc)

# Range of time intervals -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
confint(mc)

```

---

DeltaBeta

---

*Delta Method Sampling Variance-Covariance Matrix for the Elements  
of the Matrix of Lagged Coefficients Over a Specific Time Interval or  
a Range of Time Intervals*


---

## Description

This function computes the delta method sampling variance-covariance matrix for the elements of the matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

## Usage

```
DeltaBeta(phi, vcov_phi_vec, delta_t, ncores = NULL)
```

### Arguments

|              |  |
|--------------|--|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.                     |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of $\text{vec}(\Phi)$ .  |
| delta_t      | Vector of positive numbers. Time interval ( $\Delta t$ ).  |
| ncores       | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when the length of delta_t is long. |

### Details

See [Total\(\)](#).

#### Delta Method:

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $g$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n} \left( g(\hat{\theta}) - g(\theta) \right) \xrightarrow{D} \mathcal{N}(0, \mathbf{J} \mathbf{\Gamma} \mathbf{J}')$$

where  $\mathbf{J}$  is the matrix of first-order derivatives of the function  $g$  with respect to the elements of  $\theta$  and  $\mathbf{\Gamma}$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $g(\hat{\theta})$  as follows:

$$g(\hat{\theta}) \approx \mathcal{N}(g(\theta), n^{-1} \mathbf{J} \mathbf{\Gamma} \mathbf{J}')$$

The uncertainty associated with the estimator  $g(\hat{\theta})$  is, therefore, given by  $n^{-1} \mathbf{J} \mathbf{\Gamma} \mathbf{J}'$ . When  $\mathbf{\Gamma}$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\theta}$ , that is,  $\hat{\mathbf{V}}(\hat{\theta})$  for  $n^{-1} \mathbf{\Gamma}$ . Therefore, the sampling variance-covariance matrix of  $g(\hat{\theta})$  is given by

$$g(\hat{\theta}) \approx \mathcal{N}(g(\theta), \mathbf{J} \hat{\mathbf{V}}(\hat{\theta}) \mathbf{J}').$$

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \mathbf{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\mathbf{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\mathbf{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right) \left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

## Value

Returns an object of class `ctmeddelta` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (DeltaBeta).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**delta\_t** Time interval.

**jacobian** Jacobian matrix.

**est** Estimated total, direct, and indirect effects.

**vcov** Sampling variance-covariance matrix of the estimated total, direct, and indirect effects.

## Author(s)

Ivan Jacob Agaloos Pesigan

## References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. [doi:10.2307/271028](https://doi.org/10.2307/271028)

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. [doi:10.1080/10705511.2014.973960](https://doi.org/10.1080/10705511.2014.973960)

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. [doi:10.1007/s11336021097670](https://doi.org/10.1007/s11336021097670)

## See Also

Other Continuous Time Mediation Functions: [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)



**Examples**

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
    0.000820587, -0.002532849, 0.001634917,
    -0.001096684, 0.003328692, -0.001926088,
    0.000297815, -0.000871547, 0.002271711,
    -0.000517524, 0.001475579, -0.003705661,
    0.000686386, -0.001926088, 0.004726235
  ),
  nrow = 9
)

# Specific time interval -----
DeltaBeta(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1
)

# Range of time intervals -----
delta <- DeltaBeta(

```

```

    phi = phi,
    vcov_phi_vec = vcov_phi_vec,
    delta_t = 1:5
  )
plot(delta)

# Methods -----
# DeltaBeta has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)

```

---

|                      |   |
|----------------------|---|
| DeltaIndirectCentral | <i>Delta Method Sampling Variance-Covariance Matrix for the Indirect Effect Centrality Over a Specific Time Interval or a Range of Time Intervals</i> |
|----------------------|---|

---

## Description

This function computes the delta method sampling variance-covariance matrix for the indirect effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

## Usage

```
DeltaIndirectCentral(phi, vcov_phi_vec, delta_t, ncores = NULL)
```

## Arguments

|              |  |
|--------------|--|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.                     |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of $\text{vec}(\Phi)$ .  |
| delta_t      | Vector of positive numbers. Time interval ( $\Delta t$ ).  |
| ncores       | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when the length of delta_t is long. |

## Details

See [IndirectCentral\(\)](#) more details.

### Delta Method:

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n} \left( \mathbf{g}(\hat{\boldsymbol{\theta}}) - \mathbf{g}(\boldsymbol{\theta}) \right) \xrightarrow{D} \mathcal{N}(0, \mathbf{J}\boldsymbol{\Gamma}\mathbf{J}')$$

where  $\mathbf{J}$  is the matrix of first-order derivatives of the function  $\mathbf{g}$  with respect to the elements of  $\boldsymbol{\theta}$  and  $\boldsymbol{\Gamma}$  is the asymptotic variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ .

From the former, we can derive the distribution of  $\mathbf{g}(\hat{\boldsymbol{\theta}})$  as follows:

$$\mathbf{g}(\hat{\boldsymbol{\theta}}) \approx \mathcal{N}(\mathbf{g}(\boldsymbol{\theta}), n^{-1}\mathbf{J}\boldsymbol{\Gamma}\mathbf{J}')$$

The uncertainty associated with the estimator  $\mathbf{g}(\hat{\boldsymbol{\theta}})$  is, therefore, given by  $n^{-1}\mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'$ . When  $\boldsymbol{\Gamma}$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ , that is,  $\hat{\mathbf{V}}(\hat{\boldsymbol{\theta}})$  for  $n^{-1}\boldsymbol{\Gamma}$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}(\hat{\boldsymbol{\theta}})$  is given by

$$\mathbf{g}(\hat{\boldsymbol{\theta}}) \approx \mathcal{N}(\mathbf{g}(\boldsymbol{\theta}), \mathbf{J}\hat{\mathbf{V}}(\hat{\boldsymbol{\theta}})\mathbf{J}').$$

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}}\mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t})dt + \boldsymbol{\Sigma}^{\frac{1}{2}}d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

#### Value

Returns an object of class `ctmeddelta` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (DeltaIndirectCentral).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**delta\_t** Time interval.

**jacobian** Jacobian matrix.

**est** Estimated total, direct, and indirect effects.

**vcov** Sampling variance-covariance matrix of the estimated total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:[10.2307/271028](https://doi.org/10.2307/271028)

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:[10.1080/10705511.2014.973960](https://doi.org/10.1080/10705511.2014.973960)

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:[10.1007/s11336021097670](https://doi.org/10.1007/s11336021097670)

### See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

### Examples

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
  )
)
```

```

-0.001619422, 0.000980573, -0.000697798,
0.002079286, -0.001152501, 0.000753,
-0.001528701, 0.000820587, -0.000517524,
0.000885122, -0.00271817, 0.001813471,
-0.001152501, 0.00342605, -0.002075005,
0.000899165, -0.002532849, 0.001475579,
-0.000569404, 0.001618805, -0.004043138,
0.000753, -0.002075005, 0.004984032,
-0.000622255, 0.001634917, -0.003705661,
0.00085493, -0.000586921, 0.000463086,
-0.001528701, 0.000899165, -0.000622255,
0.002060076, -0.001096684, 0.000686386,
-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
DeltaIndirectCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1
)

# Range of time intervals -----
delta <- DeltaIndirectCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5
)
plot(delta)

# Methods -----
# DeltaIndirectCentral has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)

```

## Description

This function computes the delta method sampling variance-covariance matrix for the total, direct, and indirect effects of the independent variable  $X$  on the dependent variable  $Y$  through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

## Usage

```
DeltaMed(phi, vcov_phi_vec, delta_t, from, to, med, ncores = NULL)
```

## Arguments

|              |  |
|--------------|--|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.                     |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of $\text{vec}(\Phi)$ .  |
| delta_t      | Vector of positive numbers. Time interval ( $\Delta t$ ).  |
| from         | Character string. Name of the independent variable $X$ in phi.   |
| to           | Character string. Name of the dependent variable $Y$ in phi.   |
| med          | Character vector. Name/s of the mediator variable/s in phi.  |
| ncores       | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when the length of delta_t is long. |

## Details

See [Total\(\)](#), [Direct\(\)](#), and [Indirect\(\)](#) for more details.

### Delta Method:

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n} \left( \mathbf{g}(\hat{\theta}) - \mathbf{g}(\theta) \right) \xrightarrow{D} \mathcal{N}(0, \mathbf{J}\mathbf{\Gamma}\mathbf{J}')$$

where  $\mathbf{J}$  is the matrix of first-order derivatives of the function  $\mathbf{g}$  with respect to the elements of  $\theta$  and  $\mathbf{\Gamma}$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $\mathbf{g}(\hat{\theta})$  as follows:

$$\mathbf{g}(\hat{\theta}) \approx \mathcal{N}(\mathbf{g}(\theta), n^{-1}\mathbf{J}\mathbf{\Gamma}\mathbf{J}')$$

The uncertainty associated with the estimator  $\mathbf{g}(\hat{\theta})$  is, therefore, given by  $n^{-1}\mathbf{J}\mathbf{\Gamma}\mathbf{J}'$ . When  $\mathbf{\Gamma}$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\theta}$ , that is,  $\hat{\mathbf{V}}(\hat{\theta})$  for  $n^{-1}\mathbf{\Gamma}$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}(\hat{\theta})$  is given by

$$\mathbf{g}(\hat{\theta}) \approx \mathcal{N}(\mathbf{g}(\theta), \mathbf{J}\hat{\mathbf{V}}(\hat{\theta})\mathbf{J}').$$

**Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with } \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with } \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

**Value**

Returns an object of class `ctmeddelta` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (DeltaMed).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**delta\_t** Time interval.

**jacobian** Jacobian matrix.

**est** Estimated total, direct, and indirect effects.

**vcov** Sampling variance-covariance matrix of the estimated total, direct, and indirect effects.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**References**

- Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. [doi:10.2307/271028](https://doi.org/10.2307/271028)
- Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. [doi:10.1080/10705511.2014.973960](https://doi.org/10.1080/10705511.2014.973960)
- Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. [doi:10.1007/s11336021097670](https://doi.org/10.1007/s11336021097670)

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBETA\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPHI\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
    0.000820587, -0.002532849, 0.001634917,
    -0.001096684, 0.003328692, -0.001926088,
    0.000297815, -0.000871547, 0.002271711,
    -0.000517524, 0.001475579, -0.003705661,
    0.000686386, -0.001926088, 0.004726235
  ),
  nrow = 9
)

# Specific time interval -----
DeltaMed(
```



```

    phi = phi,
    vcov_phi_vec = vcov_phi_vec,
    delta_t = 1,
    from = "x",
    to = "y",
    med = "m"
)

# Range of time intervals -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
plot(delta)

# Methods -----
# DeltaMed has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)

```

---

|                   |  |
|-------------------|--|
| DeltaTotalCentral | <i>Delta Method Sampling Variance-Covariance Matrix for the Total Effect Centrality Over a Specific Time Interval or a Range of Time Intervals</i> |
|-------------------|--|

---

## Description

This function computes the delta method sampling variance-covariance matrix for the total effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

## Usage

```
DeltaTotalCentral(phi, vcov_phi_vec, delta_t, ncores = NULL)
```

## Arguments

|              |  |
|--------------|--|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system. |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of vec( $\Phi$ ).  |
| delta_t      | Vector of positive numbers. Time interval ( $\Delta t$ ).  |

ncores                      Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when the length of delta\_t is long.

## Details

See [TotalCentral\(\)](#) more details.

### Delta Method:

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $g$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n} \left( g(\hat{\theta}) - g(\theta) \right) \xrightarrow{D} \mathcal{N}(0, \mathbf{J}\mathbf{\Gamma}\mathbf{J}')$$

where  $\mathbf{J}$  is the matrix of first-order derivatives of the function  $g$  with respect to the elements of  $\theta$  and  $\mathbf{\Gamma}$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $g(\hat{\theta})$  as follows:

$$g(\hat{\theta}) \approx \mathcal{N}(g(\theta), n^{-1}\mathbf{J}\mathbf{\Gamma}\mathbf{J}')$$

The uncertainty associated with the estimator  $g(\hat{\theta})$  is, therefore, given by  $n^{-1}\mathbf{J}\mathbf{\Gamma}\mathbf{J}'$ . When  $\mathbf{\Gamma}$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\theta}$ , that is,  $\hat{\mathbf{V}}(\hat{\theta})$  for  $n^{-1}\mathbf{\Gamma}$ . Therefore, the sampling variance-covariance matrix of  $g(\hat{\theta})$  is given by

$$g(\hat{\theta}) \approx \mathcal{N}(g(\theta), \mathbf{J}\hat{\mathbf{V}}(\hat{\theta})\mathbf{J}').$$

### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \mathbf{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\mathbf{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\mathbf{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}}\mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t})dt + \boldsymbol{\Sigma}^{\frac{1}{2}}d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

**Value**

Returns an object of class `ctmeddelta` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (DeltaTotalCentral).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**delta\_t** Time interval.

**jacobian** Jacobian matrix.

**est** Estimated total, direct, and indirect effects.

**vcov** Sampling variance-covariance matrix of the estimated total, direct, and indirect effects.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**References**

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:[10.2307/271028](https://doi.org/10.2307/271028)

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:[10.1080/10705511.2014.973960](https://doi.org/10.1080/10705511.2014.973960)

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:[10.1007/s11336021097670](https://doi.org/10.1007/s11336021097670)

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBETA\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
```

```

data = c(
  0.002704274, -0.001475275, 0.000949122,
  -0.001619422, 0.000885122, -0.000569404,
  0.00085493, -0.000465824, 0.000297815,
  -0.001475275, 0.004428442, -0.002642303,
  0.000980573, -0.00271817, 0.001618805,
  -0.000586921, 0.001478421, -0.000871547,
  0.000949122, -0.002642303, 0.006402668,
  -0.000697798, 0.001813471, -0.004043138,
  0.000463086, -0.001120949, 0.002271711,
  -0.001619422, 0.000980573, -0.000697798,
  0.002079286, -0.001152501, 0.000753,
  -0.001528701, 0.000820587, -0.000517524,
  0.000885122, -0.00271817, 0.001813471,
  -0.001152501, 0.00342605, -0.002075005,
  0.000899165, -0.002532849, 0.001475579,
  -0.000569404, 0.001618805, -0.004043138,
  0.000753, -0.002075005, 0.004984032,
  -0.000622255, 0.001634917, -0.003705661,
  0.00085493, -0.000586921, 0.000463086,
  -0.001528701, 0.000899165, -0.000622255,
  0.002060076, -0.001096684, 0.000686386,
  -0.000465824, 0.001478421, -0.001120949,
  0.000820587, -0.002532849, 0.001634917,
  -0.001096684, 0.003328692, -0.001926088,
  0.000297815, -0.000871547, 0.002271711,
  -0.000517524, 0.001475579, -0.003705661,
  0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
DeltaTotalCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1
)

# Range of time intervals -----
delta <- DeltaTotalCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5
)
plot(delta)

# Methods -----
# DeltaTotalCentral has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)

```

```
plot(delta)
```

---

Direct

---

*Direct Effect of X on Y Over a Specific Time Interval*


---

### Description

This function computes the direct effect of the independent variable  $X$  on the dependent variable  $Y$  through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

### Usage

```
Direct(phi, delta_t, from, to, med)
```

### Arguments

|         |  |
|---------|--|
| phi     | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system. |
| delta_t | Numeric. Time interval ( $\Delta t$ ).   |
| from    | Character string. Name of the independent variable $X$ in phi.   |
| to      | Character string. Name of the dependent variable $Y$ in phi.   |
| med     | Character vector. Name/s of the mediator variable/s in phi.  |

### Details

The direct effect of the independent variable  $X$  on the dependent variable  $Y$  relative to some mediator variables  $\mathbf{m}$  is given by

$$\text{Direct}_{\Delta t, i, j, \mathbf{m}} = \exp(\Delta t \mathbf{D} \Phi \mathbf{D})_{i, j}$$

where  $\Phi$  denotes the drift matrix,  $\mathbf{D}$  a diagonal matrix where the diagonal elements corresponding to mediator variables  $\mathbf{m}$  are set to zero and the rest to one,  $i$  the row index of  $Y$  in  $\Phi$ ,  $j$  the column index of  $X$  in  $\Phi$ , and  $\Delta t$  the time interval.

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\Theta^{\frac{1}{2}}\right)\left(\Theta^{\frac{1}{2}}\right)' = \Theta$ . The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

### Value

Returns an object of class `ctmedeffect` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used ("Direct").

**output** The direct effect.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:10.1007/s11336021097670

### See Also

Other Continuous Time Mediation Functions: `DeltaBeta()`, `DeltaIndirectCentral()`, `DeltaMed()`, `DeltaTotalCentral()`, `Indirect()`, `IndirectCentral()`, `MCBeta()`, `MCIndirectCentral()`, `MCMed()`, `MCPhi()`, `MCTotalCentral()`, `Med()`, `PosteriorBeta()`, `PosteriorIndirectCentral()`, `PosteriorMed()`, `PosteriorPhi()`, `PosteriorTotalCentral()`, `TestPhi()`, `TestStable()`, `Total()`, `TotalCentral()`

### Examples

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
```

```

    nrow = 3
  )
  colnames(phi) <- rownames(phi) <- c("x", "m", "y")
  delta_t <- 1
  Direct(
    phi = phi,
    delta_t = delta_t,
    from = "x",
    to = "y",
    med = "m"
  )
  phi <- matrix(
    data = c(
      -6, 5.5, 0, 0,
      1.25, -2.5, 5.9, -7.3,
      0, 0, -6, 2.5,
      5, 0, 0, -6
    ),
    nrow = 4
  )
  colnames(phi) <- rownames(phi) <- paste0("y", 1:4)
  Direct(
    phi = phi,
    delta_t = delta_t,
    from = "y2",
    to = "y4",
    med = c("y1", "y3")
  )

```

Indirect

*Indirect Effect of X on Y Through M Over a Specific Time Interval***Description**

This function computes the indirect effect of the independent variable  $X$  on the dependent variable  $Y$  through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

**Usage**

```
Indirect(phi, delta_t, from, to, med)
```

**Arguments**

|         |  |
|---------|--|
| phi     | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system. |
| delta_t | Numeric. Time interval ( $\Delta t$ ).   |
| from    | Character string. Name of the independent variable $X$ in phi.   |

|     |  |
|-----|--|
| to  | Character string. Name of the dependent variable $Y$ in $\phi$ . |
| med | Character vector. Name/s of the mediator variable/s in $\phi$ .  |

### Details

The indirect effect of the independent variable  $X$  on the dependent variable  $Y$  relative to some mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  is given by

$$\text{Indirect}_{\Delta t} = \exp(\Delta t \Phi)_{i,j} - \exp(\Delta t \mathbf{D}_m \Phi \mathbf{D}_m)_{i,j}$$

where  $\Phi$  denotes the drift matrix,  $\mathbf{D}_m$  a matrix where the off diagonal elements are zeros and the diagonal elements are zero for the index/indices of mediator variables  $\mathbf{m}$  and one otherwise,  $i$  the row index of  $Y$  in  $\Phi$ ,  $j$  the column index of  $X$  in  $\Phi$ , and  $\Delta t$  the time interval.

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \mathbf{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\mathbf{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\mathbf{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right) \left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \Phi \boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

### Value

Returns an object of class `ctmedeffect` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used ("Indirect").

**output** The indirect effect.

### Author(s)

Ivan Jacob Agaloos Pesigan



## References

- Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:10.2307/271028
- Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:10.1080/10705511.2014.973960
- Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:10.1007/s11336021097670

## See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

## Examples

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
delta_t <- 1
Indirect(
  phi = phi,
  delta_t = delta_t,
  from = "x",
  to = "y",
  med = "m"
)
phi <- matrix(
  data = c(
    -6, 5.5, 0, 0,
    1.25, -2.5, 5.9, -7.3,
    0, 0, -6, 2.5,
    5, 0, 0, -6
  ),
  nrow = 4
)
colnames(phi) <- rownames(phi) <- paste0("y", 1:4)
Indirect(
  phi = phi,
  delta_t = delta_t,
  from = "y2",
  to = "y4",
```

```

    med = c("y1", "y3")
  )

```

---

|                 |                                   |
|-----------------|-----------------------------------|
| IndirectCentral | <i>Indirect Effect Centrality</i> |
|-----------------|-----------------------------------|

---

## Description

Indirect Effect Centrality

## Usage

```
IndirectCentral(phi, delta_t)
```

## Arguments

|         |  |
|---------|--|
| phi     | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system. |
| delta_t | Vector of positive numbers. Time interval ( $\Delta t$ ).  |

## Author(s)

Ivan Jacob Agaloos Pesigan

## See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

## Examples

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")

# Specific time interval -----
IndirectCentral(
  phi = phi,
  delta_t = 1
)

```

```

# Range of time intervals -----
indirect_central <- IndirectCentral(
  phi = phi,
  delta_t = 1:30
)
plot(indirect_central)

# Methods -----
# IndirectCentral has a number of methods including
# print, summary, and plot
indirect_central <- IndirectCentral(
  phi = phi,
  delta_t = 1:5
)
print(indirect_central)
summary(indirect_central)
plot(indirect_central)

```

---

MCBeta

*Monte Carlo Sampling Distribution for the Elements of the Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals*

---

## Description

This function generates a Monte Carlo method sampling distribution for the elements of the matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

## Usage

```

MCBeta(
  phi,
  vcov_phi_vec,
  delta_t,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL
)

```

## Arguments

|              |  |
|--------------|--|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system. |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of vec( $\Phi$ ).  |

|          |   |
|----------|---|
| delta_t  | Numeric. Time interval ( $\Delta t$ ).  |
| R        | Positive integer. Number of replications.   |
| test_phi | Logical. If test_phi = TRUE, the function runs <code>TestPhi()</code> on the generated drift matrix $\Phi$ . If the <code>TestPhi()</code> returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until <code>TestPhi()</code> returns TRUE. |
| ncores   | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.  |
| seed     | Random seed.  |

### Details

See `Total()`.

#### Monte Carlo Method:

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{\theta} \sim \mathcal{N}(\theta, \mathbb{V}(\hat{\theta}))$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{\theta}^* \sim \mathcal{N}(\hat{\theta}, \hat{\mathbb{V}}(\hat{\theta})).$$

Let  $\mathbf{g}(\hat{\theta})$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}(\hat{\theta})$ , which we refer to as  $\mathbf{g}(\hat{\theta}^*)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to 100  $(1 - \alpha)$  % are the confidence intervals.

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \mathbf{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\mathbf{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\mathbf{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $(\boldsymbol{\Theta}^{\frac{1}{2}})' (\boldsymbol{\Theta}^{\frac{1}{2}})' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \Phi \boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $dW$  is a Wiener process or Brownian motion, which represents random fluctuations.

## Value

Returns an object of class `ctmedmc` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (MCBeta).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**est** A vector of total, direct, and indirect effects.

**thetahatstar** A matrix of Monte Carlo total, direct, and indirect effects.

## Author(s)

Ivan Jacob Agaloos Pesigan

## References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:[10.2307/271028](https://doi.org/10.2307/271028)

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:[10.1080/10705511.2014.973960](https://doi.org/10.1080/10705511.2014.973960)

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:[10.1007/s11336021097670](https://doi.org/10.1007/s11336021097670)

## See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

## Examples

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
```

```

    ),
    nrow = 3
  )
  colnames(phi) <- rownames(phi) <- c("x", "m", "y")
  vcov_phi_vec <- matrix(
    data = c(
      0.002704274, -0.001475275, 0.000949122,
      -0.001619422, 0.000885122, -0.000569404,
      0.00085493, -0.000465824, 0.000297815,
      -0.001475275, 0.004428442, -0.002642303,
      0.000980573, -0.00271817, 0.001618805,
      -0.000586921, 0.001478421, -0.000871547,
      0.000949122, -0.002642303, 0.006402668,
      -0.000697798, 0.001813471, -0.004043138,
      0.000463086, -0.001120949, 0.002271711,
      -0.001619422, 0.000980573, -0.000697798,
      0.002079286, -0.001152501, 0.000753,
      -0.001528701, 0.000820587, -0.000517524,
      0.000885122, -0.00271817, 0.001813471,
      -0.001152501, 0.00342605, -0.002075005,
      0.000899165, -0.002532849, 0.001475579,
      -0.000569404, 0.001618805, -0.004043138,
      0.000753, -0.002075005, 0.004984032,
      -0.000622255, 0.001634917, -0.003705661,
      0.00085493, -0.000586921, 0.000463086,
      -0.001528701, 0.000899165, -0.000622255,
      0.002060076, -0.001096684, 0.000686386,
      -0.000465824, 0.001478421, -0.001120949,
      0.000820587, -0.002532849, 0.001634917,
      -0.001096684, 0.003328692, -0.001926088,
      0.000297815, -0.000871547, 0.002271711,
      -0.000517524, 0.001475579, -0.003705661,
      0.000686386, -0.001926088, 0.004726235
    ),
    nrow = 9
  )

# Specific time interval -----
MCBeta(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  R = 100L # use a large value for R in actual research
)

# Range of time intervals -----
mc <- MCBeta(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  R = 100L # use a large value for R in actual research
)
plot(mc)

```

```
# Methods -----
# MCBeta has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
```

---

|                   |   |
|-------------------|---|
| MCIndirectCentral | <i>Monte Carlo Sampling Distribution of Indirect Effect Centrality Over a Specific Time Interval or a Range of Time Intervals</i> |
|-------------------|---|

---

### Description

This function generates a Monte Carlo method sampling distribution of the indirect effect centrality at a particular time interval  $\Delta t$  using the first-order stochastic differential equation model drift matrix  $\Phi$ .

### Usage

```
MCIndirectCentral(
  phi,
  vcov_phi_vec,
  delta_t,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL
)
```

### Arguments

|              |   |
|--------------|---|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.  |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of $\text{vec}(\Phi)$ .   |
| delta_t      | Numeric. Time interval ( $\Delta t$ ).  |
| R            | Positive integer. Number of replications.   |
| test_phi     | Logical. If test_phi = TRUE, the function runs <code>TestPhi()</code> on the generated drift matrix $\Phi$ . If the <code>TestPhi()</code> returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until <code>TestPhi()</code> returns TRUE. |
| ncores       | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.  |
| seed         | Random seed.  |

## Details

See [IndirectCentral\(\)](#) for more details.

### Monte Carlo Method:

Let  $\boldsymbol{\theta}$  be  $\text{vec}(\boldsymbol{\Phi})$ , that is, the elements of the  $\boldsymbol{\Phi}$  matrix in vector form sorted column-wise. Let  $\hat{\boldsymbol{\theta}}$  be  $\text{vec}(\hat{\boldsymbol{\Phi}})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{\boldsymbol{\theta}} \sim \mathcal{N}(\boldsymbol{\theta}, \mathbb{V}(\hat{\boldsymbol{\theta}}))$$

Using this distributional assumption, a sampling distribution of  $\hat{\boldsymbol{\theta}}$  which we refer to as  $\hat{\boldsymbol{\theta}}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{\boldsymbol{\theta}}^* \sim \mathcal{N}(\hat{\boldsymbol{\theta}}, \hat{\mathbb{V}}(\hat{\boldsymbol{\theta}})).$$

Let  $\mathbf{g}(\hat{\boldsymbol{\theta}})$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}(\hat{\boldsymbol{\theta}})$ , which we refer to as  $\mathbf{g}(\hat{\boldsymbol{\theta}}^*)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100(1 - \alpha)\%$  are the confidence intervals.

### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $(\boldsymbol{\Theta}^{\frac{1}{2}})(\boldsymbol{\Theta}^{\frac{1}{2}})' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

## Value

Returns an object of class `ctmedmc` which is a list with the following elements:



**call** Function call.

**args** Function arguments.

**fun** Function used (MCIndirectCentral).

**output** A list with length of length(delta\_t).

Each element in the output list has the following elements:

**est** A vector of total, direct, and indirect effects.

**thetahatstar** A matrix of Monte Carlo total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:10.1007/s11336021097670

### See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCMed\(\)](#), [MCPPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

### Examples

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
  )
)
```

```

-0.000586921, 0.001478421, -0.000871547,
0.000949122, -0.002642303, 0.006402668,
-0.000697798, 0.001813471, -0.004043138,
0.000463086, -0.001120949, 0.002271711,
-0.001619422, 0.000980573, -0.000697798,
0.002079286, -0.001152501, 0.000753,
-0.001528701, 0.000820587, -0.000517524,
0.000885122, -0.00271817, 0.001813471,
-0.001152501, 0.00342605, -0.002075005,
0.000899165, -0.002532849, 0.001475579,
-0.000569404, 0.001618805, -0.004043138,
0.000753, -0.002075005, 0.004984032,
-0.000622255, 0.001634917, -0.003705661,
0.00085493, -0.000586921, 0.000463086,
-0.001528701, 0.000899165, -0.000622255,
0.002060076, -0.001096684, 0.000686386,
-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
MCIndirectCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  R = 100L # use a large value for R in actual research
)

# Range of time intervals -----
mc <- MCIndirectCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  R = 100L # use a large value for R in actual research
)
plot(mc)

# Methods -----
# MCIndirectCentral has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
plot(mc)

```

MCMed

*Monte Carlo Sampling Distribution of Total, Direct, and Indirect Effects of  $X$  on  $Y$  Through  $M$  Over a Specific Time Interval or a Range of Time Intervals*

## Description

This function generates a Monte Carlo method sampling distribution of the total, direct and indirect effects of the independent variable  $X$  on the dependent variable  $Y$  through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

## Usage

```
MCMed(
  phi,
  vcov_phi_vec,
  delta_t,
  from,
  to,
  med,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL
)
```

## Arguments

|              |  |
|--------------|--|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.   |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of $\text{vec}(\Phi)$ .  |
| delta_t      | Numeric. Time interval ( $\Delta t$ ).   |
| from         | Character string. Name of the independent variable $X$ in phi.   |
| to           | Character string. Name of the dependent variable $Y$ in phi.   |
| med          | Character vector. Name/s of the mediator variable/s in phi.  |
| R            | Positive integer. Number of replications.  |
| test_phi     | Logical. If test_phi = TRUE, the function runs <a href="#">TestPhi()</a> on the generated drift matrix $\Phi$ . If the <a href="#">TestPhi()</a> returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until <a href="#">TestPhi()</a> returns TRUE. |
| ncores       | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.   |
| seed         | Random seed.   |

### Details

See `Total()`, `Direct()`, and `Indirect()` for more details.

#### Monte Carlo Method:

Let  $\boldsymbol{\theta}$  be  $\text{vec}(\boldsymbol{\Phi})$ , that is, the elements of the  $\boldsymbol{\Phi}$  matrix in vector form sorted column-wise. Let  $\hat{\boldsymbol{\theta}}$  be  $\text{vec}(\hat{\boldsymbol{\Phi}})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{\boldsymbol{\theta}} \sim \mathcal{N}(\boldsymbol{\theta}, \mathbb{V}(\hat{\boldsymbol{\theta}}))$$

Using this distributional assumption, a sampling distribution of  $\hat{\boldsymbol{\theta}}$  which we refer to as  $\hat{\boldsymbol{\theta}}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{\boldsymbol{\theta}}^* \sim \mathcal{N}(\hat{\boldsymbol{\theta}}, \hat{\mathbb{V}}(\hat{\boldsymbol{\theta}})).$$

Let  $\mathbf{g}(\hat{\boldsymbol{\theta}})$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}(\hat{\boldsymbol{\theta}})$ , which we refer to as  $\mathbf{g}(\hat{\boldsymbol{\theta}}^*)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100(1 - \alpha)\%$  are the confidence intervals.

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $(\boldsymbol{\Theta}^{\frac{1}{2}})(\boldsymbol{\Theta}^{\frac{1}{2}})' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

### Value

Returns an object of class `ctmedmc` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (MCMed).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**est** A vector of total, direct, and indirect effects.

**thetahatstar** A matrix of Monte Carlo total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. [doi:10.2307/271028](https://doi.org/10.2307/271028)

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. [doi:10.1080/10705511.2014.973960](https://doi.org/10.1080/10705511.2014.973960)

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. [doi:10.1007/s11336021097670](https://doi.org/10.1007/s11336021097670)

### See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

### Examples

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
  )
)
```

```

-0.000586921, 0.001478421, -0.000871547,
0.000949122, -0.002642303, 0.006402668,
-0.000697798, 0.001813471, -0.004043138,
0.000463086, -0.001120949, 0.002271711,
-0.001619422, 0.000980573, -0.000697798,
0.002079286, -0.001152501, 0.000753,
-0.001528701, 0.000820587, -0.000517524,
0.000885122, -0.00271817, 0.001813471,
-0.001152501, 0.00342605, -0.002075005,
0.000899165, -0.002532849, 0.001475579,
-0.000569404, 0.001618805, -0.004043138,
0.000753, -0.002075005, 0.004984032,
-0.000622255, 0.001634917, -0.003705661,
0.00085493, -0.000586921, 0.000463086,
-0.001528701, 0.000899165, -0.000622255,
0.002060076, -0.001096684, 0.000686386,
-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)

# Range of time intervals -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
plot(mc)

# Methods -----
# MCMed has a number of methods including
# print, summary, confint, and plot
print(mc)

```

```
summary(mc)
confint(mc, level = 0.95)
```

MCPhi

*Generate Random Drift Matrices Using the Monte Carlo Method***Description**

This function generates random drift matrices  $\Phi$  using the Monte Carlo method.

**Usage**

```
MCPhi(phi, vcov_phi_vec, R, test_phi = TRUE, ncores = NULL, seed = NULL)
```

**Arguments**

|              |  |
|--------------|--|
| phi          | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.   |
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of $\text{vec}(\Phi)$ .  |
| R            | Positive integer. Number of replications.  |
| test_phi     | Logical. If test_phi = TRUE, the function runs <a href="#">TestPhi()</a> on the generated drift matrix $\Phi$ . If the <a href="#">TestPhi()</a> returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until <a href="#">TestPhi()</a> returns TRUE. |
| ncores       | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.   |
| seed         | Random seed.   |

**Details****Monte Carlo Method:**

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{\theta} \sim \mathcal{N}(\theta, \mathbb{V}(\hat{\theta}))$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{\theta}^* \sim \mathcal{N}(\hat{\theta}, \hat{\mathbb{V}}(\hat{\theta})).$$

**Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \mathbf{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\mathbf{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\mathbf{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

**Value**

Returns a list of simulated drift matrices.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
```



```

MCPhi(
  phi = phi,
  vcov_phi_vec = 0.1 * diag(9),
  R = 100L # use a large value for R in actual research
)
phi <- matrix(
  data = c(
    -6, 5.5, 0, 0,
    1.25, -2.5, 5.9, -7.3,
    0, 0, -6, 2.5,
    5, 0, 0, -6
  ),
  nrow = 4
)
colnames(phi) <- rownames(phi) <- paste0("y", 1:4)
MCPhi(
  phi = phi,
  vcov_phi_vec = 0.1 * diag(16),
  R = 100L, # use a large value for R in actual research
  test_phi = FALSE
)

```

---

|                |  |
|----------------|--|
| MCTotalCentral | <i>Monte Carlo Sampling Distribution of Total Effect Centrality Over a Specific Time Interval or a Range of Time Intervals</i> |
|----------------|--|

---

## Description

This function generates a Monte Carlo method sampling distribution of the total effect centrality at a particular time interval  $\Delta t$  using the first-order stochastic differential equation model drift matrix  $\Phi$ .

## Usage

```

MCTotalCentral(
  phi,
  vcov_phi_vec,
  delta_t,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL
)

```

## Arguments

|     |  |
|-----|--|
| phi | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system. |
|-----|--|

|              |  |
|--------------|--|
| vcov_phi_vec | Numeric matrix. The sampling variance-covariance matrix of $\text{vec}(\Phi)$ .  |
| delta_t      | Numeric. Time interval ( $\Delta t$ ).   |
| R            | Positive integer. Number of replications.  |
| test_phi     | Logical. If test_phi = TRUE, the function runs <a href="#">TestPhi()</a> on the generated drift matrix $\Phi$ . If the <a href="#">TestPhi()</a> returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until <a href="#">TestPhi()</a> returns TRUE. |
| ncores       | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.   |
| seed         | Random seed.   |

### Details

See [TotalCentral\(\)](#) for more details.

#### Monte Carlo Method:

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{\theta} \sim \mathcal{N}(\theta, \mathbb{V}(\hat{\theta}))$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{\theta}^* \sim \mathcal{N}(\hat{\theta}, \hat{\mathbb{V}}(\hat{\theta})).$$

Let  $g(\hat{\theta})$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $g(\hat{\theta})$ , which we refer to as  $g(\hat{\theta}^*)$ , can be generated by using the simulated estimates to calculate  $g$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100(1 - \alpha)\%$  are the confidence intervals.

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \mathbf{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\mathbf{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\mathbf{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $(\boldsymbol{\Theta}^{\frac{1}{2}})(\boldsymbol{\Theta}^{\frac{1}{2}})' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

## Value

Returns an object of class `ctmedmc` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (MCTotalCentral).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**est** A vector of total, direct, and indirect effects.

**thetahatstar** A matrix of Monte Carlo total, direct, and indirect effects.

## Author(s)

Ivan Jacob Agaloos Pesigan

## References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:10.1007/s11336021097670

## See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPHi\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```

set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
    0.000820587, -0.002532849, 0.001634917,
    -0.001096684, 0.003328692, -0.001926088,
    0.000297815, -0.000871547, 0.002271711,
    -0.000517524, 0.001475579, -0.003705661,
    0.000686386, -0.001926088, 0.004726235
  ),
  nrow = 9
)

# Specific time interval -----
MCTotalCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  R = 100L # use a large value for R in actual research
)

```

```
# Range of time intervals -----
mc <- MCTotalCentral(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  R = 100L # use a large value for R in actual research
)
plot(mc)

# Methods -----
# MCTotalCentral has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
plot(mc)
```

---

|     |   |
|-----|---|
| Med | <i>Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals</i> |
|-----|---|

---

**Description**

This function computes the total, direct, and indirect effects of the independent variable  $X$  on the dependent variable  $Y$  through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model’s drift matrix  $\Phi$ .

**Usage**

```
Med(phi, delta_t, from, to, med)
```

**Arguments**

|         |  |
|---------|--|
| phi     | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system. |
| delta_t | Vector of positive numbers. Time interval ( $\Delta t$ ).  |
| from    | Character string. Name of the independent variable $X$ in phi.   |
| to      | Character string. Name of the dependent variable $Y$ in phi.   |
| med     | Character vector. Name/s of the mediator variable/s in phi.  |

**Details**

See [Total\(\)](#), [Direct\(\)](#), and [Indirect\(\)](#) for more details.

### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda}\boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right) \left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\boldsymbol{\iota}$  is a term which is unobserved and constant over time,  $\boldsymbol{\Phi}$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\boldsymbol{\Sigma}$  is the matrix of volatility or randomness in the process, and  $d\mathbf{W}$  is a Wiener process or Brownian motion, which represents random fluctuations.

### Value

Returns an object of class `ctmedmed` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (Med).

**output** A matrix of total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

- Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:10.2307/271028
- Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:10.1080/10705511.2014.973960
- Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:10.1007/s11336021097670

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")

# Specific time interval -----
Med(
  phi = phi,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m"
)

# Range of time intervals -----
med <- Med(
  phi = phi,
  delta_t = 1:30,
  from = "x",
  to = "y",
  med = "m"
)
plot(med)

# Methods -----
# Med has a number of methods including
# print, summary, and plot
med <- Med(
  phi = phi,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
print(med)
summary(med)
plot(med)
```

---

|                 |  |
|-----------------|--|
| plot.ctmeddelta | <i>Plot Method for an Object of Class ctmeddelta</i> |
|-----------------|--|

---

## Description

Plot Method for an Object of Class ctmeddelta

## Usage

```
## S3 method for class 'ctmeddelta'
plot(x, alpha = 0.05, col = NULL, ...)
```

## Arguments

|       |  |
|-------|--|
| x     | Object of class ctmeddelta.                                      |
| alpha | Numeric. Significance level                                      |
| col   | Character vector. Optional argument. Character vector of colors. |
| ...   | Additional arguments.  |

## Author(s)

Ivan Jacob Agaloos Pesigan

## Examples

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
```



```

0.000885122, -0.00271817, 0.001813471,
-0.001152501, 0.00342605, -0.002075005,
0.000899165, -0.002532849, 0.001475579,
-0.000569404, 0.001618805, -0.004043138,
0.000753, -0.002075005, 0.004984032,
-0.000622255, 0.001634917, -0.003705661,
0.00085493, -0.000586921, 0.000463086,
-0.001528701, 0.000899165, -0.000622255,
0.002060076, -0.001096684, 0.000686386,
-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Range of time intervals -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
plot(delta)

```

plot.ctmedmc

*Plot Method for an Object of Class ctmedmc***Description**

Plot Method for an Object of Class ctmedmc

**Usage**

```

## S3 method for class 'ctmedmc'
plot(x, alpha = 0.05, col = NULL, ...)

```

**Arguments**

|       |  |
|-------|--|
| x     | Object of class ctmedmc.   |
| alpha | Numeric. Significance level                                      |
| col   | Character vector. Optional argument. Character vector of colors. |
| ...   | Additional arguments.  |

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```

set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
    0.000820587, -0.002532849, 0.001634917,
    -0.001096684, 0.003328692, -0.001926088,
    0.000297815, -0.000871547, 0.002271711,
    -0.000517524, 0.001475579, -0.003705661,
    0.000686386, -0.001926088, 0.004726235
  ),
  nrow = 9
)

# Range of time intervals -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,

```

```

    delta_t = 1:5,
    from = "x",
    to = "y",
    med = "m",
    R = 100L # use a large value for R in actual research
  )
  plot(mc)

```

---

plot.ctmedmed

---

*Plot Method for an Object of Class ctmedmed*


---

## Description

Plot Method for an Object of Class ctmedmed

## Usage

```

## S3 method for class 'ctmedmed'
plot(x, col = NULL, legend_pos = "topright", ...)

```

## Arguments

|            |  |
|------------|--|
| x          | Object of class ctmedmed.  |
| col        | Character vector. Optional argument. Character vector of colors. |
| legend_pos | Character vector. Optional argument. Legend position.            |
| ...        | Additional arguments.  |

## Author(s)

Ivan Jacob Agaloos Pesigan

## Examples

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")

```

```

# Range of time intervals -----
med <- Med(
  phi = phi,
  delta_t = 1:5,

```

```

    from = "x",
    to = "y",
    med = "m"
  )
  plot(med)

```

---

|               |   |
|---------------|---|
| PosteriorBeta | <i>Posterior Sampling Distribution for the Elements of the Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals</i> |
|---------------|---|

---

### Description

This function generates a posterior sampling distribution for the elements of the matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

### Usage

```
PosteriorBeta(phi, delta_t, ncores = NULL)
```

### Arguments

|         |  |
|---------|--|
| phi     | Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.                                 |
| delta_t | Numeric. Time interval ( $\Delta t$ ).   |
| ncores  | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value. |

### Details

See [Total\(\)](#).

### Value

Returns an object of class `ctmedmc` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (PosteriorBeta).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**est** A vector of total, direct, and indirect effects.

**thetahatstar** A matrix of Monte Carlo total, direct, and indirect effects.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**References**

- Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:[10.2307/271028](https://doi.org/10.2307/271028)
- Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:[10.1080/10705511.2014.973960](https://doi.org/10.1080/10705511.2014.973960)
- Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:[10.1007/s11336021097670](https://doi.org/10.1007/s11336021097670)

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
  )
)
```

```

-0.000622255, 0.001634917, -0.003705661,
0.00085493, -0.000586921, 0.000463086,
-0.001528701, 0.000899165, -0.000622255,
0.002060076, -0.001096684, 0.000686386,
-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

phi <- MCPHi(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  R = 1000L
)$output

# Specific time interval -----
PosteriorBeta(
  phi = phi,
  delta_t = 1
)

# Range of time intervals -----
posterior <- PosteriorBeta(
  phi = phi,
  delta_t = 1:5
)
plot(posterior)

# Methods -----
# PosteriorBeta has a number of methods including
# print, summary, confint, and plot
print(posterior)
summary(posterior)
confint(posterior, level = 0.95)

```

---

PosteriorIndirectCentral

*Posterior Distribution of the Indirect Effect Centrality Over a Specific Time Interval or a Range of Time Intervals*

---

## Description

This function generates a posterior distribution of the indirect effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix  $\Phi$ .

**Usage**

```
PosteriorIndirectCentral(phi, delta_t, ncores = NULL)
```

**Arguments**

|         |  |
|---------|--|
| phi     | List of numeric matrices. Each element of the list is a sample from the posterior distribution of the drift matrix ( $\Phi$ ). Each matrix should have row and column names pertaining to the variables in the system. |
| delta_t | Numeric. Time interval ( $\Delta t$ ).   |
| ncores  | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.   |

**Details**

See [TotalCentral\(\)](#) for more details.

**Value**

Returns an object of class `ctmedmc` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (`PosteriorIndirectCentral`).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**est** Mean of the posterior distribution of the total, direct, and indirect effects.

**thetahatstar** Posterior distribution of the total, direct, and indirect effects.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**References**

- Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. [doi:10.2307/271028](#)
- Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. [doi:10.1080/10705511.2014.973960](#)
- Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. [doi:10.1007/s11336021097670](#)

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBETA\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
    0.000820587, -0.002532849, 0.001634917,
    -0.001096684, 0.003328692, -0.001926088,
    0.000297815, -0.000871547, 0.002271711,
    -0.000517524, 0.001475579, -0.003705661,
    0.000686386, -0.001926088, 0.004726235
  ),
  nrow = 9
)

phi <- MCPHi(
  phi = phi,
```



```

vcov_phi_vec = vcov_phi_vec,
R = 1000L
)$output

# Specific time interval -----
PosteriorIndirectCentral(
  phi = phi,
  delta_t = 1
)

# Range of time intervals -----
posterior <- PosteriorIndirectCentral(
  phi = phi,
  delta_t = 1:5
)

# Methods -----
# PosteriorIndirectCentral has a number of methods including
# print, summary, confint, and plot
print(posterior)
summary(posterior)
confint(posterior, level = 0.95)
plot(posterior)

```

---

PosteriorMed

---

*Posterior Distribution of Total, Direct, and Indirect Effects of  $X$  on  $Y$  Through  $M$  Over a Specific Time Interval or a Range of Time Intervals*


---

## Description

This function generates a posterior distribution of the total, direct and indirect effects of the independent variable  $X$  on the dependent variable  $Y$  through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix  $\Phi$ .

## Usage

```
PosteriorMed(phi, delta_t, from, to, med, ncores = NULL)
```

## Arguments

|         |  |
|---------|--|
| phi     | List of numeric matrices. Each element of the list is a sample from the posterior distribution of the drift matrix ( $\Phi$ ). Each matrix should have row and column names pertaining to the variables in the system. |
| delta_t | Numeric. Time interval ( $\Delta t$ ).   |
| from    | Character string. Name of the independent variable $X$ in phi.   |
| to      | Character string. Name of the dependent variable $Y$ in phi.   |

|        |  |
|--------|--|
| med    | Character vector. Name/s of the mediator variable/s in phi.  |
| ncores | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value. |

### Details

See [Total\(\)](#), [Direct\(\)](#), and [Indirect\(\)](#) for more details.

### Value

Returns an object of class `ctmedmc` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (PosteriorMed).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**est** Mean of the posterior distribution of the total, direct, and indirect effects.

**thetahatstar** Posterior distribution of the total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. [doi:10.2307/271028](#)

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. [doi:10.1080/10705511.2014.973960](#)

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. [doi:10.1007/s11336021097670](#)

### See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
    0.000820587, -0.002532849, 0.001634917,
    -0.001096684, 0.003328692, -0.001926088,
    0.000297815, -0.000871547, 0.002271711,
    -0.000517524, 0.001475579, -0.003705661,
    0.000686386, -0.001926088, 0.004726235
  ),
  nrow = 9
)

phi <- MCPHi(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  R = 1000L
)$output

# Specific time interval -----
PosteriorMed(
  phi = phi,

```

```

    delta_t = 1,
    from = "x",
    to = "y",
    med = "m"
  )

  # Range of time intervals -----
  posterior <- PosteriorMed(
    phi = phi,
    delta_t = 1:5,
    from = "x",
    to = "y",
    med = "m"
  )

  # Methods -----
  # PosteriorMed has a number of methods including
  # print, summary, confint, and plot
  print(posterior)
  summary(posterior)
  confint(posterior, level = 0.95)
  plot(posterior)

```

---

PosteriorPhi

---

*Extract the Posterior Samples of the Drift Matrix*


---

## Description

The function extracts the posterior samples of the drift matrix from a fitted model from the `ctsem::ctStanFit()` function.

## Usage

```
PosteriorPhi(object)
```

## Arguments

`object`                      Object of class `ctStanFit`. Output of the `ctsem::ctStanFit()` function.

## Author(s)

Ivan Jacob Agaloos Pesigan

## See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

---

PosteriorTotalCentral *Posterior Distribution of the Total Effect Centrality Over a Specific Time Interval or a Range of Time Intervals*

---

## Description

This function generates a posterior distribution of the total effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix  $\Phi$ .

## Usage

```
PosteriorTotalCentral(phi, delta_t, ncores = NULL)
```

## Arguments

|         |  |
|---------|--|
| phi     | List of numeric matrices. Each element of the list is a sample from the posterior distribution of the drift matrix ( $\Phi$ ). Each matrix should have row and column names pertaining to the variables in the system. |
| delta_t | Numeric. Time interval ( $\Delta t$ ).   |
| ncores  | Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.   |

## Details

See [TotalCentral\(\)](#) for more details.

## Value

Returns an object of class `ctmedmc` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used (PosteriorTotalCentral).

**output** A list with length of `length(delta_t)`.

Each element in the output list has the following elements:

**est** Mean of the posterior distribution of the total, direct, and indirect effects.

**thetahatstar** Posterior distribution of the total, direct, and indirect effects.

## Author(s)

Ivan Jacob Agaloos Pesigan

## References

- Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:10.2307/271028
- Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:10.1080/10705511.2014.973960
- Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:10.1007/s11336021097670

## See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

## Examples

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
  )
)
```

```

-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

phi <- MCPHi(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  R = 1000L
)$output

# Specific time interval -----
PosteriorTotalCentral(
  phi = phi,
  delta_t = 1
)

# Range of time intervals -----
posterior <- PosteriorTotalCentral(
  phi = phi,
  delta_t = 1:5
)

# Methods -----
# PosteriorTotalCentral has a number of methods including
# print, summary, confint, and plot
print(posterior)
summary(posterior)
confint(posterior, level = 0.95)
plot(posterior)

```

---

|                  |  |
|------------------|--|
| print.ctmeddelta | <i>Print Method for Object of Class ctmeddelta</i> |
|------------------|--|

---

## Description

Print Method for Object of Class ctmeddelta

## Usage

```
## S3 method for class 'ctmeddelta'
print(x, alpha = 0.05, digits = 4, ...)
```

**Arguments**

**x** an object of class `ctmeddelta`.  
**alpha** Numeric vector. Significance level  $\alpha$ .  
**digits** Integer indicating the number of decimal places to display.  
**...** further arguments.

**Value**

Returns a matrix of time interval, estimates, standard errors, test statistics, p-values, and confidence intervals.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
    0.000899165, -0.002532849, 0.001475579,
    -0.000569404, 0.001618805, -0.004043138,
    0.000753, -0.002075005, 0.004984032,
    -0.000622255, 0.001634917, -0.003705661,
    0.00085493, -0.000586921, 0.000463086,
    -0.001528701, 0.000899165, -0.000622255,
    0.002060076, -0.001096684, 0.000686386,
    -0.000465824, 0.001478421, -0.001120949,
  )

```



```

      0.000820587, -0.002532849, 0.001634917,
      -0.001096684, 0.003328692, -0.001926088,
      0.000297815, -0.000871547, 0.002271711,
      -0.000517524, 0.001475579, -0.003705661,
      0.000686386, -0.001926088, 0.004726235
    ),
    nrow = 9
  )

# Specific time interval -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m"
)
print(delta)

# Range of time intervals -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
print(delta)

```

---

|                   |   |
|-------------------|---|
| print.ctmedeffect | <i>Print Method for Object of Class ctmedeffect</i> |
|-------------------|---|

---

## Description

Print Method for Object of Class ctmedeffect

## Usage

```
## S3 method for class 'ctmedeffect'
print(x, digits = 4, ...)
```

## Arguments

|        |   |
|--------|---|
| x      | an object of class ctmedeffect.                             |
| digits | Integer indicating the number of decimal places to display. |
| ...    | further arguments.  |

**Value**

Returns the effects.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
delta_t <- 1

# Time Interval of One -----

## Total Effect -----
total_dt <- Total(
  phi = phi,
  delta_t = delta_t
)
print(total_dt)

## Direct Effect -----
direct_dt <- Direct(
  phi = phi,
  delta_t = delta_t,
  from = "x",
  to = "y",
  med = "m"
)
print(direct_dt)

## Indirect Effect -----
indirect_dt <- Indirect(
  phi = phi,
  delta_t = delta_t,
  from = "x",
  to = "y",
  med = "m"
)
print(indirect_dt)

```

---

|               |   |
|---------------|---|
| print.ctmedmc | <i>Print Method for Object of Class ctmedmc</i> |
|---------------|---|

---

## Description

Print Method for Object of Class ctmedmc

## Usage

```
## S3 method for class 'ctmedmc'
print(x, alpha = 0.05, digits = 4, ...)
```

## Arguments

|        |   |
|--------|---|
| x      | an object of class ctmedmc.                                 |
| alpha  | Numeric vector. Significance level $\alpha$ .               |
| digits | Integer indicating the number of decimal places to display. |
| ...    | further arguments.  |

## Value

Returns a matrix of estimates, standard errors, number of Monte Carlo replications, and confidence intervals.

## Author(s)

Ivan Jacob Agaloos Pesigan

## Examples

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
```

```

0.000949122, -0.002642303, 0.006402668,
-0.000697798, 0.001813471, -0.004043138,
0.000463086, -0.001120949, 0.002271711,
-0.001619422, 0.000980573, -0.000697798,
0.002079286, -0.001152501, 0.000753,
-0.001528701, 0.000820587, -0.000517524,
0.000885122, -0.00271817, 0.001813471,
-0.001152501, 0.00342605, -0.002075005,
0.000899165, -0.002532849, 0.001475579,
-0.000569404, 0.001618805, -0.004043138,
0.000753, -0.002075005, 0.004984032,
-0.000622255, 0.001634917, -0.003705661,
0.00085493, -0.000586921, 0.000463086,
-0.001528701, 0.000899165, -0.000622255,
0.002060076, -0.001096684, 0.000686386,
-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
print(mc)

# Range of time intervals -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
print(mc)

```

**Description**

Print Method for Object of Class ctmedmcphi

**Usage**

```
## S3 method for class 'ctmedmcphi'  
print(x, digits = 4, ...)
```

**Arguments**

|                     |   |
|---------------------|---|
| <code>x</code>      | an object of class ctmedmcphi.                              |
| <code>digits</code> | Integer indicating the number of decimal places to display. |
| <code>...</code>    | further arguments.  |

**Value**

Returns the structure of the output.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```
set.seed(42)  
phi <- matrix(  
  data = c(  
    -0.357, 0.771, -0.450,  
    0.0, -0.511, 0.729,  
    0, 0, -0.693  
  ),  
  nrow = 3  
)  
colnames(phi) <- rownames(phi) <- c("x", "m", "y")  
mc <- MCPHi(  
  phi = phi,  
  vcov_phi_vec = 0.1 * diag(9),  
  R = 100L # use a large value for R in actual research  
)  
print(mc)
```

---

|                |  |
|----------------|--|
| print.ctmedmed | <i>Print Method for Object of Class ctmedmed</i> |
|----------------|--|

---

**Description**

Print Method for Object of Class ctmedmed

**Usage**

```
## S3 method for class 'ctmedmed'
print(x, digits = 4, ...)
```

**Arguments**

|        |   |
|--------|---|
| x      | an object of class ctmedmed.                                |
| digits | Integer indicating the number of decimal places to display. |
| ...    | further arguments.  |

**Value**

Returns a matrix of effects.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")

# Specific time interval -----
med <- Med(
  phi = phi,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m"
)
print(med)

# Range of time intervals -----
```

```

med <- Med(
  phi = phi,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
print(med)

```

---

|                    |   |
|--------------------|---|
| summary.ctmeddelta | <i>Summary Method for an Object of Class ctmeddelta</i> |
|--------------------|---|

---

## Description

Summary Method for an Object of Class ctmeddelta

## Usage

```

## S3 method for class 'ctmeddelta'
summary(object, alpha = 0.05, ...)

```

## Arguments

|        |   |
|--------|---|
| object | Object of class ctmeddelta.                   |
| alpha  | Numeric vector. Significance level $\alpha$ . |
| ...    | additional arguments.                         |

## Value

Returns a matrix of effects, time interval, estimates, standard errors, test statistics, p-values, and confidence intervals.

## Author(s)

Ivan Jacob Agaloos Pesigan

## Examples

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(

```

```

data = c(
  0.002704274, -0.001475275, 0.000949122,
  -0.001619422, 0.000885122, -0.000569404,
  0.00085493, -0.000465824, 0.000297815,
  -0.001475275, 0.004428442, -0.002642303,
  0.000980573, -0.00271817, 0.001618805,
  -0.000586921, 0.001478421, -0.000871547,
  0.000949122, -0.002642303, 0.006402668,
  -0.000697798, 0.001813471, -0.004043138,
  0.000463086, -0.001120949, 0.002271711,
  -0.001619422, 0.000980573, -0.000697798,
  0.002079286, -0.001152501, 0.000753,
  -0.001528701, 0.000820587, -0.000517524,
  0.000885122, -0.00271817, 0.001813471,
  -0.001152501, 0.00342605, -0.002075005,
  0.000899165, -0.002532849, 0.001475579,
  -0.000569404, 0.001618805, -0.004043138,
  0.000753, -0.002075005, 0.004984032,
  -0.000622255, 0.001634917, -0.003705661,
  0.00085493, -0.000586921, 0.000463086,
  -0.001528701, 0.000899165, -0.000622255,
  0.002060076, -0.001096684, 0.000686386,
  -0.000465824, 0.001478421, -0.001120949,
  0.000820587, -0.002532849, 0.001634917,
  -0.001096684, 0.003328692, -0.001926088,
  0.000297815, -0.000871547, 0.002271711,
  -0.000517524, 0.001475579, -0.003705661,
  0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m"
)
summary(delta)

# Range of time intervals -----
delta <- DeltaMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
summary(delta)

```



summary.ctmedmc

*Summary Method for an Object of Class ctmedmc***Description**

Summary Method for an Object of Class ctmedmc

**Usage**

```
## S3 method for class 'ctmedmc'
summary(object, alpha = 0.05, ...)
```

**Arguments**

|        |   |
|--------|---|
| object | Object of class ctmedmc.                      |
| alpha  | Numeric vector. Significance level $\alpha$ . |
| ...    | additional arguments.                         |

**Value**

Returns a matrix of effects, time interval, estimates, standard errors, test statistics, p-values, and confidence intervals.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
```

```

0.000949122, -0.002642303, 0.006402668,
-0.000697798, 0.001813471, -0.004043138,
0.000463086, -0.001120949, 0.002271711,
-0.001619422, 0.000980573, -0.000697798,
0.002079286, -0.001152501, 0.000753,
-0.001528701, 0.000820587, -0.000517524,
0.000885122, -0.00271817, 0.001813471,
-0.001152501, 0.00342605, -0.002075005,
0.000899165, -0.002532849, 0.001475579,
-0.000569404, 0.001618805, -0.004043138,
0.000753, -0.002075005, 0.004984032,
-0.000622255, 0.001634917, -0.003705661,
0.00085493, -0.000586921, 0.000463086,
-0.001528701, 0.000899165, -0.000622255,
0.002060076, -0.001096684, 0.000686386,
-0.000465824, 0.001478421, -0.001120949,
0.000820587, -0.002532849, 0.001634917,
-0.001096684, 0.003328692, -0.001926088,
0.000297815, -0.000871547, 0.002271711,
-0.000517524, 0.001475579, -0.003705661,
0.000686386, -0.001926088, 0.004726235
),
nrow = 9
)

# Specific time interval -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
summary(mc)

# Range of time intervals -----
mc <- MCMed(
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
summary(mc)

```

**Description**

Summary Method for an Object of Class ctmedmed

**Usage**

```
## S3 method for class 'ctmedmed'
summary(object, digits = 4, ...)
```

**Arguments**

|        |   |
|--------|---|
| object | an object of class ctmedmed.                                |
| digits | Integer indicating the number of decimal places to display. |
| ...    | further arguments.  |

**Value**

Returns a matrix of effects.

**Author(s)**

Ivan Jacob Agaloos Pesigan

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
```

```
# Specific time interval -----
med <- Med(
  phi = phi,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m"
)
summary(med)
```

```
# Range of time intervals -----
med <- Med(
  phi = phi,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
```

```
)
summary(med)
```

---

```
summary.ctmedposteriorphi
```

*Summary Method for Object of Class ctmedposteriorphi*

---

## Description

Summary Method for Object of Class ctmedposteriorphi

## Usage

```
## S3 method for class 'ctmedposteriorphi'
summary(object, ...)
```

## Arguments

|        |                                       |
|--------|---------------------------------------|
| object | an object of class ctmedposteriorphi. |
| ...    | further arguments.                    |

## Value

Returns a list of the posterior means (in matrix form) and covariance matrix.

## Author(s)

Ivan Jacob Agaloos Pesigan

## Examples

```
set.seed(42)
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
mc <- MCPHi(
  phi = phi,
  vcov_phi_vec = 0.1 * diag(9),
  R = 100L # use a large value for R in actual research
)$output
summary(mc)
```

TestPhi

*Test the Drift Matrix***Description**

Both have to be true for the function to return TRUE.

- Test that the real part of all eigenvalues of  $\Phi$  is less than zero.
- Test that the diagonal values of  $\Phi$  are between 0 to negative infinity.

**Usage**

```
TestPhi(phi)
```

**Arguments**

phi                      Numeric matrix. The drift matrix ( $\Phi$ ).

**Author(s)**

Ivan Jacob Agaloos Pesigan

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestStable\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

**Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
TestPhi(phi = phi)
phi <- matrix(
  data = c(
    -6, 5.5, 0, 0,
    1.25, -2.5, 5.9, -7.3,
    0, 0, -6, 2.5,
    5, 0, 0, -6
  ),
  nrow = 4
)
```

```
)
colnames(phi) <- rownames(phi) <- paste0("y", 1:4)
TestPhi(phi = phi)
```

---

TestStable

*Test Stability*


---

## Description

The function computes the eigenvalues of the input matrix `x`. It checks if the real part of all eigenvalues is negative. If all eigenvalues have negative real parts, the system is considered stable.

## Usage

```
TestStable(x)
```

## Arguments

`x`                      Numeric matrix.

## Author(s)

Ivan Jacob Agaloos Pesigan

## See Also

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [Total\(\)](#), [TotalCentral\(\)](#)

## Examples

```
x <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
TestStable(x)
x <- matrix(
  data = c(
    -6, 5.5, 0, 0,
    1.25, -2.5, 5.9, -7.3,
    0, 0, -6, 2.5,
    5, 0, 0, -6
  ),
  nrow = 4
)
```

```

    ),
    nrow = 4
  )
  TestStable(x)

```

---

Total

*Total Effect Matrix Over a Specific Time Interval*


---

### Description

This function computes the total effects matrix over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

### Usage

```
Total(phi, delta_t)
```

### Arguments

**phi** Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.

**delta\_t** Numeric. Time interval ( $\Delta t$ ).

### Details

The total effect matrix over a specific time interval  $\Delta t$  is given by

$$\text{Total}_{\Delta t} = \exp(\Delta t \Phi)$$

where  $\Phi$  denotes the drift matrix, and  $\Delta t$  the time interval.

#### Linear Stochastic Differential Equation Model:

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \mathbf{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Theta})$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\mathbf{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time  $t$  and individual  $i$ .  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\mathbf{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}(\mathbf{0}, \mathbf{I})$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right) \left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ .

The dynamic structure is given by

$$d\boldsymbol{\eta}_{i,t} = (\boldsymbol{\iota} + \Phi \boldsymbol{\eta}_{i,t}) dt + \boldsymbol{\Sigma}^{\frac{1}{2}} d\mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $dW$  is a Wiener process or Brownian motion, which represents random fluctuations.

### Value

Returns an object of class `ctmedeffect` which is a list with the following elements:

**call** Function call.

**args** Function arguments.

**fun** Function used ("Total").

**output** The matrix of total effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. *Sociological Methodology*, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. *Structural Equation Modeling: A Multidisciplinary Journal*, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. *Psychometrika*, 87 (1), 214–252. doi:10.1007/s11336021097670

### See Also

Other Continuous Time Mediation Functions: `DeltaBeta()`, `DeltaIndirectCentral()`, `DeltaMed()`, `DeltaTotalCentral()`, `Direct()`, `Indirect()`, `IndirectCentral()`, `MCBeta()`, `MCIndirectCentral()`, `MCMed()`, `MCPhi()`, `MCTotalCentral()`, `Med()`, `PosteriorBeta()`, `PosteriorIndirectCentral()`, `PosteriorMed()`, `PosteriorPhi()`, `PosteriorTotalCentral()`, `TestPhi()`, `TestStable()`, `TotalCentral()`

### Examples

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
delta_t <- 1
Total(
  phi = phi,
```



```

    delta_t = delta_t
  )
  phi <- matrix(
    data = c(
      -6, 5.5, 0, 0,
      1.25, -2.5, 5.9, -7.3,
      0, 0, -6, 2.5,
      5, 0, 0, -6
    ),
    nrow = 4
  )
  colnames(phi) <- rownames(phi) <- paste0("y", 1:4)
  Total(
    phi = phi,
    delta_t = delta_t
  )

```

---

|              |                                |
|--------------|--------------------------------|
| TotalCentral | <i>Total Effect Centrality</i> |
|--------------|--------------------------------|

---

**Description**

Total Effect Centrality

**Usage**

TotalCentral(phi, delta\_t)

**Arguments**

- phi                    Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.
- delta\_t                Vector of positive numbers. Time interval ( $\Delta t$ ).

**Author(s)**

Ivan Jacob Agaloos Pesigan

**See Also**

Other Continuous Time Mediation Functions: [DeltaBeta\(\)](#), [DeltaIndirectCentral\(\)](#), [DeltaMed\(\)](#), [DeltaTotalCentral\(\)](#), [Direct\(\)](#), [Indirect\(\)](#), [IndirectCentral\(\)](#), [MCBeta\(\)](#), [MCIndirectCentral\(\)](#), [MCMed\(\)](#), [MCPhi\(\)](#), [MCTotalCentral\(\)](#), [Med\(\)](#), [PosteriorBeta\(\)](#), [PosteriorIndirectCentral\(\)](#), [PosteriorMed\(\)](#), [PosteriorPhi\(\)](#), [PosteriorTotalCentral\(\)](#), [TestPhi\(\)](#), [TestStable\(\)](#), [Total\(\)](#)

**Examples**

```

phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")

# Specific time interval -----
TotalCentral(
  phi = phi,
  delta_t = 1
)

# Range of time intervals -----
total_central <- TotalCentral(
  phi = phi,
  delta_t = 1:30
)
plot(total_central)

# Methods -----
# IndirectCentral has a number of methods including
# print, summary, and plot
total_central <- TotalCentral(
  phi = phi,
  delta_t = 1:5
)
print(total_central)
summary(total_central)
plot(total_central)

```

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